Conjugacy of Torsional Eye Movements in Response to a Head Tilt Paradigm

Tony Pansell, Jan Ygge, and Hermann D. Schworm

**Purpose.** Vertically skewed eye movements are induced by head tilt toward the shoulder (roll). Because vertical and torsional eye movements are tightly coupled both mechanically and neurally, the purpose of the present study was to investigate the conjugacy of torsional eye movements during the Bielschowsky head tilt test (BHTT). Furthermore, the purpose was to investigate the influence of different visual and viewing condition on torsional conjugacy. The issue has clinical relevance in interpreting the outcome of the BHTT.

**Methods.** Eye movement recordings were performed using the infrared three-dimensional video-oculography (3D-VOG) technique. Objective cycloposition of 20 healthy individuals was measured in presumed primary position and in head tilt positions of 15°, 30°, and 45° to the right and left, respectively. The same paradigm was performed under different viewing conditions: binocularly without spatial orientation and both binocularly and monocularly with spatial orientation. The stimulus used with spatial orientation was a photographic picture of a historic building, whereas the stimulus with no spatial cues consisted of concentric circles.

**Results.** Consistent excyclovergence occurred in all subjects in head tilt. The relative amount increased with head tilt, regardless of the visual stimulus. Maximum excyclovergence was 0.7° in 45° head tilt during monocular fixation. Binocular viewing enhanced the torsion conjugacy by means of vergence stability (SD), whereas spatial visual cues improved the torsional conjugacy only slightly.

**Conclusions.** Consistent excyclovergence was induced in head tilt. A vestibular origin seems to provide a plausible explanation of the induced torsional disconjugacy, whereas visual feed-back seems plausible in explaining the better conjugacy in binocular viewing. *(Invest Ophthalmol Vis Sci. 2003;44:2557–2564)* DOI:10.1167/iovs.02-0987

To obtain optimal visual function, the eyes perform compensatory movements in response to head movements. The head movements can consist of either rotation—for instance, turning the head to look around—or translations, such as when walking or tilting the head to one side. The vestibular ocular reflex (VOR) is responsible for maintaining fixation during rotational and translational movements of the head. The anatomic correlates of this reflex are the semicircular canals in the inner ear, which respond to rotational acceleration (i.e., rotational-VOR, r-VOR) and the otolith organ responding to linear acceleration of the head (i.e., translation-VOR, t-VOR). Because our everyday movements consist of a mixture of rotations and translations, these two parts of the vestibular system are continuously active. In addition to the VOR, what is termed the ocular counterrolling (OCR) reflex is responsible for the rotational changes of eye position around the anterior-posterior y-axis (i.e., ocular torsion) to counter the direction of the head tilt. This reflex is mediated by the response of the semicircular canals to head rotation, and the OCR is maintained by the otolith organs during static head tilt as a result of the change of direction of the gravitational force when tilting the head to one side. The Bielschowsky head tilt test (BHTT) is used for diagnosis of paresis of the cyclovertical muscles in subjects with vertical diplopia. In our previous study when the BHTT was performed by normal subjects, a torsional amplitude of 10° was found at 45° head tilt. Correspondingly, the relative torsional compensation (i.e., gain) to the head tilt was observed to range between 14% at 45° head tilt to 27% at 15° head tilt, which is in accordance with a previous report and also with a report where a whole body paradigm was performed. However, other studies have revealed a lower gain with a static 20° head tilt ranging from 10% to 15%. The method used to record ocular torsion does not seem to influence the reported gain, because light-emitting methods (three-dimensional video-oculography [3D-VOG; Senso Motoric Instruments, Teltow, Germany] or photograph) were used in two studies with different gains, as well as the search coil method, which was used in two studies with different gain results.

A vertical deviation of the eyes in response to both dynamic and static head tilt has recently been reported. The vertical and torsional eye movements are tightly coupled, both with respect to the mechanical action of the extracocular muscles and to the close neuronal connections in the rostral brain stem. Because disconjugate vertical eye movements have been reported to occur in response to a head tilt, it necessitates a more detailed investigation of the conjugacy of OCR during head tilt.

The primary purpose of the present study was to evaluate the conjugacy of the torsional eye movements but also to observe and describe the horizontal and vertical eye movements during BHTT. Furthermore, we sought to find out whether the conjugacy of the eyes is influenced by different viewing conditions, such as binocular as opposed to monocular viewing and viewing with or without visual spatial orientation. This is of considerable clinical importance when interpreting the outcome of the BHTT.

**Material and Methods**

**Subjects**

The research adhered to the tenets of the Declaration of Helsinki. Twenty healthy individuals were enrolled in the study, 12 men and 8 women (mean age, 34; age range, 21–61). All subjects had a monocular visual acuity of 20/20 or better. Inclusion criteria for corrected ametropia were less than ±1.0 D, because no correction could be

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Supported by the Sigvard and Marianne Bernadotte Research Foundation for Children’s Eye Care; Huddinge University Hospital, Stockholm, Sweden; and Karolinska Institute Travel Funds.

Submitted for publication September 25, 2002; revised November 5, 2002, and January 8, 2003; accepted January 24, 2003.

Disclosure: T. Pansell, None; J. Ygge, None; H.D. Schworm, None

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worn when using the VOG mask. Further inclusion criteria were unimpaired binocular function (Lang 1 Stereo-Test, <550 arc second angle) and no history of ophthalmic or vestibular disease or medications with a potential influence on visual or vestibular function.

Stimuli Targets
All stimuli were presented on a translucent screen by means of back projection from a computer projector. The subject was sitting comfortably in a chair at a distance of 150 cm from the projection screen. The investigating room was dark, except for the light from the computer projector presenting the stimuli. The stimuli were constructed both with and without visual cues for spatial orientation. The stimulus used without spatial cues (test 1) was a picture of two concentric yellow circles on a black background. The periphery of the outer circle subtended a visual angle of 51°. The projector was defocused to eliminate perception of the pixel structure. A black fixation dot was located in the center of the inner concentric circle. The stimulus with spatial cues (tests 2 and 3) was a photographic image of a castle with multiple towers (vertical) and a surface of water in front (horizontal). A grid pattern (five vertical and three horizontal lines) was superimposed on the image to enhance the horizontal and vertical orientation of the image, and a red fixation dot was added in the center of the image. This image subtended a visual angle of 51° in the horizontal and 36° in the vertical direction. The visual periphery of the VOG mask was covered so that the subject could not perceive the periphery beyond the stimulus image. The subject was instructed to pay attention to the whole visual scene shown but to fixate the center target during all experiments. A monocular eight-point horizontal and vertical calibration (amplitude 10° and 20° in secondary eye positions) using a small red dot stimulus (visual angle: 23 arc seconds) was performed before the test paradigms.

Eye Movement Recordings
Eye movements were recorded on videotape for later off-line analysis at a frequency of 25 Hz using the 3D-VOG. The head mask with the video cameras was firmly attached to the head with a rubber strap for individual adjustment to reduce unintended mask movements on the head. Unintended head movements (i.e., movements out of the roll plane) were restricted by a tilttable chin rest, including a wooden spatula bite bar and an adjustable chin rest.

Paradigms
Each recording started with the head in straight-up position and the eyes in the reference position 10° (described in the Data Analysis section). At the beginning of each test the subject viewed the fixation target for at least 20 seconds before any data were collected, followed by a head tilt of 15°, 30°, and 45° to the right shoulder and then back to the head-straight position. After that, the head was tilted correspondingly to the left shoulder in three similar steps and then returned to the straight-up position. Each paradigm thus involved a total of nine head positions. Every head position was held static for 10 seconds. The shift between the head positions was performed by manually tilting the chin rest (duration, 1 second). The rotation axis of the chin rest device was fixed at approximately 10 cm below the bite bar. A control test was performed on three subjects to localize the head-rotation axis by graphically reconstructing the axis of head rotation. The axis was found to coincide with the chin rest axis in the 15° and 30° head tilts. However, the 45° head tilt induced an upward displacement of the axis (~3 cm). Two different viewing conditions (binocular and monocular) and two visual conditions (with and without spatial orientation) were used in three test conditions: binocular viewing without spatial orientation (test 1), binocular viewing with spatial orientation (test 2), and monocular viewing with spatial orientation (test 3).

Data Acquisition and Analysis
Because of the inherent problem of defining the true primary position in the current experimental setting, the eye position adopted when looking straight ahead with the head erect was defined as the reference position. All eye positions were calculated from this reference position. The videotape recording was digitized into ASCII data for the six channels (right and left eye; horizontal, vertical, and torsional data), and the horizontal and vertical data were calibrated. With the 3D-VOG software, a torsional quality value (between 0–1.0; best) was calculated. This value corresponds to the concordance between luminance profile of the selected iris segment with the eye in the reference position and each recorded video frame. Exact concordance between the profiles yields the value 1.0, whereas it is 0 when there is no concordance. The numeric values of right- and left-eye horizontal, vertical, and torsional position was extracted. Data segments containing blinks were omitted from the file, and only data when the torsional quality value was better than 0.5 were used for further analysis. Cyclovergence was calculated from the torsional data: (right eye [RE] position + left eye [LE] position)/2. The mean eye position during the last 5 seconds in each of the nine head positions was determined. Cyclovergence (i.e., LE – RE) was calculated and its standard deviation was used as a measurement of cyclovergence stability to compare the influence of the three test conditions.

Definitions
In this article, the word cycloduction is used to describe monocular torsional movement and the term cyclovergence to describe the conjugate torsional movement of both eyes. Cyclovergence is calculated according to the formula (LE + RE)/2. The term cyclovergence is used to describe the disconjugate movement of the torsional eye position. Cyclovergence is calculated according to the formula (LE – RE). The change in eye cycloposition as a response to the head tilt was divided by the amount of head tilt and considered to be the positional gain. The direction of torsional eye movements (i.e., clockwise and counterclockwise) was defined from the patient’s point of view. A positive torsional movement corresponds to a clockwise, downward, or leftward rotation of the eye. Skew is the vertical vergence movement of the eyes in response to a head tilt.

Control Experiments
Because it can be assumed that both the action of gravity and inertia during head movements can lead to movement of the VOG head mask, a control experiment was performed with three subjects to measure the amount of mask movements induced during the head tilt. The three subjects wore occulopad patches (Nexcare Opticlude Orthoptic Eye Patch; 3M Company, Sollentuna, Sweden) attached to the skin surrounding the eye. These patches had manually drawn pictures of an eye with iris and a pupil (i.e., phantom eye). The phantom eye was positioned so that the drawn pupil was located straight in front of the subject’s eye. The VOG mask was worn as in the experiments, and the cameras were centered and focused on the phantom eye. Any mask movement thus changed the camera position in relation to the phantom eye and thereby was interpreted as an eye movement by the VOG software (i.e., chimeric movements). Two head tilt tests were performed with the same paradigm as just described. In test 1 the left eye was occluded, whereas in test 2 both eyes were occluded by phantom eyes. The purpose of test 1 was to compare the eye movements of the right eye (not occluded) with that of the left phantom eye. The purpose of test 2 was to quantify the presumed mask rotation. The stimulus with spatial cues (see above) was used as the visual stimulus in test 1. A nine-point calibration was performed before the first control experiment. The calibration on the right eye, while the left eye was occluded by the patch. The data acquisition was performed as described earlier, except for the calibration of the left eye. Because no movement of the mask was permitted after the calibration had been performed, the left eye was covered during the calibration and during test 1. The calibration file from the right eye was used to approximate the left phantom eye torsional (θo), horizontal (θi), and vertical (φd) displacement in degrees. The head mask was removed before test 2 to occlude the right
eye with the phantom eye. The calibration file from test 1 was imported to test 2.

RESULTS

General Findings

Head tilt induced compensatory eye movements in all subjects. Approximately 4% of the data in each recording were excluded because of low torsional quality due to blinks and other interference. A spontaneous torsional fluctuation was found in the recording (<0.2°). The horizontal and vertical eye positions were steady during the first head-straight position. The subsequent head tilt induced horizontal and vertical compensatory eye movements to maintain fixation on the target (i.e., VOR). The latency for the torsional response to the head tilt was found to be the same as for the horizontal eye movement, as these two movements could be seen to start at the same time after the head tilt. No subject experienced diplopia.

Contribution of Listing's Law to OCR

The head tilt induced conjugate horizontal eye movements in the direction opposite that of the head movement. The 45° head tilt induced the largest horizontal rotation of the eye, 7° from the reference position (Fig. 1). The horizontal eye movements during the head tilt paradigm were generally larger than the vertical eye movements. A head tilt induced a vertical disconjugacy (i.e., vertical vergence) that increased with the head tilt. In 15 of the subjects the rightward head tilt induced a vertical disconjugacy (i.e., vertical vergence) that increased with the head tilt. In 15 of the subjects the rightward head tilt induced a vertical disconjugacy (i.e., vertical vergence) that increased with the head tilt. In 15 of the subjects the rightward head tilt induced a vertical disconjugacy (i.e., vertical vergence) that increased with the head tilt.

The torsional eye position change in response to the head movement was a consistent torsion movement in the same direction as the head—thus, in an anticompensatory direction. This torsion movement was a consistent finding in all subjects in response to head tilt. After this initial quick change, the torsional position changed in a direction opposite the head tilt and thus in a false torsion induced would give rise to an increase or decrease of the torsional value measured.

OCR Amplitude and Gain

In all recordings, the torsional eye position showed a spontaneous drift over time (Fig. 3) that was influenced by the amount of head tilt. The drift was in the direction opposite to that of the head tilt and resulted in increased OCR. The torsional position was found to be most stable (torsional position SD ~0.3°) during the first head-straight position before any head tilt. The torsional position was less stable (SD ~0.9°) during the second and third head-straight positions but always more stable than during the six head-tilt positions, even though no head movement was present (Table 1; Fig. 3). The first torsional eye position change in response to the head movement was a fast torsion movement in the same direction as the head—thus, in an anticomparatory direction. This torsion movement was a consistent finding in all subjects in response to head tilt. After this initial quick change, the torsional position changed in a direction opposite the head tilt and thus in a
The mean OCR (cycloversion) from each test condition in response to 15°, 30°, and 45° head tilt toward the right and left shoulders is shown in Fig. 5. The mean OCR (cycloversion) from each test condition in response to 15°, 30°, and 45° head tilt toward the right and left shoulders is shown in Fig. 5. The mean OCR (cycloversion) from each test condition in response to 15°, 30°, and 45° head tilt toward the right and left shoulders is shown in Fig. 5. The mean OCR (cycloversion) from each test condition in response to 15°, 30°, and 45° head tilt toward the right and left shoulders is shown in Fig. 5.

**OCR Disconjugacy**

The head tilt induced OCR disconjugacy. A consistent finding was a larger OCR excycloduction of the superior eye (i.e., contralateral to the head tilt) than the OCR incycloduction of the inferior eye, thus inducing an excyclovergence (Table 2; Fig. 6). This disconjugacy increased with the amount of head tilt, and the maximum excyclovergence was 4.9° (Table 2). The cyclovergence was significant in tests 1 ($P < 0.05$) and 3 ($P < 0.02$) when performing a general linear model analysis for repeated measures. In test 2, the disconjugacy was not statistically significant. The largest mean amount of disconjugacy was observed during the rightward head tilt, but no statistically significant difference was found between the rightward and leftward directions. A control experiment was performed in three subjects to investigate whether a reversed order (first to the right and then to the left) had an effect on the asymmetry of the disconjugacy (see Fig. 6). When the head was tilted first toward the left shoulder, a larger disconjugacy occurred with the leftward head tilt than with the rightward tilt. When the head was straightened from the 45° right tilt to a straight-up position the torsional return movement of the left eye was larger than the corresponding movement of the right eye, inducing an incyclovergence. This movement was actually of larger amplitude than the preceding excyclovergence, thus inducing an incyclovergence compared with the initial reference position (Table 2). In the following leftward head tilts, an excyclovergence was again induced. Only a weak correlation between the OCR and cycloversion amplitudes (coefficient of determination, $r^2 = 0.15$) was found.

**FIGURE 4.** The mean of the relative torsional compensation (gain) in response to each head-tilt position. It is worth noting the decrease in gain in response to increased head tilt. The higher gain in the 15° leftward head tilts is almost certainly a result of the incomplete return of torsion position when straightening the head from 45° rightward to the head-straight position.

**FIGURE 5.** The mean OCR (cycloversion) from each test condition in response to 15°, 30°, and 45° head tilt toward the right and left shoulders. Positive (+) corresponds to a clockwise OCR from the subject's point of view. Note the similarity in amplitude between all test conditions and the incomplete return of torsional eye position to the reference position when the head was raised from the 45° head tilts.

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**Table 1. Minimum and Maximum OCR in Response to Each of the Nine Head Positions in the Three Test Conditions**

<table>
<thead>
<tr>
<th>Head Position</th>
<th>Test 1</th>
<th></th>
<th>Test 2</th>
<th></th>
<th>Test 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max/Min</td>
<td>Mean</td>
<td>SD</td>
<td>Max/Min</td>
<td>Mean</td>
</tr>
<tr>
<td>Upright</td>
<td>0.72/−0.67</td>
<td>0.06</td>
<td>0.30</td>
<td>0.60/−0.61</td>
<td>0.06</td>
</tr>
<tr>
<td>15° Right</td>
<td>−0.32/−5.84</td>
<td>−2.64</td>
<td>1.85</td>
<td>−0.61/−5.85</td>
<td>−2.52</td>
</tr>
<tr>
<td>30° Right</td>
<td>−1.15/−10.02</td>
<td>−4.57</td>
<td>2.45</td>
<td>−1.52/−10.03</td>
<td>−4.76</td>
</tr>
<tr>
<td>45° Right</td>
<td>−0.64/−10.72</td>
<td>−5.43</td>
<td>2.79</td>
<td>−1.30/−10.72</td>
<td>−5.97</td>
</tr>
<tr>
<td>15° Left</td>
<td>4.62/−0.11</td>
<td>2.45</td>
<td>1.35</td>
<td>4.72/0.43</td>
<td>2.51</td>
</tr>
<tr>
<td>30° Left</td>
<td>6.63/1.17</td>
<td>4.49</td>
<td>1.50</td>
<td>8.63/1.32</td>
<td>4.62</td>
</tr>
<tr>
<td>45° Left</td>
<td>9.39/2.11</td>
<td>5.96</td>
<td>1.90</td>
<td>10.48/3.02</td>
<td>5.94</td>
</tr>
<tr>
<td>Upright</td>
<td>2.45/−0.98</td>
<td>1.09</td>
<td>0.82</td>
<td>3.25/0.60</td>
<td>1.07</td>
</tr>
</tbody>
</table>

The corresponding mean value (in degrees) and standard deviation of OCR was calculated for each head position and test condition.
Table 2. Differences in OCR between the Right and Left Eye Torsion in Response to Each of the Nine Head Positions in the Three Test Conditions

<table>
<thead>
<tr>
<th>Head Position</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max/Min</td>
<td>Mean</td>
<td>SE</td>
</tr>
<tr>
<td>Upright</td>
<td>1.18/−2.05</td>
<td>−0.21</td>
<td>0.25</td>
</tr>
<tr>
<td>15° Right</td>
<td>2/−2.91</td>
<td>−0.47</td>
<td>0.31</td>
</tr>
<tr>
<td>30° Right</td>
<td>1/−2.86</td>
<td>−0.56</td>
<td>0.25</td>
</tr>
<tr>
<td>Upright</td>
<td>2.76/−1.96</td>
<td>0.21</td>
<td>0.35</td>
</tr>
<tr>
<td>15° Left</td>
<td>0.67/−1.45</td>
<td>−0.07</td>
<td>0.20</td>
</tr>
<tr>
<td>30° Left</td>
<td>0.61/−1.49</td>
<td>−0.24</td>
<td>0.23</td>
</tr>
<tr>
<td>45° Left</td>
<td>1.25/−1.66</td>
<td>−0.14</td>
<td>0.27</td>
</tr>
<tr>
<td>Upright</td>
<td>2.33/−0.78</td>
<td>0.24</td>
<td>0.26</td>
</tr>
</tbody>
</table>

The corresponding mean value (in degrees) and standard error of OCR was calculated for each head position and test condition.

Visual and Viewing Conditions Influences on the OCR

To estimate the influence of visual and viewing conditions on torsional conjugacy, a value describing the fluctuation (i.e., SD) of the cyclovergence was calculated for each subject and test. The values were compared in an analysis of variance (ANOVA). No difference was found between the two visual conditions (test 1, 0.71° ± 0.22°, mean ± SD, and test 2, 0.68° ± 0.22°), but a significant difference was found between the two viewing conditions (test 2, 0.68° ± 0.22°, and test 3, 1.22° ± 0.51°).

Control Experiment

The control experiments performed with the help of phantom eyes turned out to be a useful method of estimating VOG mask movements. The control experiments thus verified that head tilts give rise to a small displacement of the VOG mask that can then be interpreted as eye movements (from now on referred to as chimeric movements). In test 1 the amplitude of the chimeric movements was always smaller than the amplitude of eye movements (from now on referred to as chimeric movements). In test 2 the amplitude of the chimeric movements was always smaller than the amplitude of eye movements (from now on referred to as chimeric movements). In test 3 the amplitude of the chimeric movements was always smaller than the amplitude of eye movements (from now on referred to as chimeric movements).

More interesting for the purpose of this study was the vertical chimeric movements (φ) were generally found to be small (see Fig. 7A). However, in one subject, the maximum φ corresponded to a 3° vertical eye movement. The largest disconjugate φdiff was found to be 2°, which corresponds to a torsion (ω) of 0.5°. The chimeric torsion (ω) due to the vertical movements (φdiff) of the VOG mask was found to be conjugate and range between ±0.1° in the maximum head-tilted positions. The largest chimeric horizontal displacement (θ) was found to be 0.7°.

Discussion

Methodological Considerations

This study has no head-position data because we were not able to implement the technique with the VOG technology when the experiments were performed. The purpose of the study was to investigate the conjugacy of torsional eye movements in static tilted head position. No disconjugate chimeric torsion movement was induced by any mask movement in the control sequence of the present study. The video cameras were mounted in a robust mask, and their relative position was fixed. For the discussion to follow on the control experiments the reader is referred to Figure 7. The rapid anticompenatory torsion peak could not be explained by mask movements, because no rapid twitch movement of the mask was found. If the torsion peaks in the right eye in control test 1 were the result of VOG mask movements, a similar chimeric torsion peak should have been visible for the left phantom eye. The incomplete return of torsion position to reference position (~0.8°) in the second and third head-straight positions could not be explained by mask movements in the control experiments. This amplitude did not correspond to the chimeric movements of the left phantom eye and, perhaps more important, the direction of the chimeric movements did not correspond to the direction of the incomplete return of torsion position. If the incomplete torsional return in the right fixating eye in control test 1 had been induced by camera rotation, the same amount of torsional rotation would also have occurred in the left phantom eye. The drift of torsion position during the static head tilt could not be explained by a movement of the VOG mask. In control test 1 there was unmistakable torsional drift of the right eye, whereas the left phantom eye position remained fixed during the static head-tilted position. This finding provides even greater corroborations of our hypothesis of vertical skew to correct for the visual foveal misalignments (described later). The horizontal displacement of the mask that was observed did not induce disconjugate chimeric movements and is therefore considered to be of less importance in the results of this study. However, the observed vertical mask...
movements induced conjugate ($\phi$) and disconjugate ($\phi^{\text{diff}}$) chimeric vertical movements (i.e., skew) as well as conjugate chimeric torsional movements ($\omega$). The largest chimeric vertical skew in control test 2 was 2° and the consequent chimeric torsion was 0.5°. The mask skew displacement ($\alpha$) can be approximated in millimeters by geometry ($\sin 0.5^\circ = a/\text{interpupillary distance}$) which yields an approximate mask skew of 0.5 mm.

The vertical vergence data presented in this study undoubtedly include both chimeric movements and true vertical eye movements. It is not possible to eliminate mask movements during head movements as long as the VOG mask is not securely fixed to the skull. Presumably, it was movement of the face and head skin to which the VOG mask was attached that gave rise to the chimeric movements observed.

Horizontal and Vertical Eye Movements

The horizontal eye movements in connection to the head tilt corresponded well with the movements that were calculated from the experimental setup. Linear intra-aural stimulation of the utricles have been shown to induce compensatory horizontal eye movements that are dependent on viewing distance to the visual target and the frequency of the head movement. In the second and third head-straight positions, after the first tilt to the right and the second tilt to the left, respectively, the horizontal eye position did not return exactly to the initial position. An unintended adjustment of the teeth on the bite bar may have changed the head position slightly and thereby contributed to the shift of the horizontal reference eye position. Another potential origin may be VOG mask movement (see control experiment). The head tilt also induced disconjugate vertical eye movements that were not consistent among the subjects. For example, 15 subjects exhibited a vertical disconjugacy with the right eye over the left eye in a rightward head tilt, whereas five subjects showed a response with the left eye over the right eye in a rightward head tilt. In most cases, the left eye vertical displacement had larger amplitude than the right eye, thus inducing the vertical vergence. Previous reports have shown similar findings with a vertical skew in response to both a static and a dynamic head roll. Jauregui-Renaud et al. suggested that the vertical semicircular canals were responsible for the skew in response to a dynamic head roll. We have shown vertical skew induced by a dynamic head tilt with elevation of the contralateral eye and depression of the ipsilateral eye. The nonconsistent disconjugate response in the present study may be explained by a difference in the ocular visual and torsional axes. If the axes are not the same, an OCR (rotating around the torsional axis) would displace the visual axis from the fixation target (Figs. 8A, 8B) and the image on the two retinas would not project on corresponding retinal locations and thus would fail to maintain single binocular percept. A vertical vergence movement of the eyes is thus necessary (Figs. 8C), to maintain single binocular vision. Depending on the direction of displacement of the torsional axis (e.g., nasally, temporally) from the visual axis the direction of the vergence movement will differ. We therefore suggest a visual model to explain our findings of vertical skew in the static head tilt.

Listing’s Contribution to Measured OCR

Without the exact location of the primary position, it is not possible to evaluate the contributions of Listing’s law to the measured torsion in the present study. However, there must be some false torsion induced by the combination of horizontal and vertical eye movements. If the primary position were located above the reference position, a horizontal nasal movement would elicit a false excycloduction provided that the Fick coordinate system is used. If the same movement were performed but with the primary position located below the reference position, a false incycloduction would be induced. The eccentricity of the reference position to the primary position has a significant effect on the outcome of false torsion. The closer the two positions are located to each other, the less the false torsion induced by the horizontal and vertical eye movements. When reference position and primary position are located close to each other, the false torsion ($\theta_{\text{Fick}}$) induced by the horizontal ($\theta_{\text{Fick}}$) and vertical ($\phi_{\text{Fick}}$) geometrical properties of the Fick system can be approximated by a formula in which all angles are given in degrees.

$$\phi_{\text{Fick}} = \frac{\theta_{\text{Fick}} \times \phi_{\text{Fick}}}{100}.$$
The mean horizontal and vertical eye movements induced by the 45° head tilt were 7° and 2°, respectively. According to this formula, a torsion of 0.14° would be induced if the reference position and the primary position were located close to each other. This value is just above the resolution of the recording system used, and therefore we believe that any false torsion induced by our experiments would have only a minor impact on the torsional eye movements measured.

**Ocular Counterrolling**

The torsional fluctuation found in the recordings corresponded well with that reported by Ferman et al. The fast anticompen-satory torsion movement in connection with the initiation of the head tilt has been reported.

OCR was observed in all subjects, which agrees with the outcome of previous studies. The relative compensation (i.e., gain) of OCR to a 15° head tilt was 0.22, and that also fits in well with previous studies. The head tilt from 30° to 45° induced a smaller amount of OCR than head tilt from head straight to 15°. The gain thus decreased in response to increased head tilt. This fact is well known and has been explained by a progressive increase of the saccular impact on OCR in response to the increase in head tilt. The larger gain in the first leftward head tilt is definitely the result of the failure to return to the initial torsional reference position after the preceding rightward head tilt. There were large interindividual differences in OCR amplitude. As seen in Table 1, the largest OCR induced by the 15° head tilt was 5.8° (i.e., gain, 0.39) and the smallest 0.3° (i.e., gain, 0.02). The large variations in the OCR amplitude may be one explanation for there being no statistical significance in the analyses of visual and viewing influences on the OCR. The drift in torsional position and the fact that the torsional position did not return exactly to the initial reference position when raising the head to straight-up position is of unknown origin.

**Disconjugate OCR**

The excyclovergence in response to a head tilt has not been reported previously, as far as we know. The head tilt changes the effect of gravitation on the peripheral vestibular complexes. Many investigators have come up with a model to explain the relationship between utriculus and sacculus. De Graaf et al. estimated the relationship between utricular and saccular impact on OCR to be 3:1. With increased head tilt there is a decline in utricular input and an increase in saccular input in the brain circuits controlling the OCR. The utriculus is thought to generate conjugated torsional eye movements and the sacculus to generate disconjugate torsional eye movements. This may be one explanation for the findings of excyclovergence in response to a head tilt in the present study. There is no evidence for a separate cyclovergence system. The disconjugacy may be the result of an unequal OCR of the right and left eye. Each eye is driven by both utricles, but there is no reason to expect that these eye movements are inherently conjugate. A tendency of asymmetry in OCR conjugacy was seen between rightward and leftward head tilts. The control experiment verified the asymmetry, thus indicating that it was caused by the direction the head was tilted (i.e., right- or leftward). This finding necessitates significant consideration when performing the BHTT, because it will have bearing on the outcome of the test. Some type of torsional adaptation seems plausible to explain the asymmetry.

**Viewing and Visual Conditions**

The enhanced torsional vergence stability during binocular compared with monocular viewing found in the present study is probably an effect of visual feedback during binocular viewing that presumably corrects for vergence errors induced by the head tilt. This was also the case in conditions with visual cues compared with those with no visual cues. It is possible that a larger degree of sensory fusion of the cyclo disparities in head tilt leads to a smaller degree of motor fusion and thereby the disconjugacy of torsion position. The appearance of spatial visual cues had only a limited effect on the stability of torsional vergence. The OCR amplitude was dependent on neither the tested viewing nor visual conditions.

The finding made by Betts et al. with a vertical vergence in a static head tilt was confirmed in this study. Furthermore, a disconjugacy of the torsional eye position in response to a similar head-tilt paradigm has been shown to exist. A vestibular origin seems to provide a plausible explanation for the induced torsional disconjugacy.

**Acknowledgments**

The authors thank Roberto Bolzani for help with statistical analysis.

**References**


