Neural Processing of Gravito-Inertial Cues in Humans. IV. Influence of Visual Rotational Cues During Roll Optokinetic Stimuli

L. H. ZUPAN AND D. M. MERFELD
Jenks Vestibular Physiology Laboratory, Massachusetts Eye and Ear Infirmary, Department of Otology and Laryngology, Harvard Medical School, Boston, Massachusetts 02114
Submitted 20 June 2001; accepted in final form 4 September 2002


The vestibular and visual systems provide the central nervous system (CNS) with information about head motion and orientation in space. This information is essential to elicit eye movements that compensate for head motion (Young 1984). The vestibular system includes two types of sensors: the semicircular canals and the otolith organs. The semicircular canals behave as integrating angular accelerometers measuring head angular velocity (Wilson and Melvill Jones 1979). The otolith organs behave as linear accelerometers measuring gravito-inertial force (GIF), which is the sum of gravitational force and inertial force due to linear acceleration. According to Einstein’s equivalence principle, a change in gravitational force due to tilt is indistinguishable from a change in inertial force due to translation. Therefore the central nervous system (CNS) must use other sensory cues to distinguish tilt from translation. For example, the CNS might use dynamic visual cues indicating rotation to help determine the orientation of gravity (tilt). This, in turn, might influence the neural processes that estimate linear acceleration, since the CNS might estimate gravity and linear acceleration such that the difference between these estimates matches the measured GIF. Depending on specific sensory information inflow, inaccurate estimates of gravity and linear acceleration can occur. Specifically, we predict that illusory tilt caused by roll optokinetic stimuli should lead to a horizontal vestibulo-ocular reflex compensatory for an interaural estimate of linear acceleration, even in the absence of actual linear acceleration. To investigate these predictions, we measured eye movements binocularly using infrared video methods in 17 subjects during and after optokinetic stimulation about the subject’s nasooccipital (roll) axis (60°/s, clockwise or counterclockwise). The optokinetic stimulation was applied for 60 s followed by 30 s in darkness. We simultaneously measured subjective roll tilt using a somatosensory bar. Each subject was tested in three different orientations: upright, pitched forward 10°, and pitched backward 10°. Five subjects reported significant subjective roll tilt (>10°) in directions consistent with the direction of the optokinetic stimulation. In addition to torsional optokinetic nystagmus and afternystagmus, we measured a horizontal nystagmus to the right during and following clockwise (CW) stimulation and to the left during and following counterclockwise (CCW) stimulation. These measurements match predictions that subjective tilt in the absence of real tilt should induce a nonzero estimate of interaural linear acceleration and, therefore, a horizontal eye response. Furthermore, as predicted, the horizontal response in the dark was larger for Tilters (n = 5) than for Non-Tilters (n = 12).

INTRODUCTION

The vestibular and visual systems provide the central nervous system (CNS) with information about head motion and orientation in space. This information is essential to elicit eye movements that compensate for head motion (Young 1984). The vestibular system includes two types of sensors: the semicircular canals and the otolith organs. The semicircular canals behave as integrating angular accelerometers measuring head angular velocity (Wilson and Melvill Jones 1979). The otolith organs behave as linear accelerometers measuring gravito-inertial force (GIF), which is the sum of gravitational force and inertial force due to linear acceleration. According to Einstein’s equivalence principle, a change in gravitational force due to tilt is indistinguishable from a change in inertial force due to translation. Therefore the central nervous system (CNS) must use other sensory cues to distinguish tilt from translation. For example, the CNS might use dynamic visual cues indicating rotation to help determine the orientation of gravity (tilt). This, in turn, might influence the neural processes that estimate linear acceleration, since the CNS might estimate gravity and linear acceleration such that the difference between these estimates matches the measured GIF. Depending on specific sensory information inflow, inaccurate estimates of gravity and linear acceleration can occur. Specifically, we predict that illusory tilt caused by roll optokinetic stimuli should lead to a horizontal vestibulo-ocular reflex compensatory for an interaural estimate of linear acceleration, even in the absence of actual linear acceleration. To investigate these predictions, we measured eye movements binocularly using infrared video methods in 17 subjects during and after optokinetic stimulation about the subject’s nasooccipital (roll) axis (60°/s, clockwise or counterclockwise). The optokinetic stimulation was applied for 60 s followed by 30 s in darkness. We simultaneously measured subjective roll tilt using a somatosensory bar. Each subject was tested in three different orientations: upright, pitched forward 10°, and pitched backward 10°. Five subjects reported significant subjective roll tilt (>10°) in directions consistent with the direction of the optokinetic stimulation. In addition to torsional optokinetic nystagmus and afternystagmus, we measured a horizontal nystagmus to the right during and following clockwise (CW) stimulation and to the left during and following counterclockwise (CCW) stimulation. These measurements match predictions that subjective tilt in the absence of real tilt should induce a nonzero estimate of interaural linear acceleration and, therefore, a horizontal eye response. Furthermore, as predicted, the horizontal response in the dark was larger for Tilters (n = 5) than for Non-Tilters (n = 12).

The vestibular and visual systems provide the central nervous system (CNS) with information about head motion and orientation in space. This information is essential to elicit eye movements that compensate for head motion (Young 1984). The vestibular system includes two types of sensors: the semicircular canals and the otolith organs. The semicircular canals behave as integrating angular accelerometers measuring head angular velocity (Wilson and Melvill Jones 1979). The otolith organs behave as linear accelerometers measuring gravito-inertial force (GIF), which is the sum of gravitational force and inertial force due to linear acceleration. According to Einstein’s equivalence principle, a change in gravitational force due to tilt is indistinguishable from a change in inertial force due to translation. Therefore the central nervous system (CNS) must use other sensory cues to distinguish tilt from translation. For example, the CNS might use dynamic visual cues indicating rotation to help determine the orientation of gravity (tilt). This, in turn, might influence the neural processes that estimate linear acceleration, since the CNS might estimate gravity and linear acceleration such that the difference between these estimates matches the measured GIF. Depending on specific sensory information inflow, inaccurate estimates of gravity and linear acceleration can occur. Specifically, we predict that illusory tilt caused by roll optokinetic stimuli should lead to a horizontal vestibulo-ocular reflex compensatory for an interaural estimate of linear acceleration, even in the absence of actual linear acceleration. To investigate these predictions, we measured eye movements binocularly using infrared video methods in 17 subjects during and after optokinetic stimulation about the subject’s nasooccipital (roll) axis (60°/s, clockwise or counterclockwise). The optokinetic stimulation was applied for 60 s followed by 30 s in darkness. We simultaneously measured subjective roll tilt using a somatosensory bar. Each subject was tested in three different orientations: upright, pitched forward 10°, and pitched backward 10°. Five subjects reported significant subjective roll tilt (>10°) in directions consistent with the direction of the optokinetic stimulation. In addition to torsional optokinetic nystagmus and afternystagmus, we measured a horizontal nystagmus to the right during and following clockwise (CW) stimulation and to the left during and following counterclockwise (CCW) stimulation. These measurements match predictions that subjective tilt in the absence of real tilt should induce a nonzero estimate of interaural linear acceleration and, therefore, a horizontal eye response. Furthermore, as predicted, the horizontal response in the dark was larger for Tilters (n = 5) than for Non-Tilters (n = 12).

1 The specific gravitoinertial force measured by the otolith organs (f) is defined as the sum of gravitational force per unit mass (g) plus an inertial force per unit mass (−a) acting on the otolith organs and exactly opposing the direction of linear acceleration (a).

The costs of publication of this article were defrayed in part by the payment of page charges. The article must therefore be hereby marked “advertisement” in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.
Definition makes it possible to validate or reject a relationship between gravity and linear acceleration, as previously suggested (e.g., Merfeld et al. 1999; Merfeld and Zupan 2002), an experimentally developed neural internal model2 representing the physical relationship between gravity and linear acceleration, as previously suggested (e.g., Merfeld et al. 1999; Merfeld and Zupan 2002). We refer to this horizontal VOR component, represented by an eye rotation vector about the z-axis, as an “induced VOR.” Since the tilt direction of the estimate of gravity (ĝ) depends on rotation direction of the visual cues, the induced VOR component is also predicted to depend on the rotation direction of the visual cues (Fig. 2).

To gain insight into how human subjects distinguish tilt from translation, we designed an experiment that created a conflicting sensory situation between visual and otolith cues, and we simultaneously measured perceptual tilt and reflexive slow phase eye movements. While subjects were seated in either an upright or a pitched-backward position, we created a conflict between the visual and otolith cues by introducing an illusory tilt to the visual scene while keeping the otoliths upright.

The GIF resolution hypothesis (e.g., Merfeld et al. 1993a; Merfeld and Young 1995; Merfeld and Zupan 2002), an explicit refinement of the “multisensory integration” hypothesis (Guedry 1974; Mayne 1974; Oman 1982; Young 1984), states that additional sensory information is required for the CNS to resolve the GIF ambiguity. Specifically, the CNS systematically separates the otolith GIF measurement (f) into estimates of gravity (ĝ) and linear acceleration (â) using multisensory convergence, so that the difference between these estimates approximately matches the measured GIF (f = ĝ - â). In other words, the GIF resolution hypothesis suggests that the CNS has developed a neural internal model representing the physical relationship between gravity and linear acceleration, as previously suggested (e.g., Merfeld et al. 1999; Merfeld and Zupan 2001; Merfeld and Zupan 2002; Merfeld et al. 2001; Zupan et al. 2000).

Visual and otolith cues may provide the CNS with conflicting sensory information. Consider the sensory situation experienced by a subject statically positioned in an upright orientation (Fig. 1A) during a sustained CW rotation of an optokinetic drum about the subject’s nasooccipital axis. First, for this experimental protocol, the otolith organs measure a constant GIF due to gravity alone (Fig. 2A, f = g). In the upright orientation, this force is aligned with the subject’s rostrocaudal axis. At the same time, the visual system provides the CNS with dynamic rotational cues about the subject’s nasooccipital axis. These visual cues are known to influence the perceived orientation of gravity, leading to illusory tilt (Dichgans et al. 1972; Held et al. 1975; Howard and Childress 1994). This evidence suggests that the CW visual roll rotational cue influences the estimated orientation of gravity (ĝ) such that the estimate of gravity (ĝ) rotates in the same direction as if there were an actual roll rotation of the head in the direction ofvection (CCW), as shown on Fig. 2A. We hypothesize that the CNS computes estimates of gravity (ĝ) and linear acceleration (â) such that their difference matches the measured GIF, which equals gravity in this example (f = ĝ - g). Therefore a nonzero estimate of linear acceleration (â = ĝ - g) would be generated whenever the estimate of gravity (ĝ) does not match true gravity (g), as shown in Fig. 2. Since a nonzero estimate of interaural linear acceleration (â) is predicted, an appropriate horizontal compensatory translational vestibulo-ocular reflex (VOR) response might be elicited (Fig. 2), as in response to a true interaural linear acceleration (Niven et al. 1966; Paige and Tomko 1991; Schwarz et al. 1989; Schwarz and Miles 1991). We refer to this horizontal VOR component, represented by an eye rotation vector about the z-axis, as an “induced VOR.” Since the tilt direction of the estimate of gravity (ĝ) depends on rotation direction of the visual cues, the induced VOR component is also predicted to depend on the rotation direction of the visual cues (Fig. 2).

To gain insight into how human subjects distinguish tilt from translation, we designed an experiment that created a conflicting sensory situation between visual and otolith cues, and we simultaneously measured perceptual tilt and reflexive slow phase eye movements. While subjects were seated in either an upright or pitched-backward position, we created a conflict between the visual and otolith cues by introducing an illusory tilt to the visual scene while keeping the otoliths upright.

2 We define internal models as neural systems that mimic physical principles associated with sensory transduction and/or body movement in some relevant way. To allow experimental investigation, we use an even more conservative definition, limiting internal models to those neural systems that mimic physical principles that we can unambiguously represent mathematically (e.g., f = g - a). This conservative definition makes it possible to validate or reject a hypothesized internal model objectively.
upright or slightly pitched (10° forward or 10° backward) orientation, visual roll rotational cues were presented with an optokinetic drum placed in front of their face. As hypothesized, we found a horizontal eye movement that correlated with the measured illusory roll tilt.

**Methods**

**Experimental set-up and eye movement recording**

Informed consent was obtained in accordance with institutional procedures and subjects were instructed about potential risks, including motion sickness, prior to each testing session.

All protocols were conducted on our “Markham chair,” which allowed us to appropriately position the subject by use of two gimbals. An inner gimbal allowed us to rotate the chair about the subject’s yaw axis. An outer pitch/roll gimbal powered by a small 10 N-m DC motor provided rotations about an earth-horizontal axis. Each subject was seated on a “race car” seat mounted in the device’s inner yaw gimbal. The subject’s body was restrained using two shoulder belts and a waist belt, lateral shoulder supports, and a resting foot plate. The subject’s head was secured in an adjustable foam-lined head restraint. The center of the subject’s head was aligned with both the outer gimbal earth-horizontal axis and the inner gimbal yaw axis. An optokinetic drum (Fig. 1A) was placed in front of the subject’s face (the drum opening was 5 cm in front of the subject’s eyes); the optokinetic drum prevented subjects from getting orientation cues from the surrounding room. The optokinetic drum was a 35-cm-long and 40-cm-diam opaque cylinder opened on one end; the inside surface was covered with randomly distributed 2-cm-diam colored dots. (Five different colors were used for the dots with a density of approximately 1000 dots/m².) The drum rotation axis was powered with a 12 V DC motor and stayed aligned with the subject’s naso-occipital axis throughout the experimental protocol (the drum moved with the subject’s head as shown in Fig. 1B).

Binocular eye movements were recorded (Panasonic AG-DS850 SVHS VCR) using small video cameras (Machine Vision Hyper CCD Cameras CV-36SH) mounted on a bite-bar assembly. Infrared LEDs provided lighting for the video cameras. A mold of each subject’s mouth was formed on the bite-bar using a dental impression compound (3M Express, 3M Dental Products, St. Paul, MN). The weight of the camera assembly was supported by wires attached to the helmet with Velcro attachment.

An off-line application of a custom image analysis program provided measurements of the horizontal and vertical coordinates of the pupil center for each field of the video image (59.94 video fields/s). Methods for calibration of the video measurement system, calculation of horizontal and vertical slow phase velocities (SPV), and accuracy of these measurements are detailed in a companion paper (Zupan et al. 2000).

When the quality of video recording allowed it and the subject had a distinctive irl pattern (consistently possible for 10 of 17 subjects but we only report the 5 subjects who consistently had the highest-quality version for both upright trials), torsional eye position was obtained by use of a cross-correlation technique. At the beginning of a trial, on a reference image, a circular arc was selected on the iris and gray levels were sampled along this reference arc to provide a gray-level reference profile. Torsional eye position was determined by cross-correlation of the gray level reference profile obtained on the reference image with the gray level profiles obtained on subsequent images. More specifically, the iris arc was obtained at a fixed displacement from the pupil edge, as determined by an ellipse fit to the pupil edge points. The iris arc defined an ellipse concentric with the pupil ellipse. Subsequent arcs were sampled along a concentric ellipse at the same fixed distance from the ellipse fit to the pupil in the current image. Typically six concentric arcs were sampled with displacements of two pixels between the arcs. A measure of torsion was obtained from the shift in the peak of the cross-correlation function for each arc, and the median value of the six torsion measures provided the final torsion value.

**Experimental protocols**

Seventeen healthy subjects age 19 to 50 (8 males and 9 females with an average age of 27 yr) with no history of peripheral or central vestibular disorders volunteered for this study. Clinical testing (including but not limited to rotating chair test battery, Hallpike maneuvers, computerized dynamic posturography, and caloric testing) was performed on all subjects and indicated no abnormalities.

To minimize order effects, lights were turned on for 2 min between trials while the subjects were upright and stationary. At the beginning of each trial, the test subjects were seated in an upright orientation. The optokinetic drum was turned on and rotated in either a CW or CCW direction (from the subject’s perspective) at a constant angular velocity (60/s) about the subject’s naso-occipital axis (aligned with an earth-horizontal axis at the beginning of each trial). During a trial, the drum rotation axis stayed fixed with respect to the subject’s head; then, using the motorized outer pitch/roll gimbal, the subject was orientated in one of three final orientations: upright, pitched-forward 10°, and pitched-backward 10°. (Even when the final orientation was upright, we pitched the subject back and forth so that subjects could not be certain of their final orientation.) Once the subject was in the final orientation, the drum kept rotating for 60 s. The lights then went off and the subject stayed in complete darkness for 30 s. Both eye movements and subjective tilt were measured during this 90-s period (60 s in light + 30 s in darkness). The trial order was randomized andsecret, with the direction of rotation (CW or CCW) and head orientation (upright, pitched-forward 10°, and pitched-backward 10°) counter-balanced across subjects.

During data collection in light, the subjects were asked to pay attention to the moving dots on the inside of the optokinetic drum without pursuing any of them and to look “through” the 10-cm-diam blackened cylinder placed at the center of the drum (gaze eccentricity could not exceed 7° in any direction). In darkness, the subjects were asked to open their eyes and to look straight ahead without focusing on any real or imagined point.

**Perceptual roll tilt**

Simultaneous with the measurement of the eye movements, all subjects provided an objective measure of their perceived subjective roll tilt using a “somatosensory” task (Merfeld et al. 2001; Wade and Curthoys 1997), which requires subjects to set a handheld bar in alignment with the perceived earth-horizontal. This task has two main advantages over a visual task (in which subjects are usually asked to align a light bar with perceived earth-horizontal): 1) the somatosensory settings are not contaminated by offsets due to torsional eye movements, which occur during roll optokinetic stimulation, and 2) the task can be performed while simultaneously recording three-dimensional eye movements.

Our somatosensory bar consisted of a hollow square (2.54 cm) aluminum tube, 30.5-cm long, pivoted about its center point. The bar was attached to the Markham chair so that it could rotate in a plane parallel to the subject’s coronal plane, approximately 35 cm from the midriff of the seated subject. (In pitch orientations, the somatosensory bar pitched with the subject.) The bar was attached to the central pivot point so that there was modest resistance to movement, less than that encountered with power steering in an auto. Subjects held the bar with one hand placed at each end of the bar and rotated the bar around its central pivot point until it was in the desired position. During settings, subjects were required to keep their hands at the end of the bar and not move them along the length of the bar. A precision potentiometer (0.5% linearity) was coaxial with the bar shaft and provided an analog measure of the bar orientation. Subjects were instructed “to as quickly
and accurately as possible set the bar to be aligned with the perceived horizontal.” Before each setting, the subjects rapidly offset the bar in both directions. This helped minimize any undue influence of the previous setting. This task was performed “continuously” during each trial. With this measurement technique, we obtained a set of discrete measures at variable time intervals for each trial.

Data analysis

HEAD-FIXED REFERENCE FRAME. All vector coordinates (physical variables and internal estimates) were expressed in an orthogonal, right-handed, head-fixed frame of reference with x-, y-, and z-axes corresponding to the subject’s nasooccipital, interaural and rostrocaudal axes, respectively. The positive axes were directed nasally (x), toward the left ear (y), and toward the top of the skull (z).

FICK ANGLES. To describe eye position and eye angular velocity, we used Fick angles and angular rates de
c
complete description was accidentally deleted from that paper.

The same interpolation method was used for sub-
interp1 function with spline method in Matlab software package from
measures (typically provided at intervals between 1 and 4 s with a
tilt data between subjects, we interpolated between discreet roll tilt
aligned with perceived earth-horizontal. To compare subjective roll
when subjects hit a button to validate that their present bar setting
set of discrete roll tilt measures for each trial; each measure is taken
whether a measurement was signi
fi
whether a measurement was signi

R E S U L T S

Tilt psychophysics

During the 30 s before extinction of lights, subjects (n = 17) experienced an average illusory subjective roll tilt of 6° for CW stimulation and 8° for CCW stimulation (Fig. 3). Five subjects experienced an average illusory tilt across trials >10°; they are referred to as “Tilters”. Twelve subjects experienced an average illusory subjective roll tilt smaller than 5°; they are referred to as “Non-Tilters”. No subject experienced an average subjective tilt between 5° and 10°. (For each subject, the average subjective roll tilt was calculated by taking the mean of the absolute value of all subjective tilt measures during the last 30 s of the “lights on” period.)

We statistically analyzed the measured responses during the last 30 s before the lights were turned off (between t = −30 s and t = 0 s) and during the 3 s that began 2 s after the lights were turned off (between t = 2 s and t = 5 s). These two periods are referred to as “in light” and “in darkness”. No subject experienced an average subjective tilt across subjects for both directions of rotation (Fig. 3). In darkness, it took more than 30 s for the subjective roll tilt to decay to zero for both stimulation directions (Fig. 3). Finally, the SD for Non-Tilters was significantly smaller than for Tilters (P < 0.05) for both periods considered. Such large variability among Tilters has been reported previously (Dichgans et al. 1972).

Eye movement responses

During roll optokinetic stimulation with subjects upright, we measured both a torsional optokinetic nystagmus (OKN) and

FIG. 3. Subjective roll tilt during roll optokinetic stimulation in an upright orientation. CW and CCW refer to the direction of drum rotation from the subject’s perspective. Positive indicates roll tilt to the subject’s right; negative indicates roll tilt to the subject’s left. Shading indicates the SE of the average response for Tilters (n = 5; light shading) and Non-Tilters (n = 12; dark shading). The middle line with no standard error shading indicates the average subjective roll tilt for all subjects (n = 17). The vertical dashed line (time 0) indicates when lights are turned off. A: average roll tilt measurement during and after CW drum rotation. B: average measurement during and after CCW drum rotation.

J Neurophysiol • VOL 89 • JANUARY 2003 • www.jn.org
afternystagmus (OKAN) and a horizontal nystagmus (Fig. 4). By differentiating the eye position and then removing saccades, we calculated the slow phase velocity (SPV). The example presented shows the subject with the largest torsional nystagmus (Fig. 4, A and B). When considering all subjects for whom we were able to obtain torsional data consistently (n = 5), the average torsional gain (defined as peak torsional velocity over 60°/s peak stimulus velocity) for the upright trial in light was 0.054 ± 0.013 for CW rotations and 0.044 ± 0.016 for CCW rotations, consistent with previous studies (Cheung and Howard 1991; Collewijn et al. 1985; Jackson 1992; Morrow and Sharpe 1989). The example in Figs. 4, A and B, also demonstrated a horizontal nystagmus with an average SPV magnitude of about 4°/s for both directions, about four times larger than the average SPV across all subjects (Fig. 4C). This subject was a Tilter and, as described later, this group of subjects had a larger horizontal response than the Non-Tilters.

For the upright orientation, the average horizontal SPV in the light across 17 subjects was nearly constant but small. It rarely exceeded 1.5°/s in magnitude (Fig. 4C) but was significantly different from zero for both CW (P < 0.001) and CCW (P < 0.005) optokinetic stimulation. The horizontal SPV reversed with stimulation direction as predicted by the GIF resolution hypothesis (see DISCUSSION). In darkness, the horizontal SPV decayed to zero over a 15-s period and was significantly different from zero for both directions of optokinetic stimulation (P < 0.005).

Since the horizontal SPV was very small, we calculated the horizontal slow cumulative eye position (HSCEP), which is the integral of the horizontal SPV. (For the HSCEP in light, we chose HSCEP = 0 at t = −60 s; for the HSCEP in darkness, we chose HSCEP = 0 at t = 0 s.) Since integration is a linear process, the HSCEP for upright orientation (Fig. 5A) was significantly different from zero in light for both CW (P < 0.001) and CCW (P < 0.005) optokinetic stimulation (as previously shown for the SPV). In darkness, the HSCEP for upright orientation (Fig. 5B) was also significantly different from zero following both CW (P < 0.001) and CCW (P < 0.005) optokinetic stimulation.

Two hypotheses could explain the presence of horizontal eye movements. One hypothesis, referred to as the “economical axis-shift hypothesis,” states that the rotation axis of reflexive eye movements (primarily torsional OKN and OKAN) may shift toward alignment with gravity through the “smallest angle,” therefore resulting in a horizontal response, as observed experimentally in humans during optokinetic stimulation (Furman and Koizuka 1994; Gizzi et al. 1994; Wei et al. 1994), after a postrotatory tilt (Fetter et al. 1992; Furman and Koizuka 1994; Zupan et al. 2000), during off-vertical axis-rotation (Harris and Barnes 1987), and during centrifugation (Merfeld et al. 2001). Another hypothesis referred to as the “GIF resolution hypothesis” states that a horizontal induced VOR compensatory for an interaural estimate of linear acceleration may superimpose on the torsional OKN and OKAN, as observed experimentally after a postrotatory tilt (Merfeld et al. 1999; Zupan et al. 2000) and after yaw optokinetic stimulation about an earth-horizontal axis (Wall et al. 1999). To discriminate between these two hypotheses, which are not exclusive, we tested our 17 subjects in two additional orientations: pitched-forward 10° and pitched-backward 10°. In the following sta-

![Figure 4](http://jn.physiology.org/)

**FIG. 4.** Reflexive eye movements in upright orientation. A: horizontal (H) and torsional (T) nystagmus for 1 subject during CW drum rotation. B: same as A during CCW drum rotation. C: average horizontal slow phase eye velocity (SPV) across subjects during CW (light shading) and CCW (dark shading) drum rotation. SPV is the derivative of eye position after saccades were removed. D: average subjective roll tilt across subjects during CW (light shading) and CCW (dark shading) drum rotation. The vertical dashed line (time 0) indicates when lights are turned off. Shading indicates SE (n = 17).
tistics, we simultaneously considered data for the two directions of rotations and the three head orientations (upright, pitched-forward 10°, and pitched-backward 10°). If the GIF resolution hypothesis is valid, a small 10° pitch either forward or backward should not qualitatively affect the predicted interaural estimate of linear acceleration (Fig. 2) and the direction of the corresponding horizontal induced VOR should therefore not be qualitatively affected by any small pitch: the induced horizontal VOR vector should always be rightward for CW optokinetic stimulus (see Fig. 7C, “induced VOR” vector aligned with the z-axis and oriented downward) and leftward for CCW optokinetic stimulus (see Fig. 7D, “induced VOR” vector aligned with the z-axis and oriented upward). On the contrary, if the economical axis-shift hypothesis is valid, the direction toward which the torsional VOR response is shifting to align with gravity should reverse between “pitched-forward” and “pitched-backward” orientations (see Fig. 7, C and D). Therefore the use of the pitched orientations should help us to discriminate between the two hypotheses.

First, we verified that the subjective roll tilt measurement was not affected substantially by pitch head orientations for Tilters. Indeed, the amplitude and dynamics of the subjective roll tilt were very similar for each orientation and direction of optokinetic stimulation (Fig. 6). Because the somatosensory bar was fixed with respect to the subject, the subjective tilt task was harder in pitched orientations, and three Non-Tilter subjects did not perform the task during substantial periods of time for some trials. Thus these three subjects were not included in statistical analyses for the influence of head orientation on subjective roll tilt (n = 14 instead of n = 17).

During and after optokinetic stimulation, the HSCEP (Fig. 7A and B) was significantly different between the three orientations in both light (P < 0.05) and darkness (P < 0.05). However, the average subjective roll tilt across subjects was not significantly different between the three orientations (Fig. 6; n = 14) in either light or darkness. When all orientations were considered (only the upright orientation was considered before when comparing Tilters with Non-Tilters), the average subjective roll tilt across subjects (n = 14) was still significantly larger for Tilters than for Non-Tilters in both light (P < 0.005) and darkness (P < 0.01). However, the HSCEP was only significantly different between Tilters and Non-Tilters in darkness (P < 0.05; n = 17).

DISCUSSION

Only one other study has measured both eye movement and subjective roll tilt responses on the same group of subjects, human (Merfeld et al. 2001) or animal, though several other studies report eye movements alone and infer what must be occurring with tilt (Angelaki et al. 1999; Zupan et al. 2000). We not only report subjective roll tilt and eye movement responses during roll optokinetic stimulation but also compare these responses.

Tilt psychophysics

Roll optokinetic cues induced the perception of a significant illusory subjective roll tilt (larger than 10°) in a minority (n = 5) during roll optokinetic stimulation for all orientations (upright, pitched-forward 10°, and pitched-backward 10°). CW and CCW refer to the direction of drum rotation from the subject’s perspective. Positive indicates roll tilt to the subject’s right; negative indicates roll tilt to the subject’s left. The vertical dashed line (time 0) indicates when lights are turned off. The subjective roll tilt does not seem to be substantially influenced by the 10° pitch (either backward or forward).
5) of our 17 subjects. The small size of measured subjective roll tilt was probably due to the nearness of the visual field since foreground stimuli have less of an effect than background stimuli (Brandt et al. 1975; Ohmi et al. 1987). The illusory subjective roll tilt reversed with rotation direction of the optokinetic drum (Fig. 2), establishing the direct influence of optokinetic stimulation on orientation perception: the illusory subjective roll tilt is in the same direction as if there were an actual body roll tilt in the direction of the perceived vection. The time course of the subjective roll tilt was similar for both directions of rotations: once established, the roll tilt illusion stayed rather constant and then decayed once lights were turned off. These findings are consistent with earlier data (Dichgans et al. 1972).

**Eye movements**

In addition to the expected OKN and OKAN, we found a consistent measurable horizontal response during and after the optokinetic roll stimulation. While the average horizontal SPV rarely exceeded 1.5°/s, it was significantly different from zero (P < 0.001 for CW and P < 0.005 for CCW) and reversed with stimulation direction. For the three orientations, the average HSCEP (which is the integral of the horizontal SPV) was significantly larger for Tilters than for Non-Tilters in darkness only (P < 0.05). In addition, the average HSCEP for the pitched-forward orientation was significantly larger than for the pitched-backward orientation for both directions of rotation in light and dark (P < 0.05).

According to the GIF resolution hypothesis (Angelaki et al. 1999; Merfeld et al. 1993a, 2001; Merfeld and Young 1995; Merfeld and Zupan 2001, 2002; Zupan 1995; Zupan et al. 2000, 2002), this horizontal component could include an induced VOR, compensatory for an interaural estimate of linear acceleration, even in the absence of actual linear acceleration. Specifically, subjects may experience an illusory subjective tilt to the left during CW stimulation and to the right during CCW stimulation (Fig. 3). (Significant subjective tilt in the opposite direction was never measured.) Assuming that the illusory subjective tilt reflects the state of the internal estimate of gravity (g), this estimate of gravity (ĝ) is not aligned with the otolithic measurement of (GIF, f), which equals gravity in this particular case (f = g). According to the GIF resolution hypothesis, during such a discrepancy between estimated and measured gravity the CNS elicits a nonzero estimate of linear acceleration (ˆa) so that the difference between estimates of gravity and linear acceleration matches the measured GIF (f = g = ̂g − ˆa, Fig. 2), mimicking the physical relationship between GIF, gravity, and linear acceleration (f = g − a). When subjects are upright, the estimate of linear acceleration (ˆa) has a nonzero interaural component (A-shift). The appropriate eye movement response for this interaural estimate of linear...
acceleration is a horizontal induced linear VOR component, identical to the eye movement response to an actual interaural linear acceleration (Niven et al. 1966; Paige and Tomko 1991; Schwarz et al. 1989; Schwarz and Miles 1991). Since the illusory tilt direction reverses with roll optokinetic stimulation (Fig. 3), we hypothesized that the directions of both the estimate of linear acceleration and induced horizontal component should reverse, as was observed experimentally (Fig. 4).

Comparison of tilt perception and eye movement responses

For the three orientations, we observed that the HSCEP was significantly larger for Tilters than for Non-Tilters in darkness only. This result was predicted by the GIF resolution hypothesis. Indeed, the amplitude of the estimate of linear acceleration (\( \hat{a} \)) decreases with decreasing illusory tilt (\( \hat{\theta} \)) as demonstrated in Fig. 8. Therefore the horizontal SPV and HSCEP should be larger for Tilters than for Non-Tilters. Similarly, the GIF resolution hypothesis predicts that the horizontal SPV should decay as the tilt decays following the extinction of lights (Fig. 3), as was qualitatively confirmed experimentally (Fig. 4).

According to the GIF resolution hypothesis, there is an explicit geometrical correlation between central estimates of gravity and linear acceleration (Fig. 2); the greater the roll tilt, the greater the estimate of interaural linear acceleration (Fig. 8). If this hypothesis is valid, we might find a strong positive correlation between subjective roll tilt and the horizontal linear VOR component. (Therefore the use a one-tailed t-test is justified.) However, the correlation between the two measures may not be as robust as the correlation between central estimates of gravity and linear acceleration, since both measures are indirect and may be processed centrally through different neural pathways. In addition, the near-constancy of both measures in light and the rapid decrease of them as soon as lights are off introduce additional statistical challenges. We decided therefore to perform a nonparametric Spearman statistical correlation analysis on rank data (Lehmann and D’Aubera 1998) for Tilters only (n = 5). Since the ranking between subjects should not be affected by orientation and rotation direction, we computed rank data (see Fig. 9 legend for details) for each of the six experimental conditions. (For CW trials, we multiplied both tilt and horizontal linear VOR measures by −1 to keep the ranking consistent.) We then performed a correlation analysis on the average rank data for the horizontal linear VOR as a function of the average rank data for the subjective roll tilt across the six experimental conditions in the dark (Fig. 9). This positive correlation (\( r^2 = 0.74 \)) was significant (\( P < 0.05 \)).

Influence of head orientation on eye movement responses

An alternative and/or concomitant explanation must also be considered. It has been observed that the eye rotation axis of reflexive eye movements tends to shift toward alignment with gravity in response to either I) optokinetic stimulation in humans (Furman and Koizuka 1994; Gizzi et al. 1994; Wei et al. 1994) and monkeys (Cohen et al. 1999; Dai et al. 1991; Rapahan and Cohen 1988) or 2) canal stimulation in humans (Fetter et al. 1992; Furman and Koizuka 1994; Harris and Barnes 1987; Merfeld et al. 2001; Zupan et al. 2000) and monkeys (Angelaki and Hess 1994; Jaggi-Schwarz et al. 2000; Merfeld and Young 1992, 1995; Merfeld et al. 1993a; Wearne et al. 1999). The axis-shift component is very small in humans during both optokinetic and canal stimulation. In addition, this axis-shift seems to be “economical” in the sense that the eye movement rotation axis always shifts toward alignment with gravity “through the smallest angle,” as was suggested in our recent model of reflexive eye responses to visual-vestibular interactions (Zupan et al. 2002) and by numerous experimental investigations (Angelaki and Hess 1994; Dai et al. 1991; Fetter et al. 1992).
et al. 1996; Furman and Koizuka 1994; Gizzi et al. 1994; Harris and Barnes 1987; Jaggi-Schwarz et al. 2000; Merfeld et al. 1993b; Raphan and Cohen 1988; Wearne et al. 1999). For example, after a postrotatory pitch following a roll rotation about an earth-vertical axis in either a supine or prone orientation, eye movements in rhesus monkeys include a horizontal VOR component in addition to the expected compensatory torsional VOR (Angelaki and Hess 1994). Because of the presence of this additional horizontal VOR (represented by a rotation vector aligned with the subject’s yaw axis or z-axis), the VOR rotation axis appears to shift toward alignment with the direction of gravity. Indeed, if the VOR response was purely torsional, it would be represented by a rotation vector aligned with the roll or x-axis; but, because of the additional horizontal VOR component aligned with the yaw or z-axis, the resultant rotation vector (that includes both torsional and horizontal components) appears to tilt toward alignment with gravity in the (x, z) plane. In rhesus monkeys, the axis-shift seems to always be economical since the VOR rotation axis always tends to align with gravity through the smallest angle. If the same is true in humans for OKN and OKAN responses during roll optokinetic stimulation, an axis-shift toward alignment with gravity could result in a horizontal response as observed. However, the upright orientation is ambiguous to determine if it is an axis-shift “through the smallest angle” as previously observed following yaw and pitch optokinetic stimulation in humans (Gizzi et al. 1994). Indeed, since the rotation axis of the torsional optokinetic response (OKN and OKAN) is originally at an angle of 90° with gravity, no “smallest angle” for alignment with gravity can be defined, and both upward and downward axis-shifts are appropriate.

To investigate this axis-shift, we tested subjects in two additional orientations: pitched-forward 10° and pitched-backward 10°. During a CW optokinetic stimulation, both torsional OKN and OKAN responses are clockwise, and the horizontal component resulting from a small shift of the rotation axis toward alignment with gravity through the smallest angle should therefore be negative (to-the-right) for forward pitch and positive (to-the-left) for backward pitch (Fig. 7C). On the contrary, the horizontal induced VOR component predicted by the GIF resolution hypothesis should stay negative (to-the-right) for both orientations since the direction of the illusory tilt does not reverse between the two orientations and the magnitude of the illusory tilt was not significantly different between the two orientations. During a CCW optokinetic stimulation (Fig. 7D), the small horizontal axis-shift component should also reverse between the two orientations, while the horizontal induced VOR component should be very similar. As observed experimentally (Fig. 7), the HSCEP did not reverse between the two orientations for either stimulation direction. Therefore the hypothesis that the horizontal component observed during roll optokinetic stimulation is due only to a small axis-shift component is not valid.

The hypotheses that the horizontal VOR is either an induced VOR component or an economical axis-shift component toward alignment with gravity through the smallest angle are not mutually exclusive. Indeed, we did observe that the HSCEP for pitched-forward was significantly larger than for pitched-backward in both light and darkness (P < 0.05). This asymmetry could be explained by the simultaneous presence of both an induced VOR and an axis-shift component that is smaller than the induced VOR, with the two components adding for the pitched-forward orientation and subtracting for the pitched-backward orientation.

Asymmetry of the visual field sensitivity, smooth pursuit, and gaze direction

The mean gain of horizontal OKN slow phases is higher in humans when a horizontal optokinetic stimulus is presented to the lower visual field than when it is presented to the higher visual field (Muratore and Zee 1989). During our roll optokinetic stimulation, such an asymmetry, if present, might induce a positive (to-the-left) horizontal response during CW rotation and a negative response (to-the-right) during CCW rotation. These predictions are opposite the observed directions of the horizontal component.

While pursuit afternystagmus has been reported to last ≈10–15 s after the lights are turned off (Muratore and Zee 1979), this seems unlikely to explain the horizontal response we observed. First, and foremost, the subjects were not performing pursuit, since there were no images on the fovea to pursue. Recall that subjects were instructed to look straight ahead in the middle of the blackened cylinder. As previously reported, the subjects performed this task accurately. Therefore the image falling on the fovea was essentially black and amorphous without image contrast as would be required for smooth pursuit. Furthermore, the horizontal response we measured sometimes lasted ≈30 s (Fig. 4), exceeding the duration of reported pursuit afternystagmus.

If the observed horizontal response were due to a gaze direction effect, subjects would have to always look upward during both CW and CCW stimulation. We did measure that subjects’ average gaze direction was slightly upward for all orientations. For upright orientation, the average gaze eccentricity was 1.1 ± 0.2° (mean ± SE) when both directions were pooled. Since the torsional gain was below 0.1, the slightly eccentric gaze direction can only account for, at most, a 0.1°/s horizontal component, more than one order of magnitude smaller than the measured horizontal response (Fig. 4C).

Finally, for both forward and backward orientations, the average gaze eccentricity was 0.9 ± 0.1° and 0.7 ± 0.1° (mean ± SE), respectively, when both directions of optokinetic rotation were pooled. Since gaze eccentricity was in the same direction for both forward and backward orientations, a doll’s eye reflex (looking up when pitched forward and looking down when pitched backward) cannot explain the asymmetry observed in both OKN (Fig. 7A) and OKAN (Fig. 7B) between both orientations.

Conclusion

The GIF resolution hypothesis accurately predicted that eye movement responses during roll optokinetic stimulation include a horizontal “induced” VOR component, in addition to the OKN and OKAN. The induced VOR component is consistent with the idea of a response compensatory to an internally generated neural estimate of linear acceleration, even though no physical linear acceleration is present. The hypothesis that the rotation axis of the eye movement response shifts toward alignment with gravity through the smallest angle is not consistent with the observation that the horizontal component
for a given optokinetic stimulation direction is in the same direction for pitched-forward and pitched-backward orientations, though such a component may also contribute to the overall response. Therefore it appears that visual rotational cues utilize the same (or similar) internal models previously demonstrated for rotational cues from the semicircular canals (Angelaki et al. 1999; Hess and Angelaki 1999; Merfeld et al. 1999, 2001; Zupan et al. 2000). Such internal models are consistent with those reported by other investigations studying sensory and motor responses.

We thank M. Crockett, K. King, and Z. Weber for data acquisition and analysis. We thank Drs. Conrad Wall III and Rick Lewis and members of the Jenks Vestibular Diagnostic Lab for assistance in screening subjects for consistent with those reported by other investigations studying (Angelaki et al. 1999; Hess and Angelaki 1999; Merfeld et al. 1999, 2001; Zupan et al. 2000). Such internal models are consistent with those reported by other investigations studying sensory and motor responses.

We thank M. Crockett, K. King, and Z. Weber for data acquisition and analysis. We thank Drs. Conrad Wall III and Rick Lewis and members of the Jenks Vestibular Diagnostic Lab for assistance in screening subjects for consistent with those reported by other investigations studying (Angelaki et al. 1999; Hess and Angelaki 1999; Merfeld et al. 1999, 2001; Zupan et al. 2000). Such internal models are consistent with those reported by other investigations studying sensory and motor responses.

REFERENCES


