Effect of Horizontal Vergence on the Motor and Sensory Components of Vertical Fusion

Naoto Hara,1 Heimo Steffen,2,3 Dale C. Roberts,2 and David S. Zee2

PURPOSE. To compare motor and sensory capabilities for fusion of vertical disparities at different angles of horizontal vergence in healthy humans.

METHODS. Eye movements were recorded from both eyes of 12 healthy subjects using three-axis search coils. The stimulus was a cross (+) (3.4 × 3.2°, vertically and horizontally, respectively) presented to each eye with a stereoscopic display. Vertical disparities were introduced by adjusting the vertical position of the cross in front of one eye. The disparity was increased in small increments (0.08°) every 8 seconds. Viewing was defined as “near” if there was a horizontal disparity that elicited 6° to 15° convergence, depending on the subject’s capability for horizontal fusion; viewing was defined as “far” at 1° convergence. Maximum motor (measured), sensory (stimulus minus motor), and total (motor plus sensory) vertical fusion were compared.

RESULTS. In 9 (75%) of 12 subjects the maximum total vertical fusion was more in near than in far viewing. The three who did not show this effect had relatively weak horizontal fusion. For the entire group, the motor component differed significantly between far (mean, 1.42°) and near (mean, 2.13°). Total vertical fusion capability (motor plus sensory) also differed significantly between far (mean, 1.68°) and near (mean, 2.39°). For the sensory component there was no difference between far (mean, 0.268°) and near (mean, 0.270°). As vertical disparity increased in a single trial, however, there was a small gradual increase of the contribution of the sensory component to vertical fusion.

CONCLUSIONS. Vertical fusion capability usually increases with convergence. This increase is caused primarily by an increase in the motor component. There is a gradual but small increase in the sensory component as target disparity slowly increases.

The capability for fusion of vertical disparities is much less robust than that for horizontal disparities.1-5 If the vertical disparity is introduced gradually, a larger value of vertical disparity can be fused.6 Training has been shown to improve vertical fusion capability.7-10 and larger than normal vertical fusion capabilities have been shown in patients with vertical strabismus.11-12 There is also evidence of a sensory component of the fusion response, but the motor component (vertical vergence) dominates the vertical fusion response.13,14

The influence of the fixation distance on the capability of vertical fusion has been largely neglected, although Gräfe15 reported, in examining himself, that near viewing considerably increased the capability of vertical fusion. The amplitude of vertical fusion, viewing at 10 cm, was larger (6°) than viewing at 6 m (3°). In contrast, Berens et al.1 studied 218 men and found no difference in vertical fusion capability (mean, −2.5°) when viewing at 6 m or 25 cm. Eye movements were measured in neither of these studies, and the relative contributions of motor and sensory mechanisms to vertical fusion for near versus far targets are therefore unknown. We examined the effect of convergence on the motor and the sensory components of vertical fusion.

METHODS

Subjects

Twelve people (seven men and five women, aged 27–37 years) participated in this study. All provided their informed written consent according to a protocol conforming to the Declaration of Helsinki and approved by the Johns Hopkins Joint Committee on Clinical Investigation. Four subjects had myopia to a maximum of −5.00 diopters. They wore their full spectacle correction. None had anisometropia greater than 1.50 D. All had normal stereoscopic vision, determined by the Titmus test.

Visual Stimuli

The stimulus was a cross, with a bar thickness of 0.16°, subtending 3.4 × 3.2° vertically and horizontally, respectively. It was generated with a virtual-reality stereoscopic display, with a field of view of 19° horizontally and 16° vertically. The stereoscopic display was calibrated by having a subject superimpose the stimulus generated by the virtual-reality display on a calibrated array of light-emitting diodes, while viewing with...
Effect of Horizontal Vergence on Vertical Fusion

Figure 1. Vertical vergence responses from one subject. Vertical stimulus disparity (i.e., target disparity) in degrees is on the abscissa, and the motor and sensory components of fusion in degrees are on the ordinate (right eye minus left eye). The (o) indicates the vertical disparity. The solid line represents the mean amplitude of the motor component, with the SD (error bars) calculated over 21 points in a period of 2 seconds (every 10th sample) during stable fixation at each target disparity. The arrows indicate the point just before fusion was lost. (A) Response to stimulus R/L-r in far viewing; (B) response to stimulus L/R-r in near viewing. Note the gradual increase in the sensory and motor components.

Recording of Eye Movements and Calibration Procedure

Horizontal, vertical, and torsional eye movements were recorded using the magnetic field search coil method with dual coils annuli (horizontal, vertical, and torsional). An accurate calibration was ensured by calibrating the dual coils in vitro as described by Straumann et al. The annuli were then placed on each eye after administration of a topical anesthetic (proparacaine HCl 0.5%, Ophthetic; Allergan, Irvine, CA). Subjects sat with the head at the center of the magnetic field and immobilized with a bite bar. The output signals from the phase detectors were filtered with a bandwidth of 0 Hz to 90 Hz and sampled by a digital computer at 100 Hz with 12-bit resolution.
System noise limited resolution to approximately 0.05°. Data were stored to disc for later off-line analysis using commercial software (MATLAB; Mathworks). The positions of the eyes were calculated in rotation vectors. Because we were primarily interested in the vertical and torsional response to vertical disparity, we expressed eye movement data in a Fick coordinate reference frame.19 For subjects who wore their corrective spectacles during testing (subjects 1, 2, 6, and 12), the stimulus disparity was scaled according to the magnification factor of the spectacles that was determined behaviorally during refixations around an array of light-emitting diodes. To describe torsion, we adopted the convention that positive torsion refers to excyclorotation of the right eye (RE) and incyclorotation of the left eye (LE), that is, clockwise in relation to the subject.

**Experimental Protocol**

At the beginning of each trial the crosses were adjusted to zero vertical disparity, as described. The alignment of both eyes was recorded during a period of 10 seconds with zero disparity. The disparity was then changed by increments of 0.08° every 8 seconds. Subjects were instructed to attempt to maintain single vision and to report when images became persistently double. At the end of each paradigm, the crosses were readjusted to zero disparity. When fixation was stable, the horizontal, vertical, and torsional positions of the eyes were checked to look for coil slippage. This paradigm was performed at two vergence angles ("far" and "near") with four stimulus patterns presented in the same order.
TABLE 1. The Change in Size of the Sensory Component

<table>
<thead>
<tr>
<th>Subjects</th>
<th>Far Viewing</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>Near Viewing</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Slope</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Slope</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.294</td>
<td>0.95</td>
<td>26</td>
<td>&lt;0.001</td>
<td>0.247</td>
<td>0.95</td>
<td>34</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.273</td>
<td>0.87</td>
<td>14</td>
<td>&lt;0.001</td>
<td>0.065</td>
<td>0.67†</td>
<td>23</td>
<td>0.180</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.075</td>
<td>0.75</td>
<td>43</td>
<td>&lt;0.001</td>
<td>0.170</td>
<td>0.87</td>
<td>67</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.542</td>
<td>0.94</td>
<td>11</td>
<td>&lt;0.001</td>
<td>0.137</td>
<td>0.72</td>
<td>19</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.256</td>
<td>0.98</td>
<td>27</td>
<td>&lt;0.001</td>
<td>0.221</td>
<td>0.86</td>
<td>25</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.160</td>
<td>0.93</td>
<td>8</td>
<td>&lt;0.014</td>
<td>0.329</td>
<td>0.94</td>
<td>43</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.299</td>
<td>0.58†</td>
<td>10</td>
<td>0.084</td>
<td>0.182</td>
<td>0.64</td>
<td>21</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.199</td>
<td>0.68</td>
<td>20</td>
<td>&lt;0.004</td>
<td>0.037</td>
<td>-0.20†</td>
<td>14</td>
<td>0.470</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0.207</td>
<td>0.82</td>
<td>25</td>
<td>&lt;0.001</td>
<td>0.227</td>
<td>0.72</td>
<td>23</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.186</td>
<td>0.86</td>
<td>14</td>
<td>&lt;0.001</td>
<td>0.060</td>
<td>0.53</td>
<td>24</td>
<td>0.011</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>0.264</td>
<td>0.98</td>
<td>22</td>
<td>&lt;0.001</td>
<td>0.119</td>
<td>0.49†</td>
<td>11</td>
<td>0.116</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>0.112</td>
<td>0.90</td>
<td>43</td>
<td>&lt;0.001</td>
<td>0.062</td>
<td>0.86</td>
<td>63</td>
<td>&lt;0.001</td>
<td></td>
</tr>
</tbody>
</table>

* The number of the sensory component at each stimulus disparity in one trial.
† Not significant; Spearman’s rank correlation test.

1. Right over left (R/L-r): The stimulus for the RE was moved up.
2. Right over left (R/L-l): The stimulus for the LE was moved down.
3. Left over right (L/R-r): The stimulus for the RE was moved down.
4. Left over right (L/R-l): The stimulus for the LE was moved up.

At far viewing, the eyes had a convergence angle of 1°. At near viewing, a symmetrical horizontal convergence angle of 15° was elicited. If necessary, the horizontal disparity was reduced to 6° to 14° depending on the person’s ability to maintain horizontal fusion. This vergence angle was used for the near viewing experiment. Trials lasted from 4 to 9 minutes depending on the fusion capability. Subjects rested for at least 1 minute between trials to minimize any phoria adaptation. One trial was obtained for each of the four stimulus conditions.

Data Analysis

The relative vertical alignment or vertical vergence was calculated by subtracting the vertical position of the LE from the RE. Horizontal and torsional alignments were calculated in a similar manner. We selected the largest vertical fusion response from each subject across all stimulus combinations for each viewing distance. Sensory fusion was defined as the difference between the total vertical fusion response (determined by the size of the target disparity) and the motor component (vertical vergence). A 2-second epoch of stable fixation was selected just before the next disparity was imposed, and eye position was sampled every 100 msec during this 2-second period. The amounts of vertical and torsional eye movement were measured relative to the zero position of each eye before any disparity was introduced and the position of the eyes immediately before fusion was lost. The maximum responses in far and near viewing in all subjects were compared using the Wilcoxon signed rank test, and correlations were calculated using Spearman’s rank correlation test.

RESULTS

Vertical Fusion Responses

A typical vertical fusion response for one subject in far viewing is shown in Figure 1A. The total fusion response, determined by the target disparity immediately before the perception of diplopia, was 3.36°, consisting of a motor component of 3.27° and a sensory component of 0.09°. The response of the same subject in near viewing, with 10° of convergence is shown in Figure 1B. The total vertical fusion was 5.36°, with a motor component of 5.04° and a sensory component of 0.32°. This subject had a particularly robust response.

Correlation between Vertical Fusion and the Motor and Sensory Components

The total, motor, and sensory components of the maximum fusion responses for each individual in far viewing and in near viewing are shown (Fig. 2A, 2B, 2C, respectively). In 8 of 12 subjects, vertical fusion capability was better in far viewing. In one subject there was little difference, and in three subjects vertical fusion capability was worse in near viewing. These four subjects had a relatively weak capability for horizontal fusion. The convergence position in near viewing was 10°, 7°, and 10° in the three subjects, with a better response at distance and 6° in the subject who showed little difference between near and far viewing. The mean values among subjects for total vertical fusion (Fig. 2A) were significantly different (1.68° in far viewing, and 2.39° in near viewing; P = 0.045; Wilcoxon signed rank test). Similarly, the mean readings for the motor component (Fig. 2B) were significantly different (1.42° in far viewing and 2.13° in near viewing; P = 0.015). For the sensory component, however, there was no significant difference between the means (0.268° in far viewing, and 0.270° in near viewing; P = 0.754). Note also the relatively small range of values for the sensory component among subjects. The motor component compensated for 62% to 99% (0.44°-3.30°) of the disparity in far viewing and 76% to 98% (0.68°-5.04°) in near viewing. Consequently, the range of the sensory component in all subjects was from 1% to 38% of the
overall vertical fusion in far viewing and 2% to 24% in near viewing. These results led to the general conclusion that the increase in the value for maximum vertical fusion associated with convergence was primarily caused by an increase in the motor component.

During the individual trials, as vertical disparity was gradually increased, there was also an increase in the sensory component. This change in the sensory component in one subject who had a particularly large capability of vertical fusion is shown in Figure 3. The correlation in all subjects between target disparity and the sensory component of vertical fusion is listed in Table 1. In almost all subjects there was a strong correlation between target disparity and the sensory component of vertical fusion. In each subject, however, there were no significant differences ($P = 0.077$, Wilcoxon signed rank test) between the slopes (vertical disparity versus sensory component) in far and near viewing.

Pattern of Vertical Eye Movement

The four patterns of eye movements that were made in response to a vertical disparity imposed by moving the target in front of one eye only are shown in Figure 4. In the version type (Fig. 4A) both eyes moved, showing a conjugate and a disconjugate response. This was the most common pattern (six subjects in far viewing and seven in near viewing). In the monocular type (Fig. 4B), only the eye exposed to the target that changed position moved; the fellow eye remained stationary. This pattern was seen in four subjects in far viewing and in two subjects in near viewing. In the pure vergence type (Fig. 4C), both eyes moved in opposite directions. Only one subject, in far and near viewing, showed this pattern. This pattern was seen in four subjects in far viewing and in two subjects in near viewing. In the fluctuating type (Fig. 4D), the response in a given trial could not be easily classified and was variable. Two subjects in far viewing and two subjects in near viewing showed this pattern. Five subjects showed the same pattern of response in far and near viewing.
The left-over-right (L/R stimulus) disparity produced maximum total fusion in 9 (75%) of 12 subjects in far viewing and in 8 (67%) in near viewing. These percentages were not significantly different from that expected in a random occurrence ($P > 0.5$; Fisher’s exact test). Six subjects, however, showed the maximum response to the same disparity direction in the same eye at both distances. Eight responded best to the target moving in the same eye between far and near viewing. In seven subjects we determined the dominant eye by a pointing test and found no correlation between the results of that test and the eye that remained closest to the target.

**Pattern of Torsional Eye Movement**

We also examined the correlation between the direction of vertical fusion and cyclovergence or cycloversion. Torsional eye movements were measured relative to a reference position (zero) of each eye (before any disparity was introduced). In four subjects at both distances, there appeared to be torsional coil slippage during the stimulus presentation, because the zero position changed before and after the stimulus presentation. The change in torsion coil position was greater than one SD, which ranged from 0.78° to 1.25° in all subjects, depending on the viewing distance and stimulus configuration. We excluded data from these four subjects. Illustrated in Figure 5 are the torsional eye movements that occurred in response to the L/R disparity in a subject in far viewing (Fig. 5A) and in a subject in near viewing (Fig. 5B). Although the direction of the vertical disparity was the same, the pattern of change in cycloversion was opposite. In Figure 5C, data are shown from the same trial as data shown in Figure 4C. This subject had the pure vergence type of response. Cycloversion showed only a small counterclockwise change (in relation to the subject) toward the end of the trial. Neither the amount of cycloversion (Fig. 6A) nor cycloversion (Fig. 6B) was correlated with the motor component of vertical fusion in the eight subjects without slippage of the coil. All correlations are shown in Table 2.

**DISCUSSION**

The main finding of this study is that when the eyes converged, the capability for vertical fusion was increased. We showed further that the increased capability for vertical fusion in near viewing was primarily caused by an increase in the motor component of fusion; the sensory component changes little. The subjects who had the largest capability of vertical fusion in far viewing tended to have a larger capability in near viewing. Finally, we showed that during an individual trial, the sensory component of vertical fusion gradually increased with increasing vertical disparity.

**Comparison with Previous Data on Vertical Fusion**

The values for vertical fusion that we found here are similar to those reported previously. Yamamoto and Arai, using a synoptophore, studied the amplitude of vertical fusion using a stimulus pattern subtending approximately 2° of visual angle. They found values of 1.4° ± 0.4° in 20 healthy subjects. Sharma and Abdul-Rahim found that the mean vertical fusion amplitude using a vertical prism bar was 2.66° in 60 healthy subjects.
between the ages of 18 and 63 years. In these studies, however, no objective measurement of vertical fusion was performed. Perlmutter and Kertesz,13 used a dichoptic stimulus consisting of a single horizontal line subtending 8.5°. They reported that the maximum fusible vertical disparity was less than 1°. The motor component of total fusion was 80% to 85% of the imposed disparity. A somewhat smaller sensory component to vertical fusion has been reported by Duwaer.21 Recently, Howard et al.22 used a sinusoidally oscillating disparity stimulus in which the target changed position in front of one eye. They reported a range of vertical vergence capabilities among their four subjects similar to the range observed in ours. They found values of the motor component from 1.25° to 2.8° for a 4° disparity presented at a distance of 57 cm. Our stimulus and responses were similar to those of Perlmutter and Kertesz,13,14 but in addition we have shown that convergence enhances vertical fusion. This finding agrees with the previous subjective report of Gräfe15 but not with that of Berens et al.1 In both reports, however, the visual stimuli were much different from the ones used in our study. If we had used larger stimuli that extended into the periphery, or stimuli with different contrasts, or if there had been an accommodation component to the near stimulus, we might have seen different vertical vergence capabilities and a different effect of horizontal vergence angle.

**Vertical Sensory Component**

In our experiments, in near and far viewing, the sensory component of vertical fusion increased in proportion to disparity as the trial progressed. This finding suggests that there may be dynamic changes in Panum's fusion area, perhaps as a function of vertical disparity. Others have previously shown that Panum's fusion area may change with the characteristics of the stimulus.23,24 In our experiments, the changes in the sensory component could be a function of the relatively slow change in disparity and/or the relatively long duration of the motor response, perhaps inducing some type of sensory adaptation. These potential factors require further investigation. In con-

**Table 2. Correlation between the Motor Component of Vertical Fusion and Torsion**

<table>
<thead>
<tr>
<th></th>
<th>'Far' Viewing</th>
<th></th>
<th>'Near' Viewing</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>r*</td>
<td>P</td>
<td>n</td>
<td>r*</td>
</tr>
<tr>
<td>Cycloversion (n = 8)</td>
<td>-0.357</td>
<td>0.353</td>
<td>8</td>
<td>0.381</td>
</tr>
<tr>
<td>Cyclovergence (n = 8)</td>
<td>-0.381</td>
<td>0.321</td>
<td>8</td>
<td>-0.500</td>
</tr>
</tbody>
</table>

* Spearman's rank correlation test.
Contrast, we found that the horizontal vergence angle had little effect on the maximum value of the sensory component of vertical fusion or on the slopes of the correlation between the sensory component of vertical fusion and disparity. The sensory component of vertical fusion seems to be independent of the apparent distance of the stimulus.

**Pattern of Vertical Eye Movements**

As others have found, our subjects showed variability in the overall pattern of the vertical eye movement response to a vertical disparity. This has been reported with asymmetrical and asymmetrical (as we used) vertical disparity stimuli. We found various combinations of conjugate (vertical version) and disconjugate (vertical vergence) responses. Remarkable, however, was the consistency and the appropriateness of the motor component of the vertical fusion response. Although both eyes might have drifted away from the center of the target, causing the images to be located away from the center of the fovea, the absolute difference between the positions of the eyes remained appropriate for the disparity of the stimulus. This finding is confirmation of the well-known fact that extrafoveal disparity can drive fusion responses. Because our stimulus did not require visual discrimination at the center of the stimulus, it is not surprising that relatively small drifts of the eyes away from the target were well tolerated. A conjugate component might also have appeared if there had been a superposition of a conjugate eye movement (pursuit) on a disjunctive movement. Such a mechanism has been suggested for the monocular pattern of response to a slowly changing asymmetrical (monocular) disparity stimulus. We also studied the responses to symmetrical stimuli in a few subjects and found no differences in their patterns of response compared with those for asymmetrical stimuli.

**Pattern of Torsional Eye Movements**

Previous workers have suggested that certain patterns of torsional eye movements are associated with vertical vergence. Enright and van Rijn et al. reported that disparity-induced vertical vergence was associated with cycloversion. Left-over-right vertical disparity was associated with counterclockwise cycloversion and right-over-left vertical disparity with clockwise cycloversion. Michael et al. found a similar but smaller effect, whereas Straumann and Müller found no effect. In our experiments vertical fusion was not consistently related to cycloversion or to cycloversion for several possible reasons. Compared with those in previous work, our visual stimuli were usually smaller, and the rate of change of disparity was slower. The duration of the stimulus presentation and the eye movement response was much longer. Thus, the chance for coil slippage in our experiments was increased. Although we looked carefully for slippage of the annulus and eliminated data when it appeared to happen, small amounts could have gone undetected. Cycloversion is also known to undergo spontaneous fluctuations over time. Finally, adaptive changes in vertical eye alignment (phoria adaptation) could have occurred and altered any associated torsional responses.

**The Functional Significance of the Effect of Convergence on Vertical Fusion**

The natural circumstance in which a vertical realignment of the eyes must take place is when viewing targets are close to the head and off to the side. Viewing targets at distance does not require a vertical fusion response. Some of the vertical realignment that must occur when refixating between laterally located targets seems to be independent of an immediate effect of disparity, because a vertical realignment occurs in the dark when making saccades between the imagined locations of near targets or when the images seen by the two eyes are dissociated. This ability to preprogram vertical realignment independent of visual cues may be related to central mechanisms that are under adaptive control and to orbital factors related to changes in pulling directions of vertical muscles associated with changes in horizontal position. Presumably, however, in near viewing, disparity-driven vertical fusion capability would still be necessary to supplement any preprogrammed mechanism and to fine-tune vertical alignment.

**References**


**Effect of Horizontal Vergence on Vertical Fusion**

2275

Downloaded from iovs.arvojournals.org on 07/28/2019