Vestibular Eye Movements Are Heavily Impacted by Visual Motion and Are Sensitive to Changes in Visual Intensities

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Purpose. Eye movement evaluation constitutes the basis of diagnosis in dizzy patients. Through evaluating ocular torsion and vertical skewing during balance provoking stimulation, the aim of this study was to investigate the impact of vision on a typical vestibular eye movement response.

Methods. Twelve healthy subjects (six young, six old) were exposed to (1) vestibular (VES), (2) visual (VIS), and (3) visual-vestibular (VIS+VES) stimulation. These were carried out as whole-body roll (VES), optokinetic rolling of visual scenes (VIS), and a combination of both (VIS+VES). Visual scenes were presented at two intensity levels. Eye movement velocities were used to evaluate the relative impact of visual and vestibular stimulation.

Results. Torsional velocities were lowest for VIS regardless of age. Velocities for the old group did not differ between VES and VIS+VES, whereas those for the young group were higher for VIS+VES. Regardless of age, amplified visual intensity resulted in an increased torsion-skewing ratio, seen as more degrees of torsion per degrees of skewing. The contributions of VIS and VES in proportion to VIS+VES were calculated as 0.18 (0.08) and 0.74 (0.14), respectively.

Conclusions. Our findings demonstrate that vertical skewing is physiologically seen in combination with ocular torsion as a response to visual stimulation, with young subjects exhibiting a more dynamic response. The torsion-skewing ratio was sensitive to small changes in visual intensities, which may prove useful when evaluating visual motion sensitivity. The visual contribution to the vestibular eye movement response highlights the clinical importance of visual examinations when evaluating dizzy patients.

Keywords: ocular torsion, vertical vergence, vertigo, visual motion, visual intensity

Despite the large number of patients visiting emergency clinics due to vertigo, roughly 3% of all visits, only about half of those patients show clear physiologic aberrations leading to a medical diagnosis.[1] Although prevalent among all age groups, many dizzy patients are elderly, experiencing increased disability that could have been prevented.[2,3] Balance presents complex physiology with multiple interwoven systems. It can generally be said that the foundation is built on three sensory inputs: visual, vestibular, and proprioceptive.[4,5] A mismatch between the different sensory modalities can raise a subjective sensation of vertigo and general balance discomfort.[6] Visually evoked vertigo, or visual vertigo, represents an example of sensory mismatch that has been well described by Bronstein.[7] The symptoms are triggered by intense visual information, but the condition remains difficult to diagnose.[8]

Eye movement analysis constitutes the basis of objective vertigo evaluation. Ocular torsion is a nonvoluntary eye rotation around the visual axis.[9] When tilting the head toward the shoulder, the eyes rotate in the opposite direction to the head tilt (i.e., ocular counter-rolling [OCR]). It is mainly induced by the vertical semicircular canals and maintained in static head-tilted position by the utricular otolith organ, both part of the peripheral vestibular organ.[10,11] This torsional response is also sensitive to adjustments of the vergence system, aiming to maintain stereopsis, with an increased vergence leading to a decreased OCR.[12] Vision alone can also induce ocular torsion when maintaining the head still. A visual scene with no visual motion that is tilted in front of a person in head straight position induces ocular torsion in the same direction as the scene. This visually induced ocular torsion compensates only to a minor extent for the scene rotation (1% to 4%),[13] whereas OCR yields a greater torsional gain.[14,15] The visually induced ocular torsion response shows that vision alone is capable of inducing a torsional response similar to the OCR but without the vestibular stimulation. A visual scene enriched with spatial cues, visual gravitational information, has been shown to induce a larger torsional response compared with a visual scene with less spatial cues.[13] As for proprioception, neck bending during head tilt has been shown to have a minor and variable influence on ocular torsion.[16]

Collewijn et al. showed that dynamic head tilt in the presence of a structured visual background generated more dynamic OCR than when less visual information was presented.[14] These findings imply that the OCR is not merely dependent on vestibular activation but also is driven by visual stimulation as the visual surroundings are naturally tilted in the head tilted position. This relationship is readily illustrated by the vestibular and visual sensory systems sharing several cortical areas in coding self-motion[17] and posture.[18]

The OCR induced by vestibular stimulation (i.e., head tilt) is also accompanied with a vertical skewing of the eyes, with the ipsilateral eye moving upward and the contralateral downward.[19,20] This mechanism aims to keep the visual scene stable on the retina to some extent but most importantly to avoid a breakdown of binocularity leading to diplopia. This vergence response is dependent on the fusional range (i.e., the angle at which an individual can maintain single vision) and allows for greater mobility without sacrificing visual integrity.[21] As such, the skewing response reflects the individual capacity for correlating the content of a visual field, with a poor fusional strength leading to a larger skewing response. This oculomotor response is physiologically seen during a head tilt toward the shoulder compared with the pathologic skew deviation, where this combination is seen even though the head remains straight.[22]

Although it is known that ocular torsion can be triggered by visual stimuli, it is not known if a concordant vertical skewing can be triggered in a fashion similar to that of a combined torsion-skewing response by visual stimuli alone. It would therefore be of interest to further study the oculomotor response responsible for aligning the eyes in accordance with head orientation. These responses, ocular torsion and vertical skewing, present a clear set of oculomotor responses that the subject cannot voluntarily influence, due to their lack of capacity for voluntary control. Investigating the eye movements related to balance control therefore constitutes a valuable approach toward analyzing the sensorimotor integrations of visual and vestibular balance input through a joint motor output, shedding further light on the complex physiologic phenomenon that is balance control.

This study aims to investigate the relative contributions of the vestibular and visual systems to balance provoking stimulation in the roll-plane in healthy subjects, using ocular torsion, vertical skewing, and the ratio between the two as objective measures of the reflexive balance response.

Materials and Methods

Subjects

The study was carried out on 12 healthy subjects (8 male, 4 female) with no history of balance discomfort, disorder, or drug use affecting the central nervous system. Due to the age effect on dizziness prevalence, the study population was balanced in terms of age. Half of the participants were <35 years old (four male, three female; mean age, 27.6 years [SD 4.5]) and the other half was >49 (four male, one female; mean age, 59.0 years [SD 10.2]). All participants were subject to an eye examination ensuring normal corrected visual acuity (VA $\geq$ 1.0), stereoscopic vision (TNO $\geq$ 60"), no latent strabismus larger than two exo- or esophoria at distance, and normal eye motility. In addition, the head impulse test was performed to determine a healthy vestibulo-ocular reflex, as well as Romberg's test to ensure healthy postural balance control.

All subjects were exposed to all test conditions. The test order was balanced according to test modality, visual and vestibular, and stimuli intensity, low and high. Each subject was either presented to clockwise (CW) or counterclockwise (CCW) rotation. The research was carried out in accordance with the Declaration of Helsinki. Informed consent was obtained from all subjects after explanation of the nature and possible consequences of the study. The research was approved by the Regional Ethics Committee of Stockholm (EPN 2018-1768-31-1).

Method

Each subject was exposed to solely visual or vestibular stimulation, as well as a combination of both. To minimize the effect of proprioception, the subject remained seated in the same chair during the whole experiment. Each subject was exposed to five trials: two visual, one vestibular, and two visual-vestibular. For the stimuli to be presented in a comparable direction over trials, the visual and vestibular stimuli were presented in opposite directions (i.e., a subject exposed to a CCW rotation of the visual stimuli was rotated CW in the roll plane in the chair). The direction was evenly distributed by stratified randomization between subjects.

Although the vestibular system is sensitive to both static and dynamic movement, the visual system has been shown to respond poorly to changes in dynamic stimulation (i.e., acceleration). Visual motion detection is instead more apt at detecting amplitudal changes.[23] For this reason, all stimulations were carried out with the same change in amplitude (33°). It is, however, known that there exists a positive correlation between a subjective sense of motion and optokinetic acceleration.[24] Consequently, to ensure a strong optokinetic balance provocation capable of inducing a subjective sensation of self-motion, a high visual acceleration was chosen. Considering the lower sensitivity to differences in visual accelerations compared with the vestibular sense and to match stimuli amplitudes between modalities, the acceleration for the visual stimuli was chosen as a multiple of the vestibular acceleration. The vestibular acceleration was set to $33°/s^2$ and the visual to $66°/s^2$, and both stimuli were set to an amplitude of 33°, allowing for comparisons of eye movement responses.

Visual Stimulation

Visual stimulation consisted of abstract images with varying amounts of visual information: low intensity (Fig. 1A) and high intensity (Fig. 1B). All subjects were exposed to both intensities in either CW or CCW rotation (roll) direction. The visual stimuli were presented on a projector screen (resolution, 1024×768; contrast, 2000:1; update frequency, 60 Hz) at an eye-screen distance of 2 m. The image was rotated for 1 second around its geometrical center (fixation target) with an amplitude of 33° at an acceleration of $66°/s^2$. Each experiment started with 20 seconds where the image was presented with no motion to establish a baseline measure of eye positions. The image then rotated for 1 second. After the movement, the image remained stationary for 20 seconds before the test was ended.

Vestibular Stimulation

A power sled was constructed in house for full body translation and rotation for controlled vestibular and visual stimulation (Fig. 2). The sled moves on two separate belts, moving the top and bottom segments of the chair separately by two powerful AC Brushless Servo Motors (400 V, Baldor BSM90C; Baldor Electric Company, Fort Smith, AR, USA). This allowed for precise rotational (roll) and sideways (translational interaural heave) movements, with the center of rotation adjustable along the body midline to adapt for individual differences in height of the subjects. In this study, the center of rotation was set between the eyes to achieve minimal sideways translational movement. The subject was rotated 33° with an acceleration of $33°/s^2$. To achieve uniform collection periods over all trials, the point where head velocity reached 33°/s was established using the mask accelerometers, and data were collected during this slow-phase period.

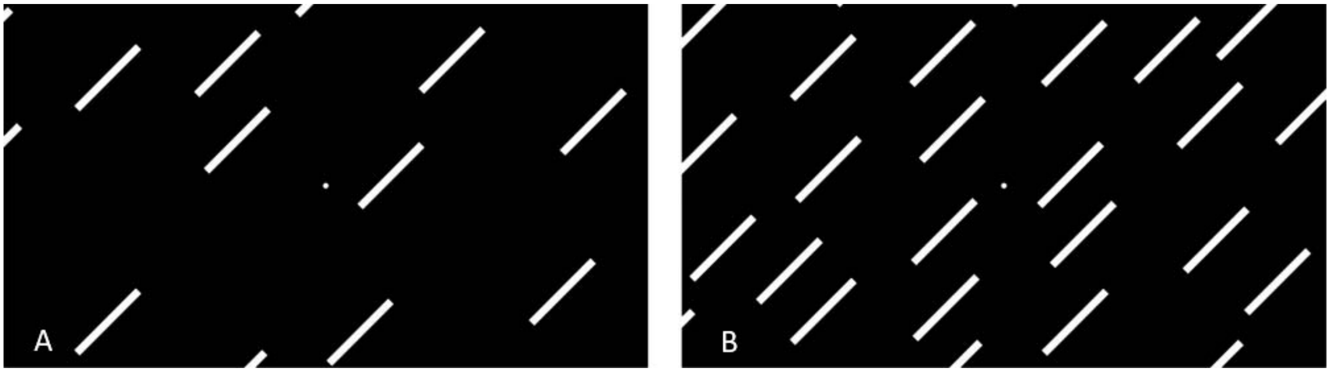

Figure 1. (**A**) Low-intensity stimulus and (**B**) high-intensity stimulus, covering roughly 50° of the subjects' field of vision. The *white lines* are 0.42 cm wide and 3.25 cm long (visual angle, 0.93°) standing at an angle of 45°. The lines rotate around a central fixation point, which is 0.32 cm in diameter. The low-intensity stimulus holds 19 lines, whereas the high-intensity stimulus holds 38.

To isolate vestibular stimulation from other stimuli, the subject was first asked to view a blinding image for 10 seconds that presented a bright projected area with a central fixation point. The image was then suddenly terminated as the projector was turned off. This created an environment of complete darkness with no visual cues. The subject then remained seated for 20 seconds before the sled rotation initiated the vestibular stimulation. After the movement, the subject remained seated for another 20 seconds at an angle of 33° before the experiment was terminated. To eliminate any unintended neck deflections from the straight position and therefore any proprioceptive input during the tilting, each subject's neck was supported by an extrication collar and hook and loop strap. Subjects were also fastened with a four-point seat belt.

Visual-Vestibular Stimulation

During this phase, the subject was seated and rotated using the same parameters previously described for the vestibular stimulation. However, the subject was concurrently exposed to either the low- or high-intensity visual stimuli during the experiment (Fig. 1). The order of stimuli presentation was balanced between subjects in the same fashion as for the visual stimulation (i.e., if a subject viewed the low intensity first and high intensity second for the visual stimulation, that order was preserved for the visual-vestibular stimulation). The visual stimulation remained stationary during the full-body roll of the subject. This ensured that the visual information on the retina would be comparable to that of the visual stimulus, as the image rotated 33° relative to the subject during body roll.

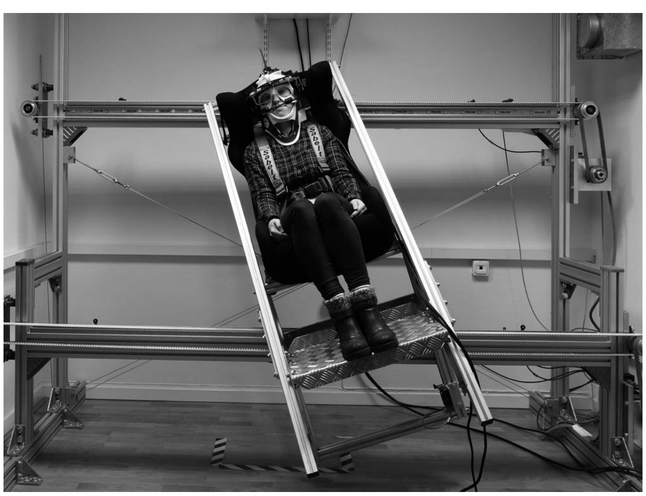

Figure 2. The mechanical sled consists of a chair mounted to two linear conveyor belts and is maneuvered by two servo-engines. This allows for high-precision linear and rotational movements for vestibular stimulation. The subject is wearing the head-mounted eye tracking system (Chronos C-ETD), extrication collar, and four-point seat belt.

Eye and Head Movement Recording

Eye movements were recorded using the head mounted Chronos Eye Tracker Device (C-ETD; Chronos Inc, Berlin, Germany; Fig. 2). The system allowed for binocular recording (200 Hz) with a high spatial resolution for horizontal and vertical eye movements (<0.05°), as well as ocular torsion (<0.1°). The torsional movements were measured as rotational displacements of the iris around the center of the pupil by tracking iris features using the Chronos Eye Tracker software. The technique is based on template matching of each frame with the initial reference frame obtained in the start of the recording. By cross-correlation, where 1.0 equals a perfect matching, each frame was given a quality measure between 0 and 1.0. Frames with a quality value below 0.5 were removed from analysis. The horizontal and vertical displacements of the pupil was initially calibrated by letting the test person do a sequence of eye movements to a pattern of dots with known separations allowing conversion of pupil displacement into angular degrees of horizontal and vertical eye rotation. Although the invasive scleral coil system has been considered the gold standard for eye movement recording, the less invasive video-based Chronos eye tracker has been proven a reliable alternative to velocity demanding tests during short stimulation periods. The coil-signal has a higher signal-to-noise ratio compared with video-based systems, but the degree of coil slippage due to lid movements or fast eye movements can be difficult, or even impossible, to interpret. The video-based systems, on the other hand, have been shown to suffer from iris occlusions, uneven light conditions, or poor pupil definition.[25] For this reason, multiple iris segments were gathered for analysis, with each being evaluated to ascertain the best possible signal quality. In addition, all measures were performed under the same lighting conditions, with the room dressed in blackout cloth and the projector being the only light source. The iris region tracked was not in proximity to any corneal light reflex or lid-shadows that could interfere with the signal. If the eye position signal was affected, due to blinking during the stimulation, the trial was repeated.

A head tracking system was integrated into the head mask for simultaneous recording of head movements in six

TABLE. Eye Movement Responses for Each Stimulus Condition, Presented as Means (SD)

Age Group, Eye Movement Response	VIS Low Intensity	VIS High Intensity	VES	VIS+VES Low Intensity	VIS+VES High Intensity
Young ($n = 6$)					
Torsional vel.	3.20 (1.72)	5.30 (2.34)	16.61 (4.20)	24.94 (3.79)	20.86 (4.38)
Skewing vel.	1.44 (0.47)	2.77 (2.00)	13.67 (11.24)	15.47 (13.64)	12.39 (5.74)
Ratio	1.38 (0.56)	2.25 (1.03)	1.23 (1.02)	1.20 (0.80)	2.06 (1.03)
Old ($n = 6$)					
Torsional vel.	2.92 (1.93)	2.75 (2.19)	13.26 (5.05)	15.98 (5.29)	19.18 (7.59)
Skewing vel.	2.07 (1.47)	2.29 (0.60)	15.83 (6.85)	12.53 (1.78)	11.09 (4.78)
Ratio	1.62 (0.51)	1.89 (0.65)	1.50 (0.68)	2.22 (1.10)	2.42 (1.21)

Intensity, level of visual intensity presented; vel, velocity (degrees/seconds); ratio, degree torsion per degree skewing.

dimensions (three rotational and three translational). This allowed for precise measurements of head movements, ensuring that the subject remains still or moving at a precise rate in accordance with the vestibular or visual stimulation prerequisites.

Analysis

The video system recorded the horizontal and vertical pupil positions and torsional displacement of iris position. The vertical skewing response, left vertical eye position minus right vertical eye position, was calculated and plotted, and the average velocity was derived from the plot. Similarly, the average velocity of the torsional response was calculated by determining the mean torsional amplitude between the two eyes. Each measurement was made on the slow phases of the nystagmic eye movement response, or in absence of nystagmic eye movements, the corresponding drift of eye position. Vertical skewing was either negative, left eye over right eye, or positive, right eye over left eye, depending on the direction of the head tilt. The torsion-skewing ratio was calculated by plotting the vertical skewing to the torsion on an *x-y* plot. Pearson's correlation coefficient was calculated to establish the torsion-skewing ratio, with values of at least $r = 0.6$ being treated as significant.

Eye movement velocity was considered the main outcome variable. It was computed by calculating the change in degrees over time in seconds between the beginning and end of the slow phase. The torsional velocity was used to calculate the relative contributions of visual and vestibular input to the eye movement response using three different stimulus conditions. The torsional response was chosen as it is well established in being more sensitive to utricular and semicircular vestibular stimulation than the vertical skewing response.[26,27] Given that all stimuli were presented with the same amplitude, acceleration, and time frame, the velocity was chosen as a common derivative. To calculate the relative contributions, the torsional velocity from the VIS and VES trials was each divided by the torsional velocity of the VIS+VES trials. This yielded the proportion that each sensory input contributed to the ocular torsion velocity.

To ensure a true physiologic torsional response, steps were made to exclude any significant impact of head-mask slippage and a so-called false torsional response, according to Listings law, due to oblique eye movements away from primary position. As the center of full-body rotation was set between the eyes, no larger horizontal or vertical eye movements were to be expected. However, due to the risk of error in adjusting the rotation center to test subject height in millimeters by manual measurement, an analysis of eye movements during the vestibular and visuo-vestibular trials was made to calculate any false torsion using the Fick-Helmholtz model.[28] As the head was still during the visual stimulation, no corrective horizontal or vertical eye movements were seen, eliminating the impact of false torsion on the results.

Statistical analysis was performed using IBM SPSS Statistics 25 for Windows (IBM, Armonk, NY, USA). Data distribution was inspected using the explore tool in SPSS. A repeated ANOVA model was used to analyze the interaction effects of modality and intensity. All data are presented as mean with the SD in parentheses. α was set to 0.05. Tests of normality were performed by Shapiro-Wilk's test, as well as visual investigation of stem-leaf plots.

RESULTS

There were no significant differences in eye movement velocities or torsion-skewing ratio between the age groups with regard to sex, order of presentation, modality, visual intensity, or stimulus direction. The calculated false torsion was not normally distributed between subjects, showing a median torsional amplitude of 0.65° (interquartile range [IQR], 0.27 to 1.66) for VES and 0.60° (IQR, 0.30 to 1.38) for VIS+VES. The direction of these false torsional responses was independent of direction of the stimulus rotation (e.g., a clockwise body tilt would lead to either a clockwise or counterclockwise false torsional response).

Torsional Response

There was no significant difference in torsional velocity related to the intensity of the visual stimuli. However, there was a highly significant modality effect with VIS+VES stimuli causing the highest torsional velocities, whereas VIS stimuli caused the lowest ($F[1:10] = 127.899$; $P < 0.001$). There was a significant between-group interaction effect depending on age, modality, and intensity, with younger subjects generally showed a faster torsional response compared with older participants ($F[1:10] = 9.158$; $P = 0.013$). The young population showed a significantly higher torsional velocity to VIS+VES compared with VES ($F[2:5] = 8.517$; $P = 0.025$). No such effect was seen for the older group. There was no significant difference in torsional velocity between the two visual intensities for either visual or vestibular stimulation. The Table shows the mean torsional velocity over all trials for all participants. An example of the graphical representation of the eye movement response can be seen in Figure 3.

Skewing Response

Data were normally distributed for the VIS+VES but not for VIS or VES alone. Age did not affect the skewing response. There was a significant increase in skewing velocities from VIS to VES

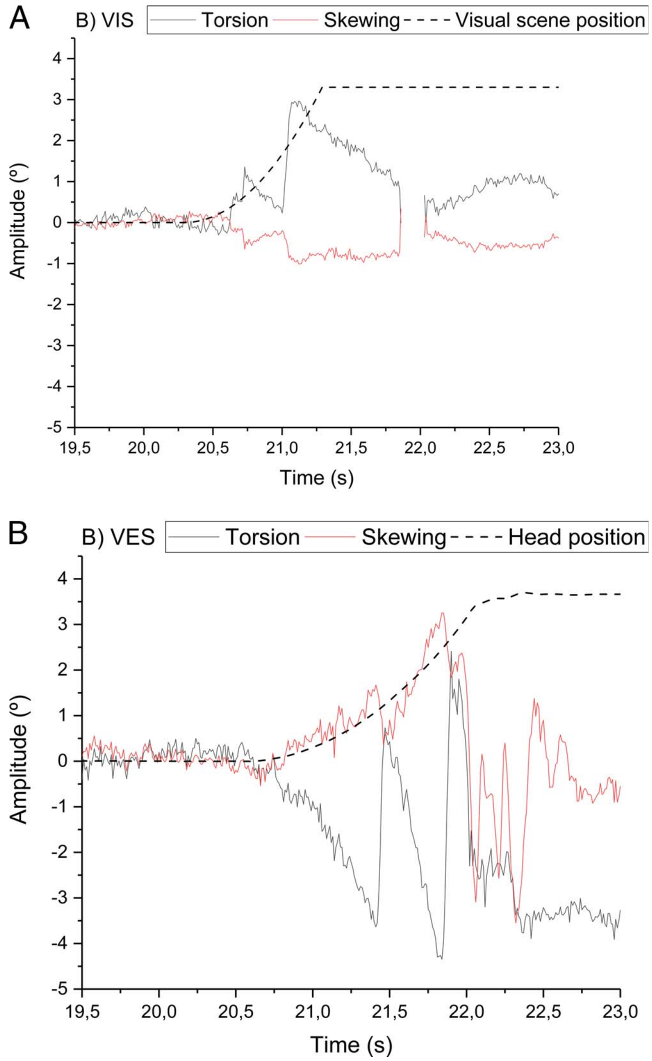

Figure 3. Unmodified raw signal examples of torsional and skewing responses for high-intensity VIS (**A**) and VES (**B**) stimuli. The *dashed line* signifies stimulus rotation (note that the amplitude has been divided by 10 for fitting purposes). The loss of signal at $t = 21.75$ (**A**) was due to a blink, and the signal distortion at $t = 22$ (**B**) was due to the subject's head coming to a sudden halt, leading to head instability.

($F[1{:}11] = 45.995$; $P < 0.001$; Table). Visual intensities had no significant effect independently of stimulus modality.

Torsion-Skewing Ratio

A combined torsion-skewing response was seen for all trials in all test subjects. The ratio was normally distributed. An increased visual intensity yielded a significantly higher torsion-skewing ratio in both VIS and VIS+VES ($F[1{:}10] = 13.363$; $P = 0.004$; Table), meaning a higher torsional velocity than skewing velocity. There was no significant difference in torsion-skewing ratio between stimulation modalities.

Relative Visual and Vestibular Contribution to Ocular Torsion Velocity

The torsional velocity was compared between stimulation modalities (Fig. 4). The difference between intensity levels in terms of relative contribution was not significant ($F[1{:}11] = 0.788$; $P = 0.394$). A paired *t*-test showed that the total

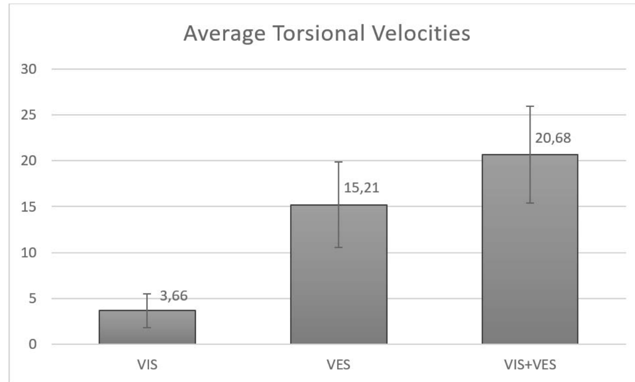

Figure 4. Mean torsional velocities for both low and high intensities for VIS, VES, and VIS+VES stimulations, given as °/s.

contribution of the vestibular and visual systems (VIS+VES) was not significantly different from 1.0 for neither low intensity ($t[11] = -0.335$; $P = 0.100$) nor high intensity ($t[11] = -1.793$; $P = 0.744$). However, when comparing the mean over both intensities, it was found to be less than 1 ($t[11] = -2.73$; $P = 0.02$). The proportional relative contribution of VIS and VES can be seen in Figure 5.

Discussion

The aim of this study was to understand how the visual and vestibular systems contributes to eye movements normally considered vestibular in origin, ocular torsion, and vertical skewing. To investigate the relative hierarchy of visual and vestibular sensory input to these eye movements, the proportional contributions of the isolated sensory systems were compared with the effect of stimuli intensity and modality.

Ocular Torsion

A significantly higher torsional velocity was seen in response to vestibular stimulation compared with visual stimulation. This was expected due to the superordinate nature of the vestibular system, a brainstem reflex, to vision, a perceptual interpretation of the surrounding, on balance. A calculation of vertical and horizontal corrective eye movements revealed a false torsional component of approximately 0.65° during the vestibular trials and 0.60° during the visuo-vestibular trials. This calculation was based on the assumption that the eye

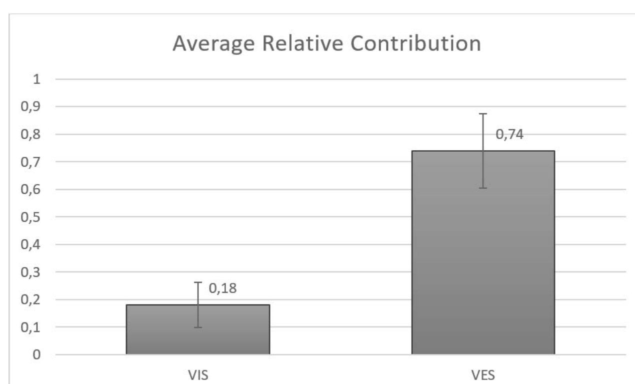

Figure 5. Mean relative contribution to torsional velocity for VIS and VES as given in proportions for both low and high visual intensity.

position, while looking straight ahead, coincided with the primary position. This would have yielded a false torsional velocity of approximately 0.46°/s for VES and 0.43°/s for VIS+VES. As seen in Figure 4, this only accounted for a fraction of the total torsional response, strengthening the validity of the torsional signal. Furthermore, the direction of this false torsion was independent of the stimulus direction, meaning that the influence of false torsion on the true response could either be additive or subtractive, effectively evening out the impact of false torsion upon group level. Considering the small difference in false torsion seen between VES and VIS+VES, one may suggest that the primary cause was mask-slippage or a misplaced center of rotation below or above the desired point between subjects' eyes. Although vestibular stimulations in darkness carry the risk of accidental gaze shifts, due to the absence of a fixation point, this would have led to a greater false torsional response during VIS compared with VIS+VES, which was not the case according to these results.

The results show that ocular torsion is not increased by the relatively subtle escalation in visual information between low and high intensity implemented in this study. However, in the young population, there was a significant increase in velocity from head tilt in darkness to head tilt while viewing a visual scene. This would suggest that the brain is reliant upon visual information in its torsional eye movement response, with a positive correlation to stimulus intensity. Furthermore, the presentation of combined visual and vestibular stimulation caused a synergistic effect. This could hypothetically be interpreted as an increased perception of self-motion. The fact that the difference in torsional velocity was seen in only the young population could be explained by a greater adaptability to the synergetic effect of visual and vestibular stimulation. It is well established that the elderly have more from dizziness, vertigo, and balance disorders in general.[3] However, the old population in this study would not be considered substantially senior on a national level, with the mean age of 59 years. Nevertheless, the findings indicate that our capacity for sensorimotor integration of balance information is negatively affected by age, as only the young group exhibited a reflexive motor adjustment to an increased intensity.

Vertical Skewing

This study clearly shows that this ratio is not only physiologic to vestibular stimuli but is also consistently seen as a response to visual stimulation. This is in contrast to the general belief that the combination of ocular torsion and vertical skewing is seen only in head tilts or brain stem lesions. Vertical skewing velocity proved to be more unevenly distributed that its torsional counterpart. The ANOVA model was still implemented on the basis that the eye movement, as a reflex, is evenly distributed in the general population. In addition, nonparametric analysis gave the same results as the ANOVA. Like ocular torsion, the skewing velocity was significantly increased from visual to vestibular provocation, which was to be expected for the same reason described above for the torsional response. Unlike the results for ocular torsion, the skewing velocity did not significantly increase from vestibular to combined trials for either age group. As such, it would seem that the brain integrates visual and vestibular input separately in terms of their joint motor output; vision has a greater impact on ocular torsion, increasing the response with aggregated visual information.

Torsion-Skewing Ratio

The torsion-skewing ratio describes a relationship between ocular torsion and vertical skewing related to head tilts as an ocular balance response. Given the nature of the combined movement as a physiologic response with the purpose of retaining an image on the fovea, one can speculate it is designed to adjust for the perception of self-movement. This study shows that the response occurs physiologically to visual and vestibular balance provocations.

In relation to visual information intensity, the increase in torsion-skewing ratio from low to high is highly significant, suggesting that the ratio of the two is more sensitive than both ocular torsion and vertical skewing alone to visual information contained in a visual scene. There was no significant difference between the solely VIS to VIS+VES. The balance response therefore does not seem to be relying on the modality provoking it, but rather only on visual stimuli intensity. Considering the findings that torsion responds to shifts in visual information while skewing does not, as discussed above, it can be stated that it is the difference in torsional response that primarily is responsible for the altered ratio.

Despite ocular torsion and vertical skewing having been studied for a long time, little is known about their relative relationship. Exploring this ratio from previous studies shows that the response changes with different vestibular stimuli,[20] although the exact nature of the relationship remains undisclosed. Nevertheless, it is clear that the torsion-skewing ratio is a dynamic relationship sensitive to changes in intensity of viewed visual information.

It is believed that ocular counter-rolling is primarily induced by a stimulation of the semicircular canals, whereas vertical skewing is seen in response to activation of the utricles.[29,30] Considering the variability of the ratio in relation to stimuli presentation, one could postulate that each pathway leads to its associated eye motor output directly, unaffected by any joint central integrator. The vestibular organ exhibits a heterogeneous set of neural afferents,[31] and it has been suggested that the nature of their signaling in terms of discharge regularity results in isolated central pathways.[32] While the vestibular signal is translated into conjugate vestibulo-ocular reflex eye movements for both semicircular canals and otoliths by a central integrator,[33] the nature of their unconjugated motor response as measured by ocular torsion and vertical skewing suggest that semicircular canals and utricular afferents are integrated separately.

The torsion-skewing ratio shows potential as a tool for both clinicians and researchers. Clinicians evaluating visually evoked vertigo would benefit from an objective measurement of perceived visual intensity, especially considering that many complaints are related to the intensity of visual clutter. From a research perspective, the ratio provides an objective avenue of deducing subjective sensitivity to visual motion.

Sensory-Specific Contribution to Ocular Torsion Velocity

When evaluating the vestibular and visual proportions to the eye movement response, the data sets for low- and high-intensity levels were not significantly different from each other. However, as illustrated in Figure 5, when the relative contributions for visual and vestibular stimulations were averaged over both intensities, there remained a small margin not explained by simple addition. Approximately 8% of the visual-vestibular torsional velocity could not be explained by visual or vestibular input, accounting for 18% and 74%, respectively. Considering that this was not seen for low and high intensities separately, it may be argued that the proportions differ depending on intensities. Although a comparison showed that this was not the case statistically, it may have been too small a change in visual intensity to show for the study population ($n = 6$) and only surfaced when both intensities were pooled ($n = 12$). Considering the complexity of balance control, it is not unlikely that additional parameters played into perception of self-motion that were not measured or controlled during this study.

Although the response may depend on various factors, the results nevertheless highlight that vision plays an important role in the integration of balance specific sensory information into oculomotor output. Considering the high number of patients with idiopathic vestibular symptoms and the high impact of vision input on balance shown here, one may suggest that visual examinations could be a readily available and cheap tool to implement when evaluating patients presenting with dizziness.

Conclusions

The purpose of this study was to examine how the visual system affected the oculomotor response normally seen as vestibular in origin during balance provocations. We were able to show that vertical skewing is physiologically evoked by visual stimulation alone and that the torsion-skewing ratio is sensitive to relative small changes in the intensity of visual information. As an ocular balance response, this measurement shows potential as a possible clinical examination tool for discerning whether the patient has an aberrant processing of visual information or not. Our findings suggest a large proportional impact of vision on self-motion perception in healthy subjects (18%), highlighting that vision examinations might play a key role in evaluating vertigo, especially that of a visually evoked nature.

Acknowledgments

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References

1. Newman-Toker DE, Hsieh YH, Camargo CA Jr, Pelletier AJ, Butchy GT, Edlow JA. Spectrum of dizziness visits to US emergency departments: cross-sectional analysis from a nationally representative sample. *Mayo Clin Proc*. 2008;83: 765–775.
2. Mueller M, Strobl R, Jahn K, Linkohr B, Peters A, Grill E. Burden of disability attributable to vertigo and dizziness in the aged: results from the KORA-Age study. *Eur J Public Health*. 2014;24:802–807.
3. Tinetti ME, Williams CS, Gill TM. Dizziness among older adults: a possible geriatric syndrome. *Annals Intern Med*. 2000;132:337–344.
4. Oman CM. Motion sickness: a synthesis and evaluation of the sensory conflict theory. *Can J Physiol Pharmacol*. 1990;68: 294–303.
5. Reason JT. Motion sickness adaptation: a neural mismatch model. *J R Soc Med*. 1978;71:819–829.
6. Bronstein AM. Multisensory integration in balance control. *Handb Clin Neurol*. 2016;137:57–66.
7. Bronstein AM. The visual vertigo syndrome. *Acta Otolaryngol Suppl*. 1995;520:45–48.
8. Bronstein AM, Lempert T, Seemungal BM. Chronic dizziness: a practical approach. *Pract Neurol*. 2010;10:129–139.
9. Vieville T, Masse D. Ocular counter-rolling during active head tilting in humans. *Acta Otolaryngol*. 1987;103:280–290.
10. Pansell T, Tribukait A, Bolzani R, Schworm HD, Ygge J. Drift in ocular counterrolling during static head tilt. *Ann N Y Acad Sci*. 2005;1039:554–557.
11. Merfeld DM, Teiwes W, Clarke AH, Scherer H, Young LR. The dynamic contributions of the otolith organs to human ocular torsion. *Exp Brain Res*. 1996;110:315–321.
12. Ooi D, Cornell E, Curthoys I, Burgess A, MacDougall H. Convergence reduces ocular counterroll (OCR) during static roll-tilt. *Vis Res*. 2004;44:2825–2833.
13. Pansell T, Sverkersten U, Ygge J. Visual spatial clues enhance ocular torsion response during visual tilt. *Exp Brain Res*. 2006;175:567–574.
14. Collewijn H, Van der Steen J, Ferman L, Jansen TC. Human ocular counterroll: assessment of static and dynamic properties from electromagnetic scleral coil recordings. *Exp Brain Res*. 1985;59:185–196.
15. Goodenough DR, Sigman E, Oltman PK, Rosso J, Mertz H. Eye torsion in response to a tilted visual stimulus. *Vis Res*. 1979; 19:1177–1179.
16. Barnes GR, Forbat LN. Cervical and vestibular afferent control of oculomotor response in man. *Acta Otolaryngol*. 1979;88: 79–87.
17. Cardin V, Smith AT. Sensitivity of human visual and vestibular cortical regions to egomotion-compatible visual stimulation. *Cereb Cortex*. 2010;20:1964–1973.
18. Wade MG, Jones G. The role of vision and spatial orientation in the maintenance of posture. *Phys Ther*. 1997;77:619–628.
19. Jauregui-Renaud K, Faldon M, Clarke A, Bronstein AM, Gresty MA. Skew deviation of the eyes in normal human subjects induced by semicircular canal stimulation. *Neurosci Lett*. 1996;205:135–137.
20. Jauregui-Renaud K, Faldon M, Clarke AH, Bronstein AM, Gresty MA. Otolith and semicircular canal contributions to the human binocular response to roll oscillation. *Acta Otolaryngol*. 1998;118:170–176.
21. Rashbass C, Westheimer G. Disjunctive eye movements. *J Physiol*. 1961;159:339–360.
22. Brodsky MC. Three dimensions of skew deviation. *Br J Ophthalmol*. 2003;87:1440–1441.
23. Werkhoven P, Snippe HP, Toet A. Visual processing of optic acceleration. *Vis Res*. 1992;32:2313–2329.
24. Wong SCP, Frost BJ. Subjective motion and acceleration induced by the movement of the observer's entire visual field. *Perception Psychophysics*. 1978;24:115–120.
25. Houben MM, Goumans J, van der Steen J. Recording three-dimensional eye movements: scleral search coils versus video oculography. *Invest Ophthalmol Vis Sci*. 2006;47:179–187.
26. Cohen B, Suzuki JI, Bender MB. Eye movements from semicircular canal nerve stimulation in the cat. *Annals Otol Rhinol Laryngol*. 1964;73:153–169.
27. Suzuki J, Tokumasu K, Goto K. Eye movements from single utricular nerve stimulation in the cat. *Acta Otolaryngol*. 1969;68:350–362.
28. Haslwanter T. Mathematics of three-dimensional eye rotations. *Vis Res*. 1995;35:1727–1739.
29. Brandt T, Dieterich M. Different types of skew deviation. *J Neurol Neurosurg Psychiatry*. 1991;54:549–550.
30. Schneider E, Glasauer S, Dieterich M. Comparison of human ocular torsion patterns during natural and galvanic vestibular stimulation. *J Neurophysiol*. 2002;87:2064–2073.
31. Goldberg JM. The vestibular end organs: morphological and physiological diversity of afferents. *Curr Opin Neurobiol*. 1991;1:229–235.
32. Goldberg JM. Afferent diversity and the organization of central vestibular pathways. *Exp Brain Res*. 2000;130:277–297.
33. Leigh RJ, Zee DS. *The Neurology of Eye Movements*. New York: Oxford University; 2015.