Magnitude and Velocity of Proximal Vergence
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Until recently proximal vergence was considered to play only a minor role in the eye alignment changes that occur when looking between distant and near targets. We measured the magnitude and velocity of proximal vergence using infrared limbal sensing to record vergence responses between two untextured luminous horizontal rods which lacked disparity and accommodative cues. The magnitude of proximal vergence responses averaged 3.9° for convergence and 3.8° for divergence, about 70% of the total vergence “demand.” Peak velocities for proximal convergence and divergence averaged 69 and 53 deg/sec, substantially faster than the velocities of comparably sized disparity or accommodative vergence responses. Its rapid velocity makes proximal vergence well suited to initiate the eye alignment changes between distant and near targets. Invest Ophthalmol Vis Sci 30:755–760, 1989

Of the four components of vergence originally identified by Maddox—tonic, accommodative, fusional (disparity), and proximal (the vergence stimulated by “awareness of nearness”)—accommodative and disparity vergence have generally been considered most important for the eye alignment changes when looking from far to near. While proximal vergence has traditionally been considered secondary,1 recent studies indicate that this vergence component can contribute substantially. Using both clinical2 3 and haploscopic3 methods, proximal vergence was found to comprise up to 70% of the steady state near vergence response.

The vergence demand when looking from distance to 40 cm is approximately 15 pd (8.5°). Established values4 for the peak velocities of disparity and accommodative vergence movements of this magnitude are up to 45 deg/sec, with a duration of about one-half second. Despite partial suppression of visual events during vergence movements,2 this inordinately long response time should produce perceptions of delay and diplopia which observers with normal binocular vision do not typically report.

The large contribution of proximal vergence to the steady state near vergence response raises the possibility that proximal vergence may be important in the expeditious change of vergence between distant and near targets. To our knowledge no study has been directed toward investigating the dynamic properties of proximal vergence, perhaps because of the difficulty in isolating proximal vergence responses from accommodative and disparity influences. In this study we designed a stimulus to isolate proximal vergence and used it to examine the dynamic properties of this vergence component in binocularly normal subjects. For comparison, we also measured the velocities of the vergence responses to accommodative and disparity stimuli in the same subjects.

Materials and Methods

Experimental Subjects

Seven young adult college students (ages 24–28) served as subjects. All had normal binocular vision and at least 20 arc sec stereopsis (Randot at 40 cm). Prior to participation in the study each subject was informed of the general nature of the research and the procedures to be used and voluntarily granted consent. During the experiment, the subjects remained naive as to the specific hypothesis being tested.

Apparatus

The magnitude and velocity of vergence eye movements were recorded in a dark room by comparing the reflected infrared light from the nasal and temporal limbi of each eye. Infrared sensitive diodes were mounted on a spectacle frame and placed approximately 10 mm from the eyes. Signals of each eye’s horizontal position were recorded on a Hewlett-Packard (Houston, TX) model 7404A oscillograph along with a difference signal indicating vergence. Paper speed was 100 mm/sec for proximal vergence responses and saccades and was generally slower for disparity and accommodative vergence responses.
Peak vergence velocities were determined from the eye movement traces by hand.

Calibration of the eye movement trace was done prior to, at the end of, and periodically during each session by having the subject make versional movements between targets separated by 8° at 3.75 m. Absence of movement of the vergence trace during these versional movements indicated accurate calibration. Since vertical eye movements can produce artifactual horizontal deflections that can be confused with vergence responses, we verified that vertical eye movements between targets at 3.75 m produced no deflection of the vergence trace.

Steady-state accommodative responses were measured for two subjects with a Vernier optometer incorporating the Scheiner principle. The subject adjusted the distance of a vertical slit target, with the lens imaged collimated light from two polarized pinhole sources in the entrance pupil of the left eye as a pair of beams separated horizontally by 4 mm. Polarization of the sources was arranged so that one was transmitted through the top half and the other through the bottom half of the slit, permitting the subject to see the half-slits aligned only when the target was conjugate with the plane of accommodation. In order to prevent the slit targets from influencing accommodation, they were flashed for 125 msec every several seconds.

Visual Stimuli

Two horizontal homogenous luminous rods which extended 100° across the visual field served as the proximal stimuli. The rods, each 1.25 cm in diameter, were viewed in an otherwise dark room at 78 and 37 cm from the subjects (vergence demands of 3.9° and 9.5° for a 60 mm interpupillary distance), with the far rod slightly above the near rod as an additional distance cue. The rods were covered with a material which fluoresced a dim bluish-white when illuminated with ultraviolet radiation from a Burton lamp. Subjects were signaled to look from rod to rod by computer-generated tones at random intervals ranging from 3 to 5 sec. That the rods provided no accommodative or disparity stimulus was verified by the absence of vergence responses when a 4° (7 pd) base out prism or a pair of -2.00 D lenses were introduced.

In addition to the vergence responses to these rods, we recorded saccadic eye movements, accommodative vergence (-2.00 D lens during monocular viewing in a lighted room), and disparity vergence movements. Disparity vergence was measured using two different stimuli: a single vertical rod with 4.6° (8 pd) of imposed base out prism and two vectogram pairs (one above or one beside the other) differing by 4.6° (8 pd) of convergent disparity. Stimuli were located at 78 cm. Finally, subjects' responses were measured when they looked between the horizontal rods in a lighted room when all vergence cues—accommodative, disparity, and proximal—were available. Under normal room lighting the texture of the fluorescent material covering the rods was visible, introducing accommodative and disparity stimuli. Except for proximal and disparity vergence, eye movements were not recorded for all conditions for each subject.

Results

Across subjects, the magnitude of vergence responses between the horizontal luminous rods averaged 3.9° for convergence and 3.8° for divergence, about 70% of the total vergence "demand" ([1/0.37 – 1/0.78] × Interpupillary distance × 0.57 deg/pd). Responses were initiated about 225 msec after the tone signaled the subject to look from one rod to the other. The mean peak velocities found for these convergence and divergence movements were 69 and 53 deg/sec respectively, which are substantially faster than velocities typically reported for vergence movements of this size. Indeed, for our subjects, the mean peak velocities for comparable magnitudes of convergence and divergence stimulated by disparity are 17 and 12 deg/sec and were similar regardless of whether base out prism was inserted or vectograms were used. For the three subjects for whom accommodative vergence was stimulated with a minus lens, average velocities of convergence and divergence were 7 and 22 deg/sec. Peak velocities of individual vergence responses are plotted as a function of amplitude in response to disparity, accommodative, and proximal stimuli and are compared to peak velocities of saccadic movements in Figure 1; for average data see Table 1.

The average velocity of convergence and divergence movements when the subjects looked from the distant to the near rod when all vergence components—accommodative, disparity, and proximal—could act together were 86 and 69 deg/sec. Clearly, these velocities are more in line with the vergence velocities measured with the proximal stimulus alone than with either disparity or accommodative stimuli. Indeed, since vergence velocities were slightly higher in the full cue condition than for the proximal stimulus alone (but generally still slower than saccadic velocities), the responses of the different vergence components may be summative.
The vergence responses to the proximal stimulus occurred as three types: disjunctive movements of similar amplitude in the two eyes, movement of just one eye, and as unequal conjugate (saccadic) movements (Fig. 2). These different types of responses occurred in each subject and in approximately equal proportions. There was no clear tendency for three types of vergence response to segregate on the main sequence plot. About 70% of the time a slow vergence movement that increased or decreased the final vergence posture occurred after the initial rapid response to the proximal stimulus.

Examples of secondary slow movements are shown in Figure 2; these occurred in association with all three types of rapid vergence responses and during both convergence and divergence.

### Table 1. Average peak velocity and magnitude of eye movements to different stimuli

<table>
<thead>
<tr>
<th>Eye movement</th>
<th>Velocity (deg/sec)</th>
<th>Magnitude (deg)</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saccades</td>
<td>163.6 ± 50.5</td>
<td>4.2</td>
<td>27</td>
</tr>
<tr>
<td>Proximal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Convergence</td>
<td>69.0 ± 23.4</td>
<td>3.9</td>
<td>24</td>
</tr>
<tr>
<td>Divergence</td>
<td>53.0 ± 26.6</td>
<td>3.8</td>
<td>27</td>
</tr>
<tr>
<td>Disparity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Convergence</td>
<td>16.6 ± 4.5</td>
<td>3.1</td>
<td>22</td>
</tr>
<tr>
<td>Divergence</td>
<td>11.8 ± 4.2</td>
<td>3.0</td>
<td>18</td>
</tr>
<tr>
<td>Accommodative</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Convergence</td>
<td>6.9 ± 5.3</td>
<td>7.0</td>
<td>12</td>
</tr>
<tr>
<td>Divergence</td>
<td>22.0 ± 10.7</td>
<td>6.9</td>
<td>11</td>
</tr>
<tr>
<td>All vergence cues</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Convergence</td>
<td>86.4 ± 29.6</td>
<td>3.6</td>
<td>15</td>
</tr>
<tr>
<td>Divergence</td>
<td>69.2 ± 29.4</td>
<td>3.5</td>
<td>13</td>
</tr>
</tbody>
</table>

To determine if the targets stimulated vergence directly, or indirectly through accommodative vergence, accommodation was measured for two subjects (AC/As of 2.1 and 1.3 deg/D) as they looked at each of the luminous rods. Under the experimental condition that eliminated blur as an accommodative stimulus, the maximum change in accommodation was 0.15 D. However, when the room lights were on and texture was visible on the rods, accommodation increased by approximately 1 D when looking from the far to the near rod.

Finally, we asked one observer to attempt to voluntarily converge and diverge in total darkness, signalled by alternate high and low tones from the computer. The peak velocities of the resulting vergence movements were similar to comparably sized rapid vergence responses to proximal stimulation (for voluntary convergence, averaging 2.1°, the mean peak velocity was 49 deg/sec; for voluntary divergence, averaging 2.9°, the mean peak velocity was 45 deg/sec); however, the latencies were substantially longer, averaging about 350 msec. These results, coupled with the observer’s report that, in darkness, she had attempted to look at imagined near and distant targets suggest to us that perceived distance, rather than volition, represents the stimulus for both types of rapid vergence responses.

### Discussion

The peak velocity of vergence movements between our horizontal luminous rod stimuli was substantially more rapid than when only disparity or accommodative stimuli were present. We verified that these rods provided no accommodative or disparity cues adequate to stimulate vergence and, indeed, no significant accommodative response occurred when look-
Fig. 2. (Upper panel). Examples are shown of vergence responses to accommodative, disparity, and proximal stimulation. For disparity and proximal responses the time scale is 100 mm/sec; for the accommodative responses the time scale is 25 mm/sec. (The scales between the left and right eye traces are in mm.) In the vergence trace downward deflections represent convergence. For the three traces (reading left to right) one small vertical division represents 0.50°, 0.44° and 0.36°. (Lower panel). Three types of proximal convergence responses are depicted: unequal saccades (left), monocular (center), and disjunctive (right). Time scale is 100 mm/sec. (The scales between the left and right eye traces are in mm.) For the three traces one small vertical division represents 0.57°, 0.35° and 0.29°. Note the secondary slow vergence responses, particularly in the center and right traces.

ing from one rod to the other. Thus, the rapid vergence movements that we observed did not result from disparity or indirectly from stimulation of accommodation and must reflect a vergence component that utilizes an alternative cue. By elimination, we deduce that this cue is perceived distance and conclude that the rapid disjunctive movements are proximal vergence. A piece of evidence consistent with this conclusion is that the magnitude of the rapid vergence responses is in similar proportion to the vergence “demand” as was found in recent steady state experiments that attempted to isolate proximal vergence. Although proximal vergence movements are much more rapid than disparity or accommodative vergence, they are not rapid enough to classify as saccades (Fig. 1). Also noteworthy in terms of classifying these responses as vergence is our finding that the relative velocities of convergence and divergence were similar for disparity and proximal vergence (although not for accommodative vergence).

Enright reported that rapid changes of vergence occurred when subjects made unequal saccades in looking between horizontally or vertically separated pins mounted at different distances. Although these stimuli provided disparity and accommodative cues, our results suggest that the rapid vergence changes found by Enright included proximal vergence. Indeed, in a subsequent experiment he measured changes in vergence posture as subjects monocularly inspected perspective line drawings with a fixed accommodative demand. Enright used a television
technique to measure eye movements and so was unable to accurately specify the velocity of these vergence movements.

Erkelens and Collewijn reported that small (less than 1°) vergence movements, which occurred when subjects shifted gaze between depth planes in random dot stereograms, were more rapid than previously reported values for disparity vergence. However, the velocities of these movements displayed substantial variability and overlapped with the velocities of slower vergence movements in response to step changes in the disparity of the entire stereogram. During prolonged inspection of a random dot stereogram Hyson et al. also recorded rapid vergence changes (up to about 3° amplitude) which they termed “vergence saccades.” This terminology must be viewed circumspectly because the velocities of the movements were not quantified. The perceived depth between different regions of random dot stereograms (produced by disparity) may have stimulated proximal vergence which contributed to the rapid vergence responses reported in these two studies.

Many other investigators have recorded eye movements in response to symmetrical and asymmetrical vergence stimuli and have failed to report rapid vergence responses except as unequal saccades. Although it is not altogether clear why these investigators failed to obtain rapid vergence responses, in most previous studies the distant and near targets were not present simultaneously. We suspect that when a vergence stimulus is suddenly introduced, disparity and/or accommodative vergence may be initiated and completed before the perceptual signal that indicates the new target’s distance can be generated and made available to the oculomotor centers controlling vergence. Even so, in studies by Alpern distant and near targets were visible simultaneously and yet rapid vergence movements were not reported. However, Enright found that the percentage of the vergence demand accounted for by rapid vergence increased with the amplitude of concurrent horizontal (or vertical) saccades, from which it seems plausible that rapid vergence movements are more likely to occur when distant and near stimuli are not aligned, as they were in Alpern’s studies. This explanation could also account for the small (0.25° and less) vergence responses reported by Erkelens and Regan and for the apparent driving of vergence by accommodation reported by McLin et al.; in both of these studies proximal stimulation was produced by changing the size of targets without altering their visual direction. Indeed, Erkelens and Regan report that saccades were relatively rare in their experiment.

Keller’s classic study of oculomotor neuron behavior during accommodative vergence, indicated that the neural signal for vergence is a step change in motor neuron firing level. Subsequent studies reported similar, but less abrupt, changes in firing of oculomotor neurons and some putative premotor neurons prior to disparity vergence responses. By themselves, these changes in neural firing that produce relatively slow accommodative and disparity vergence movements cannot also drive the much more rapid proximal vergence movements that we report. To produce these rapid vergence movements an additional transient neural signal, presumably a burst or pulse of firing, is required. In this context, we propose that the slow disjunctive movements following some proximal vergence responses (which cannot have resulted from activation of an additional vergence component) may result from pulse-step mismatches, similar to the dynamic over- and under-shoots that sometimes accompany saccades.

Because the rapid vergence movements that we (and Enright) measured occur in conjunction with saccades, it is possible that rapid vergence velocities somehow depend upon the presence of the saccadic neural pulse. However, fast proximal vergence responses occur as several types, including purely disjunctive movements, albeit in association with vertical saccades. Moreover, rapid vergence responses did not occur in our study during either horizontal or vertical saccades between vectogram targets. This result indicates that, when targets are not unambiguously perceived at different distances, the occurrence of a saccade is insufficient to produce rapid vergence. Mays et al. recently described mesencephalic neurons related to convergence or divergence with burst and burst-tonic characteristics that could provide vergence velocity signals to motor neurons. We speculate that these neurons might provide the neural pulse signals for rapid proximal vergence.

Returning to the issue of expeditious eye alignment change raised in the introduction, the rapid velocity and short duration of proximal vergence responses are ideal for initiating shifts of gaze from one distance to another without bothersome transient diplopia or perceptual delay. Proximal vergence is the most likely candidate to initiate vergence when accommodative and disparity cues are rendered ineffective by accidental occlusion of one eye (as in severely asymmetric vergence) or by substantial target eccentricity (as in looking between eye level at distance to downgaze at near). In situations such as these it seems unlikely that a saccade will first be made to place the new target near the fovea followed, after another reaction period, by accommodative or disparity vergence. Based on our results, and especially the similarity between vergence movements with only the proximal cue and with all cues available, it is likely that proxi-
mal vergence mediates the initial and major component of rapid eye alignment changes under most natural circumstances.

Key words: vergence (proximal, disparity, accommodative), main sequence

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References