Static Accommodation in Congenital Nystagmus

Editha Ong, Kenneth J. Ciuffreda, and Barry Tannen

Purpose. To conduct a comparative study of static accommodative function between individuals with normal vision (n = 10) and patients with congenital nystagmus (n = 12).

Methods. The component contribution to monocular steady-state accommodation (slope of the accommodative stimulus/response function, accommodative controller gain, tonic accommodation, and depth-of-focus) was assessed subjectively using a Hartinger coincidence-optometer, except for depth-of-focus, which was determined psychophysically.

Results. The group mean slope for the patients with nystagmus was not significantly different from that found in the normal subjects. However, their variability was markedly increased. Therefore, the patients with nystagmus were divided into three subgroups with regard to the normal accommodative stimulus/response function slope criterion. The majority of patients with nystagmus (n = 10) exhibited slopes that were outside of normal limits, being greater than (n = 4) or less than (n = 6) the normal range. Depth-of-focus was the only parameter found to be significantly different between the normal and the nystagmus groups. When the nystagmus group was divided with respect to etiology—ie, albinotic (n = 4) versus idiopathic (n = 8)—there were no significant differences found for the various accommodative parameters.

Conclusions. We speculate that the primary component contributing to the anomalous accommodative behavior was the increased depth-of-focus, with this perhaps being related to abnormal fixational eye movements and eccentric fixation, and more generally related to overall reduced sensitivity resulting from the early abnormal visual experience.

Accommodation refers to the ability to alter the dioptric power of the crystalline lens to maximize retinal-image contrast and clarity. It is influenced by a variety of stimulus parameters, including target vergence, contrast, spatial frequency composition, eccentricity, and retinal-image motion. Studies that have investigated the relation between accommodation and stimulus parameter effectiveness in individuals with normal vision have demonstrated that an optimal accommodative stimulus is represented by a stationary, high-contrast square-wave grating positioned at the fovea. Introduction of sub-optimal stimulus conditions, such as increased target motion, may adversely affect the quality of the retinal image and reduce accommodative accuracy. Of particular interest in the present study was the clinical condition of nystagmus. It exists in approximately 0.025% of the general population. Nystagmus frequently is of an idiopathic, congenital origin and is characterized by a binocularly conjugate, involuntary rhythmic oscillation of the eyes. This abnormal movement is broadly classified into pendular or jerk waveforms. The former type is characterized by an oscillation that has similar velocities in each direction, whereas the latter is characterized by markedly unequal velocities in each direction that consist of a slow
Therefore, the present study was conducted to investigate the role of an error-producing component followed by a fast error-correcting saccade. Either type of eye movement waveform can be quantified in terms of parameters such as amplitude, frequency, intensity, maximum slow-phase velocity, and foveation duration.\textsuperscript{7–10}

As a result of these abnormal eye movements, retinal-image motion is considerably increased in patients with nystagmus. This motion typically exhibits maximum velocities that exceed 3 deg/sec,\textsuperscript{9} which have been shown to impair a variety of vision functions, including visual acuity,\textsuperscript{11} threshold contrast perception,\textsuperscript{12} and visual discrimination.\textsuperscript{13} Such abnormal retinal-image motion also may cause the attenuation or even elimination of the high spatial frequency components of a square-wave-type target such as a clinical Snellen test letter, effectively "smearing" its sharp borders.\textsuperscript{14} Such motion also may decrease apparent target contrast.\textsuperscript{7} Moreover, most patients with nystagmus exhibit reduced sensory-based visual acuity\textsuperscript{15} and motor-based eccentric fixation.\textsuperscript{16} Any of the above factors have the potential to degrade the quality of the retinal image enough to reduce accommodative stimulus effectiveness.

Relatively little is known about the overall visual performance in nystagmus; this is especially true regarding accommodative ability. Ciuffreda and Goldrich\textsuperscript{17} measured the steady-state accommodative stimulus/response function and found increased accommodative error. However, only a single subject was tested, and average accommodative error was the sole parameter considered. Dickinson\textsuperscript{18} reported that accommodation followed the typical stimulus/response curve in her five patients with congenital nystagmus tested. However, no data or analysis was provided. Therefore, the present study was conducted to investigate more comprehensively, and in a relatively large group of subjects, the components of steady-state accommodative function in nystagmus.

**MATERIALS AND METHODS**

The subjects consisted of 10 individuals with normal vision and 12 patients with congenital nystagmus (8 idiopathic patients, 4 albinos). The normal group consisted of faculty and students from SUNY/State College of Optometry. Their ages ranged from 21–34 yr, with a mean of 28 yr. All had a corrected Snellen visual acuity of at least 20/20 in the tested eye, with a mean spherical equivalent refractive error of $-1.51 \pm 0.46$ D (standard error of the mean). The male-female ratio was 3:7. None of the subjects reported or had evidence of ocular, systemic, or neurologic disease. The group of patients with nystagmus was recruited from the Oculomotor Diagnostic and Biofeedback Therapy Clinic and the Low Vision Clinic at SUNY/State College of Optometry. Their ages ranged from 17–40 yr, with a mean of 30 yr. The corrected Snellen visual acuity ranged from 20/20 to 20/200. The mean spherical equivalent refractive error for the tested eye was $-1.40 \pm 0.69$ D (SEM), with a preponderance of with-the-rule astigmatism ($\kappa = -2.18$ D $\times 5$), as has been found by others.\textsuperscript{10,19} The male-female ratio was 11:1. This much higher incidence of males in the nystagmus population is consistent with previous studies.\textsuperscript{4,5,19} Both groups of subjects had amplitudes of accommodation measured with the subjective clinical "push-up" technique\textsuperscript{20} of at least 1 D beyond the highest dioptric stimulus level tested to minimize response saturation effects.\textsuperscript{21} Clinical data for each of the subjects are presented in Tables 1 and 2. Informed consent was obtained from all subjects.

**TABLE 1. Summary of Clinical and Experimental Results of Normal Subjects**

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age (yr)</th>
<th>Refractive State (Right Eye; dipters)</th>
<th>VA</th>
<th>Est Acc S/R Slope</th>
<th>DF (±D)</th>
<th>TA (D)</th>
<th>ACG (±D)</th>
<th>Abso AE (3 D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VN1</td>
<td>21</td>
<td>$-1.50$ sph</td>
<td>20/20</td>
<td>0.80</td>
<td>0.48</td>
<td>0.83</td>
<td>6.53</td>
<td>0.68</td>
</tr>
<tr>
<td>VN2</td>
<td>22</td>
<td>Plano</td>
<td>20/15</td>
<td>0.72</td>
<td>0.69</td>
<td>0.25</td>
<td>12.95</td>
<td>0.43</td>
</tr>
<tr>
<td>VN3</td>
<td>23</td>
<td>$-4.00$ sph with $-0.75$ cyl $\times 180$</td>
<td>20/15</td>
<td>0.69</td>
<td>0.87</td>
<td>1.27</td>
<td>7.01</td>
<td>0.68</td>
</tr>
<tr>
<td>VN4</td>
<td>25</td>
<td>$-0.50$ sph</td>
<td>20/20</td>
<td>0.69</td>
<td>0.74</td>
<td>1.60</td>
<td>—</td>
<td>0.06</td>
</tr>
<tr>
<td>VN5</td>
<td>28</td>
<td>$-2.25$ sph</td>
<td>20/15</td>
<td>0.80</td>
<td>0.18</td>
<td>1.27</td>
<td>1.93</td>
<td>1.02</td>
</tr>
<tr>
<td>VN6</td>
<td>28</td>
<td>$-1.00$ sph</td>
<td>20/15</td>
<td>0.67</td>
<td>0.32</td>
<td>1.81</td>
<td>17.56</td>
<td>0.28</td>
</tr>
<tr>
<td>VN7</td>
<td>31</td>
<td>$-1.75$ sph</td>
<td>20/15</td>
<td>0.67</td>
<td>0.31</td>
<td>2.08</td>
<td>3.99</td>
<td>0.08</td>
</tr>
<tr>
<td>VN8</td>
<td>32</td>
<td>Plano</td>
<td>20/15</td>
<td>0.80</td>
<td>0.54</td>
<td>1.79</td>
<td>3.14</td>
<td>0.39</td>
</tr>
<tr>
<td>VN9</td>
<td>34</td>
<td>$-3.25$ sph</td>
<td>20/15</td>
<td>0.69</td>
<td>0.28</td>
<td>2.42</td>
<td>2.07</td>
<td>0.40</td>
</tr>
<tr>
<td>VN10</td>
<td>34</td>
<td>$-1.00$ cyl $\times 90$</td>
<td>20/20</td>
<td>0.66</td>
<td>0.40</td>
<td>2.38</td>
<td>4.82</td>
<td>0.50</td>
</tr>
<tr>
<td>Mean</td>
<td>28</td>
<td>$-1.51$ sph eq</td>
<td>—</td>
<td>0.72</td>
<td>0.48</td>
<td>1.57</td>
<td>6.67</td>
<td>0.45</td>
</tr>
<tr>
<td>±SEM</td>
<td>1.55</td>
<td>0.46</td>
<td>—</td>
<td>0.02</td>
<td>0.07</td>
<td>0.22</td>
<td>1.77</td>
<td>0.09</td>
</tr>
</tbody>
</table>

from all subjects was obtained before the experiment began and after a full description of the procedures had been given. The tenets of the Declaration of Helsinki were followed, and institutional human experimentation committee approval was obtained.

Steady-state accommodation was measured monocularly in the right eye using a subjective Hartinger coincidence-optometer based on the Scheiner’s principle (Fig. 1). This optometer recently was shown to provide readings identical to that found using an open-field, infrared recording optometer with Snel- len-type visual stimuli. Appropriate refractive correction was placed in the spectacle plane over the right eye, whereas the left eye was fully occluded during the experimental session. Head movement was restrained by a chin and headrest assembly. The optometer target consisted of two sets of three vertically oriented, dimly illuminated bars (1.6° vertical, 0.8° horizontal) viewed under approximately open-looped conditions afforded by the 1 mm exit pupil of the optometer.

After a period of total darkness for 5 min to allow any accommodative hysteresis effects to dissipate, pre-task tonic accommodation was assessed in total darkness except for the dim open-loop optometer bars. To minimize potential proximal influences, the sub-
jects were instructed to “gaze beyond” the optometer bars into the distance. The two sets of optometer bar targets initially were displaced in alternating lateral directions by the experimenter. They then were gradu-
ally moved toward each other, until precise vertical alignment of the bars was reported by the subject upon depression of a hand-held clicker, with this value representing the refractive state of the eye (ie, pre-task tonic accommodation).

The accommodative stimulus/response function

TABLE 2. Summary of Clinical and Experimental Results in Patients With Nystagmus

<table>
<thead>
<tr>
<th>Subject/ Age (yr)</th>
<th>Refractive State (Right Eye; diopters)</th>
<th>Visual Acuity (RE)</th>
<th>Der Ecc Fix (deg)</th>
<th>Amp. (deg)</th>
<th>Freq (Hz)</th>
<th>Int (deg-Hz)</th>
<th>Max Slow Phase Vel (deg/sec)</th>
<th>Est Fov Dur (ms)</th>
<th>Est S/R Slope (±D)</th>
<th>TA (D)</th>
<th>ACG (3D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A/30†</td>
<td>+2.00 — 4.50 X5</td>
<td>20/100</td>
<td>Jerk</td>
<td>0.91</td>
<td>2.09</td>
<td>4.70</td>
<td>9.82</td>
<td>41.80</td>
<td>150</td>
<td>1.08</td>
<td>0.83</td>
</tr>
<tr>
<td>1B/32‡</td>
<td>-1.75 — 2.25 X180</td>
<td>20/60</td>
<td>Jerk</td>
<td>2.39</td>
<td>5.12</td>
<td>3.25</td>
<td>16.64</td>
<td>72.44</td>
<td>113</td>
<td>0.93</td>
<td>1.97</td>
</tr>
<tr>
<td>1C/38†</td>
<td>+0.25</td>
<td>20/60</td>
<td>Jerk</td>
<td>—</td>
<td>2.20</td>
<td>2.60</td>
<td>5.72</td>
<td>20.60</td>
<td>—</td>
<td>1.18</td>
<td>0.19</td>
</tr>
<tr>
<td>1D/20</td>
<td>+1.50 — 1.25 X180</td>
<td>20/70</td>
<td>Jerk</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.96</td>
<td>0.40</td>
</tr>
<tr>
<td>2A/23</td>
<td>-1.00 — 4.50 X180</td>
<td>20/40</td>
<td>Jerk</td>
<td>0.58</td>
<td>3.27</td>
<td>5.22</td>
<td>17.07</td>
<td>32.91</td>
<td>48</td>
<td>0.70</td>
<td>0.69</td>
</tr>
<tr>
<td>2B/39‡</td>
<td>+5.00 — 2.50 X10</td>
<td>20/100</td>
<td>Jerk</td>
<td>1.18</td>
<td>5.96</td>
<td>3.87</td>
<td>23.07</td>
<td>57.35</td>
<td>50</td>
<td>0.76</td>
<td>2.51</td>
</tr>
<tr>
<td>3A/17</td>
<td>-0.75 — 2.00 X20</td>
<td>20/100</td>
<td>Jerk</td>
<td>—</td>
<td>1.72</td>
<td>2.43</td>
<td>4.18</td>
<td>10.58</td>
<td>178</td>
<td>0.48</td>
<td>2.07</td>
</tr>
<tr>
<td>3B/24</td>
<td>-3.50 — 1.50 X180</td>
<td>20/30</td>
<td>Jerk</td>
<td>0.39</td>
<td>4.77</td>
<td>4.23</td>
<td>20.18</td>
<td>45.55</td>
<td>40</td>
<td>0.52</td>
<td>1.16</td>
</tr>
<tr>
<td>3C/27†</td>
<td>+0.75 — 1.50 X180</td>
<td>20/200</td>
<td>Pend</td>
<td>6.49</td>
<td>11.11</td>
<td>4.77</td>
<td>52.99</td>
<td>139.40</td>
<td>27</td>
<td>0.59</td>
<td>1.41</td>
</tr>
<tr>
<td>3D/30†</td>
<td>-1.25 — 1.00 X135</td>
<td>20/30</td>
<td>Pend</td>
<td>0.76</td>
<td>1.29</td>
<td>4.05</td>
<td>5.22</td>
<td>17.56</td>
<td>60</td>
<td>0.21</td>
<td>0.76</td>
</tr>
<tr>
<td>3E/38‡</td>
<td>-3.00 — 2.25 X70</td>
<td>20/100</td>
<td>Jerk</td>
<td>0.04</td>
<td>2.42</td>
<td>2.39</td>
<td>5.78</td>
<td>19.67</td>
<td>160</td>
<td>0.47</td>
<td>0.59</td>
</tr>
<tr>
<td>3F/40</td>
<td>-3.00 — 0.75 X180</td>
<td>20/20</td>
<td>Jerk</td>
<td>0.25</td>
<td>1.46</td>
<td>3.15</td>
<td>4.60</td>
<td>8.94</td>
<td>134</td>
<td>0.56</td>
<td>0.93</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>±SEM</td>
<td>0.69</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Indicates albinos.
† Received auditory biofeedback training.
‡ Indicates the presence of strabismus.

Subject subgroups: IA-D (high slopes); 2A-B (normal slopes); 3A-D (low slopes).

then was generated using a target that consisted of a high-contrast, reduced Snellen visual acuity chart (total angular extent = 3°) with letters ranging from 20/40 to 20/200. This chart was incorporated into Badal’s system, which ensured that retinal-image size and illumination remained constant.22 The Snellen chart (luminance = 50 cd/m²) was illuminated with a tungsten filament lamp and was reflected into the eye by a partially silvered mirror. The subjects were instructed to fixate a letter from the row of letters that was at or one line above their visual resolution limit. The position of the optometer bars then was adjusted until they were immediately adjacent to the fixated letter (Fig. 1, inset). The subjects were instructed to keep the letter in focus at all times, but to refrain from exerting any special effort21; patients with nystagmus were told to refrain from adopting any learned or trained strategy to control their eye movements.8,17 While attempting to maintain accurate fixation and focus, the subject’s task was to report vertical alignment of the optometer bars. This value represented the steady-state accommodative response. The dioptric stimulus levels generally were 0, 1, 2, 2.5, 3, 4, 5, 5.5, and 6 D, although most subjects did not receive all stimuli because of amplitude limitations.

The order of stimulus presentation, as well as initial offset magnitude and direction of the optometer targets, were randomized. Brief rest periods between measurements were provided, wherein the subjects were instructed to gaze and focus upon a set of vertical 1 cycle per degree black-and-white square-wave gratings that subtended an angle of 5° outside the instrument located 3 feet from the subject to minimize fatigue and accommodative hysteresis effects. Immediately after the accommodative stimulus/response function was measured, post-task tonic accommodation was obtained to assess possible hysteresis effects. Six measurements were taken at each stimulus condition and referenced to the corneal plane to approximate their ocular accommodation. From this information, the slope over the linear region (excluding the <2 D nonlinear region)22 of the accommodative stimulus/response function (closed-loop system gain) could be determined.

The patients with nystagmus who underwent 5–15 wk of previous successful biofeedback training (n = 6),8,17,26 were, in addition, re-assessed at accommodative stimuli levels of 0 and 2.5 D. However, they were now explicitly instructed to adopt whatever strategy they learned during their biofeedback training to stop or reduce their abnormal eye movements. Aside from this difference in the instruction set to this subgroup of patients with nystagmus, the experimental procedures were identical to the above.

Depth-of-focus for each subject was measured subjectively using the apparatus shown in Figure 2.22,27,28

![FIGURE 2. Schematic diagram of the experimental apparatus used to measure depth-of-focus (top view, not drawn to scale). UB, uniformly illuminated diffuse background. T, target. BL, Badal’s lens. FLA, field-limiting aperture. EP, eye patch. Target configuration is shown in inset.](image-url)

It consisted of a back-illuminated, high-contrast complex target presented within Badal’s optical system. Target configuration was composed of black-and-white pie-shaped sectors arranged in a circular fashion (Fig. 2, inset). The sectors subtended an angle of 48 at their extreme peripheral ends and tapered to a fine point (<1.5 min arc) centrally. Moreover, they were superimposed on three black concentric circles of increasing diameters, with the inner, middle, and outermost circles subtending angles of 2.0°, 4.8°, and 8.0°, respectively. The target was physically divided, with the two vertical halves juxtaposed to one another. The left hemifield was fixed at a stimulus value of 1.5 D, whereas the proximal/distal dioptric position of the right half could be adjusted manually by the experimenter. The subject’s head and chin were positioned in their respective rests. The left eye was fully occluded; the right eye viewed the target through the appropriate refractive correction in the spectacle plane. The left and right targets initially were positioned in the same optical plane (1.5 D). The subject was instructed to fixate and to keep in focus the central portion of the inner circle and nearby pie-sectors on the stationary target. The experimenter then very slowly (approximately 0.05 D/sec) displaced the right half of the target in one direction, proximally or distally, until the subject indicated with a hand-held clicker slight blur of the immediate right side while maintaining fixation and clarity of focus on the central left half.

The initial direction of displacement of the right half of the target was randomized. The measurements
FIGURE 3. Block diagram of the static model of the accommodative system. The difference between the accommodative stimulus (AS) and accommodative response (AR) is the accommodative error (AE). DF represents one-half the depth-of-focus, ACG is the accommodative controller gain, and TA is tonic accommodation. AE1 is the output of AE after DF; the PLANT represents the peripheral accommodative apparatus. (Adapted from Hung and Semmlow, 1980.)

were repeated for a total of two readings in each direction. They were averaged and converted to diopters to obtain the total depth-of-focus. These data, including the tonic accommodation values, were used to calculate the accommodative controller gain (open-loop system gain) based on the model equation:

\[
\text{accommodative controller gain} = \frac{(\text{accommodative response} - \text{tonic accommodation})}{(\text{final steady-state accommodative error} - 1/2 \text{ depth of focus})}
\]

(Fig. 3) for data points in the linear response range of the accommodative stimulus/response function.

Eye movement records were obtained independently for each patient with nystagmus at the Oculomotor Diagnostic and Biofeedback Therapy Clinic at SUNY/State College of Optometry. Horizontal eye position was measured objectively using the infrared reflection technique (0.25° resolution, ±8° linearity) and recorded on a three-channel strip chart recorder (0–40 Hz bandwidth). Calibration was performed using a three-point paradigm (5° left, center, 5° right); the error in calibration, and in the estimate of eccentric fixation, was approximately 0.25°–0.5°. Amplitude and frequency were obtained from non-continuous samples of the eye movement records that totaled at least 11–38 sec and 28–58 sec, respectively. Intensity was calculated by multiplying the amplitude by its frequency. Maximum slow-phase velocity, on the other hand, was obtained as the average from discrete portions of records from at least 10–17 sec. Estimated (motor-based) eccentric fixation was derived from taking the time-average position of the eye during the nystagmus slow-phase, with the mean being obtained from random samples that totaled 15 beats. Estimated foveation duration was taken as the time interval per nystagmus beat during which the eye was judged to be stationary by direct visual inspection of the eye movement records. This represented baseline/foveation and was averaged across 15 cycles of nystagmus.

RESULTS

The accommodative findings for each of the subjects are presented in Tables 1 and 2. Group mean accommodative stimulus/response functions for the normal subjects and the patients with nystagmus are shown in Figure 4. Regression analysis over the linear range of the functions indicated that the slope was 0.72 ± 0.02 (SEM) with a range of 0.66–0.80 for the normal subjects and 0.70 ± 0.08 (SEM) with a range of 0.21–1.18

FIGURE 4. Group accommodative stimulus/response functions for the subjects with normal vision and patients with nystagmus. The corresponding symbols, linear regression functions, and correlations are as indicated. Sample size for the normal group was 10; sample size for the patients with nystagmus was at least 9 for all the closed symbol data and equal to or less than 5 for the open symbol data. The 1:1 line is the theoretical accommodative demand line. Symbols and error bars represent the group mean ± 1 SEM.
for the patients with nystagmus. This difference in slope was not significant (t-test, \( P > 0.05 \)). However, the group variability in slope (ie, SEM) for the patients with nystagmus was significantly greater (4X) than that of the normal subjects (\( F = 24.24, \text{df} = 11.9, P < 0.005 \)). The nystagmus accommodative data therefore were divided into subgroups according to a slope criterion (Fig. 5). A plot for a representative subject from each subgroup also is shown in Fig. 6. The individual slopes for the first subgroup (\( n = 4 \)) were at least 3 SEMs greater than the mean slope of the normal group. The second subgroup (\( n = 2 \)) consisted of individuals whose slope was within ±3 SEMs of the normal group mean. The last nystagmus subgroup (\( n = 6 \)) had individual slopes that were at least 3 SEMs below that of the normal subjects’ mean value. Nystagmus slope means were 1.04, 0.73, and 0.47 for subgroups 1, 2, and 3, respectively. A one-way analysis of variance confirmed that the accommodative response differences among the normal group and the three nystagmus subgroups were significant (\( F = 28.11, \text{df} = 3,18, P < 0.001 \)). Furthermore, Tukey’s honestly significant difference (HSD) test indicated that significant differences existed between all groups (\( P < 0.05 \)), except (as expected) the second nystagmus subgroup and the normal group.

Both inter- and intra-subject response variability were greater in the patients with nystagmus than in the normal subjects. Regarding inter-subject variability, the group mean SEM was 0.13 D ± 0.02 for the normal subjects (across all stimulus levels) and 0.24 D ± 0.03 for the patients with nystagmus (across a stimulus range of 0–5 D). With respect to intra-subject variability, the patients with nystagmus showed an increased mean and range of SDs for far and near tar-
gets in each subject. They exhibited a mean SD of 0.42 D (range 0.09–1.03) and 0.36 D (range 0.12–0.63) for accommodative stimulus levels 0 and 3 D, respectively. In contrast, the normal subjects exhibited a mean SD of 0.24 D (range 0.12–0.34) and 0.25 D (range 0.09–0.47) for accommodative stimulus levels 0 and 3 D, respectively.

The mean absolute accommodative error for the normal subjects and patients with nystagmus is shown in Figure 7. It was 50% greater in the patients with nystagmus than in the normal subjects. However, only at stimulus levels of 1, 4, and 6 D was the mean absolute accommodative error significantly greater in the patients with nystagmus (t-test, \( P < 0.01 \)).

In addition to the accommodative slope and related absolute accommodative error, other accommodative parameters investigated included accommodative controller gain (ACG), tonic accommodation (TA), and depth-of-focus (DF; Fig. 2). The corresponding group mean (±1 SEM) ACG, TA, and \( \frac{1}{2} \)DF were 6.67 ± 1.77, 1.57 ± 0.22 D and 0.48 ± 0.07 D, respectively, for the normal subjects and 7.83 ± 3.05, 1.38 ± 0.24 D, and 1.11 ± 0.20 D, respectively, for the patients with nystagmus. These are graphically presented in Figure 8. The only parameter with a significant group mean difference was depth-of-focus (t = −2.75, \( P < 0.02 \)). The one-way analysis of variance for the normal subjects and the nystagmus subgroups also revealed a significant difference only for DF (F = 3.23, df = 3.18, \( P < 0.05 \)). However, Tukey’s HSD test showed no significant difference. This lack of subgroup significance appears to have resulted from the relatively low probability of our analysis of variance test (\( P = 0.046 \)) and the reduced power of the post-hoc comparison analysis with the reduced sample sizes.

There was no significant correlation between slope of the accommodative stimulus/response function and the other accommodative parameters (\( P > 0.05 \)). Correlation performed between each of the four accommodative parameters and the six eye movement parameters indicated that significant correlations were found only between ACG and nystagmus frequency \( (r = −0.71, P < 0.05) \) and between ACG and saccade duration \( (r = +0.74, P < 0.05) \). A lack of significant correlation \( (P > 0.05) \) was found between the four accommodative parameters and the clinically derived Snellen visual acuity.

The eye movement results for each of the patients with nystagmus are presented in Table 2. Eye movement parameter values were determined for the patients with nystagmus based on objective recordings. The means (±1 SEM) of amplitude, frequency, intensity, maximum slow-phase velocity, derived eccentric fixation, and estimated saccade duration were: 3.76° ± 0.88°, 3.70 ± 0.30 Hz, 15.02 ± 4.33 deg-Hz, 42.38 ± 11.44 deg/sec, 1.44° ± 0.67°, and 96 ± 17.98 ms. Significant positive correlations were found between Snellen acuity and eye movement amplitude \( (r = 0.70, P < 0.02) \), intensity \( (r = 0.69, P < 0.02) \), maximum slow-phase velocity \( (r = 0.72, P < 0.02) \), and derived eccentric fixation \( (r = 0.80, P < 0.02) \).

For the patients with nystagmus who underwent successful auditory biofeedback training \((n = 6)\), group mean accommodative responses increased in magnitude by approximately 25% (from 1.78 ± 0.18 D to 2.25 ± 0.30 D) and 35% (from 1.96 ± 0.37 D to 2.66

![Figure 7. Histogram of the group mean absolute accommodative error as a function of accommodative stimulus level. Bar graphs and error bars represent the group mean ± 1 SEM. No data for stimulus levels 2.5 and 5.5 D were obtained for the normal subjects.](http://iovs.arvojournals.org/pdfaccess.ashx?url=/data/journals/iovs/933395/ on 06/24/2017)

![Figure 8. Plot of the group data for the different accommodative parameters. AS/R slope, accommodative stimulus/response slope in the linear range. DF, one-half depth-of-focus. TA, tonic accommodation. ACG, accommodative controller gain. Units for DF and TA are in diopters. Plotted is the mean ± 1 SEM. Sample sizes are as indicated, except for ACG, where \( n = 9 \).](http://iovs.arvojournals.org/pdfaccess.ashx?url=/data/journals/iovs/933395/ on 06/24/2017)
biofeedback training (from 1.78 ± 0.18 D to 2.25 ± 0.30 D), whereas it decreased slightly (from 0.83 ± 0.24 D to 0.66 ± 0.28 D) for the 2.5 D stimulus level. However, the group mean pre/post-dioptric differences were not significant at either stimulus level (t-test, \( P > 0.05 \)).

A separate analysis also was conducted in which the nystagmus group was subdivided with respect to etiology into idiopathic patients and albinos. There was no significant difference between the two subgroups for the four accommodative parameters (t-test, \( P > 0.15 \)). Therefore, both groups contributed to the overall finding of increased depth-of-focus in the patients with nystagmus. Lack of difference in the four accommodative parameters also was true when the above two subgroups were compared with the normal subjects (Tukey’s HSD, \( P > 0.05 \)). This is consistent with our earlier analysis of variance result when the three nystagmus slope-derived subgroups were compared with the normal subjects. Finally, when the albinos were excluded, there was significant correlation between slope and ACG (\( r = +0.78, P < 0.05 \)).

DISCUSSION

The present finding of abnormal accommodative behavior in the majority of patients with nystagmus is not completely surprising. This initially might be attributed to their general overall increase in retinal-image motion. The abnormal eye movements, in and of themselves, present a less than ideal situation for appropriate stimulation of the accommodative system. Eye movements result in smearing of the target’s edges, adversely affecting its retinal contrast gradient.2 This also reduces the target’s high spatial frequency components.3 Previous work6–8 has demonstrated that the absence of higher-order, odd-harmonics may adversely affect the accuracy of static and dynamic accommodation,9,32,35 preventing the system from “fine-tuning” its accommodative response.35

More specifically, what is the effect of the jerk nystagmus slow-phase on steady-state accommodative accuracy? First, there is the continuous increase in slow-phase velocity. Recent results in individuals with normal vision have shown that retinal-image motion greater than approximately 10°/sec (range 6–12°/sec) was sufficient to degrade accommodation, with the response approaching the tonic accommodative level.2,3 Therefore, the period of extended foveation (≤5°/sec) plus the subsequent slow-phase component (5–10°/sec) can provide some degree of blur stimulation to the accommodative system. This is consistent with the work of others regarding detailed vision tasks, such as visual acuity.4,9 However, for nondetailed vision tasks, such as detecting a flash of light38 or target motion,39 the entire slow-phase period may be useful.

Second, there is the continuous increase in retinal eccentricity. Eye movements cause the retinal image to impinge upon different retinal loci at various times during the slow phase of the nystagmus, with these foveal and near eccentric retinal loci continually changing the effective accommodative stimulation, hence increasing accommodative variability.1,124,41 This is consistent with the increased response variability found in the present group of patients with nystagmus. As a result of this, the retinal image would impinge, on average, at a peripheral locus that produces slightly reduced accommodative gain compared to the fovea. Using a time-average definition, essentially all patients with nystagmus would exhibit some degree of (motor-based) eccentric fixation,16 with the present group of patients with nystagmus showing a mean (derived) eccentric fixation of 1.4°. However, the effect of eccentric stimulation depends upon nystagmus slow-phase velocity. Only when the velocity is less than 10°/sec, with the target still providing some degree of accommodative stimulus effectiveness, would eccentricity also contribute to the reduced accommodation. Above 10°/sec, the retinal-image motion is too rapid to provide much stimulation to the accommodative system, regardless of the degree of eccentric retinal stimulation; thus, the accommodative response would transiently and passively drift to its tonic level. This demonstrates the presence of a critical and complex velocity/eccentricity interaction. A similar argument regarding constantly changing retinal image velocity and eccentricity can be made for the subjects with pendular nystagmus.

The patients who reduced their nystagmus using a strategy learned during prior eye movement auditory biofeedback treatment showed little consistent improvement in accommodative accuracy, although there was a tendency for the mean accommodative error to decrease by approximately 0.20 D at near. Note that despite the presence of eye movements that constantly displaced the eyes away from the object of regard, there also were compensatory saccadic eye movements in the opposite direction. These corrective eye movements function to re-establish foveation. These periods of foveation, albeit of short duration (27–178 ms; mean 96 ms), apparently were sufficient to enable the subject to assess accommodative stimulus magnitude, detect the accommodative error, and respond within the tolerance imposed by the quality of the retinal image and subsequent neurosensory processing limitations. Furthermore, each of these patients already had consistent periods of extended foveation (\( \bar{x} = 107 \) ms; \( n = 5 \)) without biofeedback. Therefore, it is not surprising that the improved fixa-
tional ability with biofeedback had only a relatively small positive impact on steady-state accommodative accuracy, because the biofeedback did not necessarily enable them to attain an average slow-phase velocity of less than 10°/sec most of the time.

We speculate that the degradation effects of eye movements during the early development of the visual system must have imposed critical limitations on its sensory development. This is evident from our data that show a significantly increased depth-of-focus for the group of patients with nystagmus. Furthermore, the increased depth-of-focus also may explain the atypical response profiles of the patients with nystagmus. Because the accommodative system under monocular viewing conditions responds primarily to defocus blur, an increased depth-of-focus would mean that an object can be moved within a greater range of distances before it is perceived as out-of-focus, and therefore be capable of driving the accommodative system. Within the depth-of-focus range, the system essentially is in the open-loop mode and receives no feedback regarding its response accuracy. Thus, the patients with nystagmus could respond in either direction—i.e., exhibit considerable over-accommodation or under-accommodation relative to that of normal subjects without inducing a perceptible change in the quality of the retinal image. This has been suggested in normal subjects, wherein accommodation was less accurate and responded in either direction to sub-optimal blur stimuli consisting of low spatial frequency sinusoids. In other words, the accommodative system responded in an even-error manner, considering only blur magnitude and not direction. The direction of the static error then may be regarded as somewhat inconsequential, because it would not adversely affect retinal-image quality in any perceptually unique manner.

The rationale behind the patients with nystagmus assuming a particular directional accommodative response is only speculative at this point. Under-accommodation relative to the normal subjects is expected and is more consistent with typical findings from investigations in patients who manifest various ocular abnormalities (e.g., amblyopia), because nonoptimal visual systems generally demonstrate reduced accommodative function. Over-accommodation, on the other hand, may reflect an unconscious effort by the patient with nystagmus under everyday binocular conditions to try to “see better,” which then is carried into the monocular experimental paradigm to induce more (perhaps voluntary convergence-accommodation) accommodation. The latter would lead to increased convergence that might dampen the nystagmus. This also may explain why accommodative responses increased in magnitude at the two tested dioptric levels when the subjects were instructed to adopt the strategy they learned during previous auditory biofeedback training sessions. Alternatively, and perhaps more likely, the patients with nystagmus may find the target difficult to accommodate upon because of their increased retinal-image motion; therefore, they may exert more attention and effort to focus accurately, the result being blur-induced accommodative overdrive.

The absence of a significant correlation between most accommodation and eye movement parameters may be due to the complexity of the dynamic interactions of the eye movement parameters. As a result, demonstrating the isolated effects of any single component may be difficult, although it has been suggested that waveform, and thus foveation duration, may indicate a person’s visual capability, with pendular waveforms exhibiting the smallest percent foveation time per cycle. The present results revealed a significant correlation between ACG and foveation duration, which is consistent with the above idea. In addition, the two patients with nystagmus who exhibited pendular waveforms in the present study were classified as belonging to the subgroup characterized by their slopes being significantly less than normal limits.

Our findings suggest that the abnormal underlying neurology is responsible for the anomalous accommodative behavior in congenital nystagmus. The latter could be attributed to the abnormal visual experience resulting from the onset of nystagmus very early in life. The presence of these abnormal eye movements, especially at critical stages of development, perhaps coupled with the high uncorrected astigmatism exhibited by most patients with nystagmus, have been suggested to produce neural deficits. Eye movements result in increased retinal-image motion. This, as an isolated entity, reduces the quality of the retinal image. Because of the degraded retinal image, the developing and immature visual neurologic system does not have the opportunity to “fine-tune” and develop maximally, resulting in its impaired sensory development. The findings of increased depth-of-focus in the present subjects and poorer contrast sensitivity for patterns lying orthogonal to the primary direction of oscillation support this notion.

It is conceivable that accommodative function also would be impaired after such abnormal rearing conditions. Apparently, the normal development of the visual system of a patient with nystagmus is disrupted at this early stage and remains somewhat immature throughout life. However, the degree of such disruption in albinos, with their congenitally maldeveloped fovea and already poor neurosensory system, is predicted to be less. Therefore, even if the nystagmoid eye movements were now controlled and reduced to within normal limits, the accommodative function of patients with nystagmus, although it may improve slightly, would not necessarily normalize, because accommodative accuracy will not be any better than that...
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delimited by the underlying suboptimally developed neurologic substrate.

Key Words
accommodation, eye movements, depth-of-focus, nystagmus, retinal-image motion.

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