Kinematic Principles of Primate Rotational Vestibulo-Ocular Reflex
I. Spatial Organization of Fast Phase Velocity Axes

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Hess, Bernhard J. M. and Dora E. Angelaki. Kinematic principles of primate rotational vestibulo-ocular reflex. I. Spatial organization of fast phase velocity axes. J. Neurophysiol. 78: 2193–2202, 1997. The spatial organization of fast phase velocity vectors of the vestibulo-ocular reflex (VOR) was studied in rhesus monkeys during yaw rotations about an earth-horizontal axis that changed continuously the orientation of the head relative to gravity (“barbecue spit” rotation). In addition to a velocity component parallel to the rotation axis, fast phases also exhibited a velocity component that invariably was oriented along the momentary direction of gravity. As the head rotated through supine and prone positions, torsional components of fast phase velocity axes became prominent. Similarly, as the head rotated through left and right ear-down positions, fast phase velocity axes exhibited prominent vertical components. The larger the speed of head rotation the greater the magnitude of this fast phase component, which was collinear with gravity. The main sequence properties of VOR fast phases were independent of head position. However, peak amplitude as well as peak velocity of fast phases were both modulated as a function of head orientation, exhibiting a minimum in prone position. The results suggest that the fast phases of vestibulo-ocular reflexes not only redirect gaze and reposition the eye in the direction of head motion but also reorient the eye with respect to earth-vertical when the head moves relative to gravity. As further elaborated in the companion paper, the underlying mechanism could be described as a dynamic, gravity-dependent modulation of the coordinates of ocular rotations relative to the head.

INTRODUCTION

To stabilize gaze in space during head movements, the vestibulo-ocular reflex (VOR) transforms head angular velocity into appropriate neural commands to rotate the eye at the same velocity but in opposite direction as the head. Alternating with slow compensatory phases, fast phases rotate the eye rapidly in the direction in which the head is moving and reorient at the same time the gaze line toward targets of potential interest in the visual field.

Most studies of vestibulo-ocular eye movements have focused on issues of gaze stabilization during the slow, compensatory phases of nystagmus while relatively little work has been devoted to elucidate the determinants of fast phase generation. Accordingly, not much is known about any vestibular mechanisms that determine the spatial organization of VOR fast phases. Although gaze stabilization mechanisms dictate that slow phase movements should be confined to the plane of head rotation, this is not necessarily the case for fast phases. To keep the eye in its working range and to prevent mechanical saturation, fast phase movements only need to have one component in the direction of the head movement. This component is tightly controlled by vestibular signals (i.e., the semicircular canals), which thus determine at least one of the three rotational degrees of freedom of fast phase rotation axes. What are the mechanisms that control the remaining degrees of freedom of fast eye movements and which are the underlying principles? Are fast phase axes randomly oriented around the axis of head rotation or do they comply to a particular organizational principle?

It has been thought traditionally that vestibular signals control slow phase eye movements whereas fast phases of nystagmus and saccades are generated relatively independently. Studies of the main sequence characteristics supported this view because little differences have been found, for example, for horizontal fast phases and saccades, suggesting that both movements are generated by the same premotor neural circuits (Chun and Robinson 1978; Ron et al. 1972). Moreover, the same cells in the paramedian pontine reticular formation and in the rostral interstitial nucleus of the medial longitudinal fascicule were found responsible for the generation of saccades and fast phases of nystagmus (Bender and Shanzer 1964; Büttner et al. 1977; Henn et al. 1984; King and Fuchs 1979). Permanent or reversible lesions of these structures affected both fast phases and saccades to the same extent (Crawford and Vilis 1992; Suzuki et al. 1995; Vilis et al. 1989).

Despite these results, which suggest that visually guided saccades and VOR fast phases share at least part of the same premotor circuitry, the concept of largely independent control of slow and fast phases of nystagmus might be too simplistic and inadequate in accounting for the more complex three-dimensional properties of eye movements. Recent three-dimensional oculomotor studies have stressed the point that the slow compensatory components of the vestibulo-ocular reflex do not comply in general with the kinematic constraints imposed by Listing’s law on visually guided eye movements (Frens et al. 1996a; Misslisch et al. 1994). Studies in the monkey have suggested further that VOR fast phases limit deviations of compensatory slow phase movements with respect to these constraints (Crawford and Vilis 1991).

The present work investigates the three-dimensional (3-D) organization of VOR fast phase rotation axes. For this, we have chosen to elicit VOR by earth-horizontal axis rotations where the head changes continuously its orientation relative to gravity. In this first report, we characterize the 3-D properties of fast phase angular velocity vectors. Because angular
velocity vectors are collinear with the instantaneous axis of rotation of the eye, this approach provides the simplest and most intuitive access to the spatial organization of VOR fast phases. In the accompanying paper, we take this analysis one step further and examine the underlying more complex spatial organization of VOR eye position vectors. We report that the spatial orientation of fast phase velocity axes depends systematically on head position relative to gravity, reflecting both the gravity-dependent kinematics of fast phase eye positions and an associated dynamic modulation of primary eye position (companion paper Hess and Angelaki 1997b). Part of this work has been reported in short communications (Hess and Angelaki 1995, 1997a).

METHODS

Eye movement recording

Four juvenile rhesus monkeys (Macaca mulatta) were prepared chronically with a scleral dual-search coil for 3-D eye movement recording and head bolts for restraining the head during the experiment. Details of fabrication, implantation, and calibration of the dual-search coil have been reported elsewhere (Hess 1990; Hess et al. 1992). Horizontal, vertical, and torsional eye positions were digitized with 12 bit resolution at a sampling rate of 833 Hz and expressed as rotation vectors, \( \mathbf{E} = \tan (\rho/2) \mathbf{u} \), where \( \mathbf{u} \) is a unit vector pointing along the rotation axis of the eye, and \( \rho \) is the angle of rotation about \( \mathbf{u} \) (Haustein 1989). The components of eye position vectors were smoothed and differentiated using quadratic 31-point Savitzky-Golay filters (Press et al. 1992). The eye angular velocity vector, \( \mathbf{\Omega} \), was computed from the eye position vector, \( \mathbf{E} \), and the rate of change in eye position, \( \dot{\mathbf{E}} \), according to the equation: \( \mathbf{\Omega} = 2 (\mathbf{E} + \mathbf{\mathbf{E}} \times \dot{\mathbf{E}}) / (1 + ||\dot{\mathbf{E}}||^2) \). This equation captures in simple geometric terms the eye position dependence of eye angular velocity when the monkey looks away from primary position (see also Tweed and Vilis 1987). In contrast to 3-D eye positions that define the (virtual) rotation of the eye relative to a reference position (usually primary position), angular velocity vectors describe the instantaneous orientation of the rotation axis of the eye. The following analysis focuses on these angular velocity vectors.

The contribution of eye position in the estimate of angular velocity was estimated by comparing the rate of change in eye position, \( \dot{\mathbf{E}} \), scaled by a factor of 2, with the angular velocity, \( \mathbf{\Omega} \). Listing’s plane and primary eye position were determined from spontaneous eye movement data in the light with the head upright and stationary. Rotation vectors were expressed relative to a right-handed coordinate system where the \( x \) axis was aligned with primary gaze direction (positive \( x \) direction is forward) and the \( y \) and \( z \) axes were lying in Listing’s plane (positive \( y \) and \( z \) directions are leftward and upward, respectively). This standard coordinate system was aligned closely in all four animals with the head roll, pitch, and yaw coordinates (i.e., magnetic field coordinates; for the animal’s head posture, see below) being rotated downward by \( \approx 6^\circ \) and leftward or rightward by \( \approx 2^\circ \). According to the right-hand rule, a positive torsional component corresponded to a rotation of the upper pole of the eye toward the right ear, a positive vertical component corresponded to a downward rotation, and a positive horizontal component corresponded to a leftward rotation.

Experimental protocols

During the experiments, animals were seated in a primate chair with their heads restrained in a position of 15° nose-down relative to the stereotaxic horizontal and placed inside the inner frame of a multiaxis turntable with three motor-driven gimbaled axes. The experimental protocols consisted of earth-horizontal axis rotations (in complete darkness) at constant positive or negative speeds of 58, 110, and 184°/s, starting always with the animal in supine position. The order in which the animals were rotated through the four cardinal head positions was: supine, left-ear down, prone, and right-ear down for a positive yaw rotation, and the reverse for a negative yaw rotation. For each VOR record (each of the positive and negative rotational speeds were repeated once or twice in each animal), 5–20 cycles were included in the analysis.

Data analysis

After eye positions had been expressed in the standard head-fixed coordinates (relative to upright primary position), data records were divided for each head revolution into 12 sectors (\( S_1, S_2, \ldots, S_{12} \)) of 30° width each. These sectors, which were spaced equally throughout each stimulus cycle, were shifted relative to the onset of each cycle by \( -15^\circ \). The sectors corresponding to the four cardinal head positions were sector \( S_1 \), centered around supine (i.e., \( \pm 15^\circ \) ); sector \( S_2 \), centered around right ear-down (i.e., \( \pm 75^\circ \) ); sector \( S_3 \), centered around left ear-down (i.e., \( \pm 105^\circ \) ); and sector \( S_4 \), centered around left ear-down position (i.e., \( \pm 155^\circ \) ). Fast phases of nystagmus were isolated from slow phase segments based on amplitude and time windows that were set for the second derivative of the magnitude of the eye velocity vector and interactively checked by visual inspection of the signals on a graphic screen. This derivative was computed numerically using a quadratic 11-point Savitzky-Golay smoothing filter (Press et al. 1992).

The average spatial orientation of fast phase velocity axes in each sector was estimated using two independent procedures. 1) A 3-D straight line was fitted to all pooled fast phases in each sector. This procedure ignored possible variations in the velocity profiles and aimed only at estimating the average 3-D orientation of a given sample of fast phases. The number of pooled fast phases in each sample varied typically between 5 and 20. The direction cosines of each fitted 3-D line formed a normalized vector, \( \mathbf{k}_{1, i} \), one for each sector \( i (i = 1 \ldots 12) \). We estimated the uncertainty boundaries of the fitted line parameters, i.e., the components of the normalized velocity vector, \( \mathbf{k} \), by a statistical bootstrap method. For each sector, the line fit was applied 100 times on random samples of fast phases drawn at a time with replacement from the observed sample. Each of these 100 synthetic data sets (for each sector) had the same number of fast phases. Because of the replacement, a random fraction of the original fast phases was replaced by duplicated fast phases. Based on the resulting set of fitted direction cosines, errors of the estimated line parameters, i.e., the means and standard deviations, could be estimated (for more details see e.g., Efron and Tibshirani 1991; Press et al. 1992).

2) A separate, independent assessment of the average orientation of fast phase axes was obtained by first computing the peak velocity of each fast phase in a sector and then averaging all normalized peak velocity vectors within a sector. Thus the resulting 12 normalized vectors, described by their direction cosines, provided the average orientation of peak saccadic velocity vectors as a function of head orientation relative to gravity.

In addition to the spatial orientation of fast phase axes, their dynamic characteristics were also studied as a function of head
The basic finding is illustrated in Figs. 1 and 2: Fig. 2B shows a typical record of torsional, vertical, and horizontal eye position during yaw rotation at 184°/s about an earth-horizontal axis (barbecue spit rotation, see inset). H, head position (potentiometer output reset every 360°); pro, prone; red, right ear-down; sup, supine; led, left ear-down position.

**RESULTS**

**Spatial and dynamic properties**

During yaw rotation about an earth-horizontal axis, the fast phase axes of vestibular nystagmus were fanning-out relative to the z axis in a systematic, head position-dependent manner. The basic finding is illustrated in Figs. 1 and 2: Fig. 1 shows a typical record of torsional, vertical, and horizontal eye position during yaw rotation at 184°/s about an earth-horizontal axis. Although the horizontal response component exhibited an almost uniform nystagmus throughout each cycle, there was a large modulation of mean torsional and vertical eye position that was primarily due to alternating positive and negative fast phases (Angelaki and Hess 1996). In the following, we focus our analyses on the 3-D orientation of the rotational axes of the eye during these fast phases, i.e., on the angular velocity vectors of nystagmus fast phases. Figure 2 illustrates three different views of fast phase eye velocity vectors. The fast phases have been extracted from nystagmus elicited by either positive (i.e., supine → left ear-down, etc.) or negative (i.e., supine → right ear-down, etc.) head rotations at 184°/s. For clarity, only four groups of fast phases have been displayed according to the respective sectors of nystagmus to which they belonged: a first group comprises all fast phases from the sectors corresponding to head positions centered around supine position (green trajectories), a second group comprises all fast phases from the sectors around left ear-down position (yellow trajectories), a third group comprises all fast phases from sectors centered around prone position (red trajectories), and finally a fourth group comprises all fast phases collected from the sectors centered around right ear-down position (blue trajectories). Fast phases from both directions of rotation have been superimposed in the side and front views of Fig. 2, A and B. Because a constant slow phase velocity of ~80°/s was generated during constant-velocity yaw rotation at 184°/s, the baselines were shifted by adding 80°/s to positive-going fast phase trajectories (see Fig. 2, A and B, top quadrants) or subtracting 80°/s from negative-going fast phase trajectories (see Fig. 2, A and B, bottom quadrants), to avoid overlap at the coordinate origin. The top view plots illustrate results for positive and negative rotations separately and show that the velocity components in the yaw plane rotated in the same direction as gravity (see curved arrows in Fig. 2C).

Even though the fast phase trajectories did not often correspond exactly to a fixed axis rotation (e.g., see Fig. 2), it was possible to estimate the average spatial direction of pooled fast phase velocities in each sector by fitting a straight line to the data points. The direction cosines \( k_x, k_y, \) and \( k_z \) of these lines represented the \( x, y, \) and \( z \) coordinates of a normalized velocity vector, \( \mathbf{k} \), expressed in head-fixed coordinates. Based on these normalized velocity vectors, it is apparent that the fast phase trajectories exhibited a precession-like motion (i.e., like a spinning top) about the head \( z \) axis as the head rotated in space (Fig. 3A). Notice that velocity vectors for head rotation in either direction have been plotted in the same plot (Fig. 3A, rotation at 184°/s (●); rotation at −184°/s (○)). As the head rotated, they described two conical surfaces centered around the axis of head rotation (\( z \) axis) and oriented in opposite directions. The vertex of each of these cones coincided with the origin of the coordinate system (because offsets due to the slow phase velocity baseline are not shown).

The temporal correlation between fast phase orientation and head position is illustrated in Cartesian plots of the \( k_x, \) \( k_y, \) and \( k_z \) components of the fast phase velocity vectors as a function of head orientation (Fig. 3B). The \( k_x \) and \( k_y \) components were modulated in a sinusoidal fashion, approximately in phase quadrature with respect to each other, as expected from the circular path traced out by the vector tips in the \( y-x \) (yaw) plane (Fig. 3A). Fast phase velocity vectors with positive \( z \) components were tilted maximally toward the contralateral ear when the head was in ear-down position (Fig. 3B, middle). Similarly, fast phase velocity vectors with positive \( z \) components were tilted maximally forward and backward when the head was in supine and prone position, respectively (Fig. 3B, bottom). The opposite was true for fast phase velocity vectors with negative \( z \) components. As expected from the cone-shaped vector

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\(^5\) Fast phases straddling the sector borders were truncated. Such truncations, however, did not affect appreciably the displacement plane fits.
FIG. 2. Spatial orientation of fast phases of nystagmus elicited by constant-velocity rotation at +184 and −184°/s about an earth-horizontal axis. Fast phase velocities of nystagmus obtained from positive (supine → left ear-down) and negative (supine → right ear-down) head rotations are displayed in A and B in the same plot and in C in separate plots. All fast phases generated within restricted time windows of 163 ms (=30°/184°/s) around supine position (sup, green trajectories), left ear-down (led, yellow trajectories), prone (prone, red trajectories), and right ear-down position (red, blue trajectories) were pooled. A: side view (z-x plane). Fast phase velocity trajectories with positive z components were tilted forward and backward, respectively, for head positions around supine and prone position. Fast phase trajectories with negative z components were tilted oppositely. There was little tilt of fast phase trajectories in the pitch plane for right and left ear-down head positions. B: front view (z-y plane). Around ear-down positions, fast phases with positive/negative z components were tilted toward the contra-/ipsilateral ear in the roll plane. C: top view (y-x plane). Fast phase velocity components rotated in the yaw plane in the same direction as gravity (curvilinear arrows). Note that gravity rotated in the opposite direction relative to the head as the head rotated relative to space.

distribution in Fig. 3A, the $k_z$ component of the fast phase velocity vectors depended little on head position relative to gravity (Fig. 3B, top).

The spatial orientation of fast phase velocity was also assessed independently by evaluating the average peak fast phase velocity in each sector. For this, peak velocity and associated axis orientation of all fast phases in a sector were determined and averaged. This analysis yielded results that were similar to those obtained by fitting a straight line through all fast phases in a sector. Results obtained by the two methods are illustrated in Fig. 4A, which compares the respective axis orientations of fast phases in the x-y (yaw) plane of the same data records as in Figs. 1-3. Each data point in the x-y plane represents the projection of the endpoint of a unit vector that describes the average axis orientation of the fast phases in a sector. Data from the two directions of head rotation are displayed separately on the right and left sides of Fig. 4. Due to the equivalence of the two methods, only the linear approximation obtained by fitting straight lines to all fast phases velocity axes in a sector will be presented in the following paragraphs, which describe the spatial orientation as a function of head position and rotation speed.

**Effects of eye position on the spatial orientation of fast phase velocity**

The exact spatial orientation of the angular velocity vector of a fast phase movement depends on orbital eye position (due to the cross vector product $\mathbf{E} \wedge \mathbf{E}_g$ in the equation of angular eye velocity, $\Omega$). The effect, being of second order in eye position and velocity (i.e., involving products of the form $E_i E_j$, where $E_i < 1$ rad), is generally small. To exclude the possibility, however, that the observed dependence was merely due to an eye position effect, we computed the rate of change of eye position, $\mathbf{E}$, for fast phase trajectories (see...
rotations as a function of head orientation relative to gravity. As shown in Fig. 5 where these parameters have been plotted for the data set of Fig. 2–4 (negative head rotation), there was little influence of head position on duration or time to peak velocity of fast phases. However, peak fast phase velocity was modulated with head position showing a significant decrease close to prone position (Fig. 5, bottom). This effect was independent of the direction of head rotation. In parallel to peak velocity, fast phase position amplitudes also were modulated as a function of head position relative to gravity. Average amplitude and peak velocity values of pooled fast phases have been plotted separately for positive and negative rotations in Fig. 6, A and B. Even though the minimum of average fast phase amplitude and peak velocity correlated well with prone position, the dependence on head position did not follow a single sinusoidal function (values peaked approximately between right or left ear-down and supine position). This was in contrast to the simple sinusoidal dependence of the spatial orientation of mean fast phase velocity axes on head position (Fig. 3). In fact, peak velocity

**METHODS**. Comparison of the estimated spatial orientation of both $\Omega$ and $\dot{E}$ (in the $x$-$y$ plane) demonstrates that modulation of average eye position could not be the major factor in the fanning-out phenomenon of fast phase directions (Fig. 4B).

**Influence of head position on main sequence properties of fast phases**

To investigate whether not only the spatial orientation but also the metrics of fast phases were modulated by otolith inputs, we computed the amplitude, duration, peak velocity, and time-to-peak velocity of fast phases during $\pm 184^\circ/s$
Nevertheless, there was a clear change in the $k_z$ component, particularly at the highest speed of rotation. The dependence on the speed of the movement was more conspicuous in the $k_x$ and $k_y$ components. There was a gradual increase in the modulation amplitude of these two components as the speed of head rotation increased.

To further quantify these effects, we fitted sine waves to the $k_x$- and $k_y$-component data separately for each rotational speed in each animal. The amplitude of modulation for both the $k_x$ and the $k_y$ components increased linearly with a uniform, nearly unity slope ($0.95$ and $1.1$, respectively) as a function of speed of head rotation or, equivalently, the frequency of oscillation of gravity along the roll and pitch axis in the yaw plane (Fig. 8).

**DISCUSSION**

**Gravity-induced dynamic modulation of oculomotor coordinates**

In this paper, we have investigated the 3-D organization of fast phase velocity axes of the horizontal vestibulo-ocular reflex (VOR) fast phases as a function of head position. Data obtained from 1 animal during constant-velocity yaw rotation at $-184\degree/s$ (also plotted in Fig. 2–4).

Spatial organization of fast phase axes: dependence on rotation speed

These observations demonstrate that there is a profound effect of gravity on the spatial organization of VOR fast phase axes even though there seems to be no change in their dynamic properties. The specific gravity effect on VOR fast phase velocity axes can be described as follows: in addition to a fast phase velocity component along the axis of head rotation, a velocity component is also systematically present along the direction of gravity. This latter component is directed oppositely to gravity such that there is a systematic trend for the velocity axes to be oriented vertically in space.

The fast phase velocity components along the direction of gravity increased with the speed of head rotation. As a consequence, the faster the head rotated in space, the more the fast phase velocities tilted away from the rotation axis and the more vertically oriented they became. Average direction cosine data of the resulting modulation of the fast phase velocity axes from all four animals are illustrated in Fig. 7 for three different rotational speeds in the two directions ($A$: positive, $B$: negative). The $k_z$ component changed the least because it varied proportionally to the cosine of the angular deviation of fast phase velocity axes from the rotation axis.

![Fig. 5](image-url) Duration, time-to-peak velocity, and peak velocity of vestibulo-ocular reflex (VOR) fast phases as a function of head position. Data obtained from 1 animal during constant-velocity yaw rotation at $-184\degree/s$ (also plotted in Fig. 2–4).

![Fig. 6](image-url) Amplitude and peak velocity of fast phases of nystagmus as a function of head position. $A$ and $B$: average amplitude ($\pm$SD) and average peak velocity ($\pm$SD) of VOR fast phases from 3 animals during yaw rotation at $\pm 184\degree/s$ were reduced in prone as compared with supine head position for both directions of head rotation. For clarity, data points are shifted along the abscissa. $C$: correlation between peak velocity and amplitude of nystagmus fast phases elicited by $\pm 184\degree/s$ yaw rotation. Same data points as in $A$ and $B$: ---, straight line fit, $y \approx a + bx$, with $a \approx -65\degree/s$ and $b = 20 \text{ s}^{-1}$.
reflex. During head movements, vestibular signals determine the angular velocity of slow phases such that the eyes closely match head velocity (with opposite polarity) to compensate for the movement and to stabilize the gaze lines relative to space. Fast phases, on the other hand, do not simply reset the eye in the direction of head rotation: we have shown here that fast phase axes of the vestibulo-ocular reflex exhibit, in addition, a significant component parallel to the direction of gravity. In fact, fast phase axes are tilted systematically away from the axis of head rotation due to a tendency to be maintained vertically oriented in space. The dynamic dependence of fast phase velocity axes on gravity is a function of movement speed (which, in these experiments, is equivalent to the frequency of a sinusoidal modulation of gravity). The faster the head moves in space, i.e., the higher the frequency, the greater is the gravity-dependent tilt of fast phase velocity axes (Fig. 7).

This observation reveals a novel principle that governs the generation of fast phases in the vestibulo-ocular reflex. A possible explanation of these results would be that fast phases are coded in oculomotor coordinates that are not always head-fixed but rather depend on dynamic head orientation relative to gravity. This hypothesis is addressed below and further investigated in the accompanying paper (Hess and Angelaki 1997b). Such a gravity-dependent behavior of VOR fast phases seems to be a property that is not limited only to primates. In fact, similar observations regarding spatial control of fast phases of horizontal and vertical nystagmus have been reported recently in rabbits (Pettorossi et al. 1995).

It is well known that VOR fast phases usually occur well before slow phases have moved the eyes back to the midline. It also has been pointed out that fast phases do not simply prevent slow phase movements from driving the eye into...
the mechanical limits but rather subserve an orientating function by quickly rotating the eye into the direction in which the head is turning ("looking where one is going") (Chun and Robinson 1978; Meier and Dieringer 1993; Melvill Jones 1964). Our results show that fast phases exhibit an additional orientating function. Because the observed gravity-dependent velocity components are perpendicular to the yaw plane, they affect the vertical and torsional orientation of the eye in head. The results reported here suggest that fast phases are organized according to additional functional requirements that correlate with dynamic changes of head orientation relative to gravity. As will be shown in the companion paper (Hess and Angelaki 1997b), fast phase axes are oriented in local displacement planes, which appear to follow a generalized Listing’s law and tend to remain space-fixed during head motion.

We have reported previously that torsional and vertical eye position components are modulated systematically when the head changes orientation relative to gravity during yaw rotation about an earth-horizontal axis (Fig. 1) (see also Angelaki and Hess 1996). Similarly, from static tilt experiments, we know that orbital eye position changes systemically as a function of head position relative to gravity (Crawford and Vilis 1991; Haslwanter et al. 1992). Based on the kinematic dependence of angular velocity on orbital eye position, one could speculate that the observed tilt in the angular velocity vector of fast phases was the result of these eye position changes. However, as demonstrated by the data illustrated in Fig. 4B and as expected based on theoretical grounds, eye position effects per se cannot explain the large tilts of the fast phase angular velocity axes.

On the other hand, the present results on the orientation of fast phase velocity axes, as well as the observed systematic dependence of orbital eye position (see the accompanying paper, Hess and Angelaki 1997b), could be interpreted as the result of a vestibular mechanism that adjusts the primary orientation of the eye3 as the head moves in space. Let us hypothesize for the moment that the tilt of fast phase velocity axes reflects a direct effect of gravity on the reference system of ocular rotations, i.e., an effect on primary eye position. Unlike the negligible effects of eye position on angular velocity, a change of the reference system is bound to have an effect of the same order of magnitude on the orientation of angular velocity.

Comparison of the effects due to shifting the oculomotor range versus changing the reference system

To show this, we adopt, for simplicity, a description of fast phases as fixed-axis rotations that carry the eye rapidly from one fixation position, $E_1$, to the next fixation position, $E_2$, i.e., we use the formula $E(t) = E_1 + \sigma(t)(E_2 - E_1)$, where $\sigma(t)$ is a bell-shaped velocity profile (for details see Hepp 1990; Van Opstal 1993). With this model, it can be shown readily, for example, that a gravity-induced shift of the oculomotor range (in contrast to a reference change) by as much as 30° in downward direction would induce a change in the direction of fast phase velocities by only 15° in the pitch plane (Fig. 9A). The same holds true for a hypothetical shift of the oculomotor range in torsional direction by 30°, which would result in a change of the direction of fast phase velocities in the roll plane by only 15° (Fig. 9B). Thus based on these kinematic relations between eye position and velocity, which have been known since von Helmholtz (1867), and the estimated shifts in the vertical and torsional oculomotor range (±10° on average) (see Angelaki and Hess 1996), we hardly can explain the large tilt angles of fast phase velocities that we have observed (see Figs. 2, 3, 7, and 8).

In contrast to such global shifts of the oculomotor range, a rotation of the reference system would induce an equally large rotation of the velocity vectors. For example, a rotation of the reference system about the y axis by 30° downward (e.g., when the monkey is in supine position) will induce a change in the tilt of fast phase velocities in the pitch plane by the same amount (Fig. 9C). Similarly, a rotation of the reference system by 30° in the torsional direction (e.g., when the monkey is in left ear-down position) will result in a change in the tilt of fast phase velocities in the roll plane by the same amount (Fig. 9D). Indeed, at the highest speeds of head rotation, we found tilt angles of fast phase velocity vectors in this order of magnitude in both the pitch plane (when the monkey was rotating through supine or prone position) as well as in the roll plane (when the monkey was rotating through ear-down positions). According to the reference change hypothesis, nystagmus fast phases generated during a vestibulo-ocular reflex in the yaw plane would always be horizontal in terms of an intrinsic reference system that dynamically adjusts as the head moves in space (i.e., relative to gravity). In these intrinsic coordinates, torsional position components would be minimized as further discussed in Hess and Angelaki (1997b).

Regarding fast phase eye positions, the effect of such changes of the reference system is more complicated than just a simple rotation of eye positions in the respective direction (→ parallel to the respective rotation axis in Fig. 9, C and D). Even though the primary effect corresponds to a rotation in the indicated directions, there is an additional rotation in an orthogonal direction reflecting the noncommutative algebraic property of 3-D rotations (for this, compare the respective orientations of fast phase trajectories in the top left of Fig. 9, A and C and in the top right of Fig. 9, B and D). This issue will be addressed in more detail in the accompanying paper (Hess and Angelaki 1997b), where we provide evidence that passive head motion in space seems indeed to change oculomotor coordinates as defined by a dynamically changing primary eye position.

Neurophysiological substrate of a dynamically changing coordinate system in the generation of fast phases

If gaze control signals in the VOR indeed are coded with respect to space and the direction of gravity, we would ask:

3 The primary orientation of the eye can be defined when the head is stationary and upright by specifying the orientation of Listing’s plane and primary eye position in which the gaze line is orthogonal to Listing’s plane. Primary eye position determines the point of zero rotation as well as the orientation of the horizontal, vertical, and torsional rotation axes.

4 This additional rotation is due to the cross-vector product in the formula for multiplication of rotation vectors (see formula in last paragraph of METHODS). If the rotations were expressed as rotation matrices $R(t)$ and $R(t)$, it would be proportional to the matrix $C = \mathbf{R} \mathbf{R} - \mathbf{R} \mathbf{R}$, which is obviously more difficult to interpret in geometric terms.
sume that the underlying transformations occur at a relatively early stage in processing sensory inputs to motor output. Based on available experimental evidence, we cannot exclude that the superior colliculus plays a role in this process. It recently has been reported that the collicular code of saccadic direction depends on head orientation, raising the possibility that this structure receives a gravity-dependent bias signal from sites downstream in the brain stem (Frens et al. 1996b). Other areas like the cerebellum, which receives input from the motor layers of the superior colliculus (Bender and Hess 1994, 1995). These cerebellar lesions did not affect the static oto-lith-ocular reflex, suggesting that the neural control of the torsional-vertical oculomotor coordinates is more involved. There is evidence that the midbrain interstitial nucleus of Cajal, which receives strong inputs from the vestibular nuclei (for review, see Brodal 1974), is the site of the torsional-vertical velocity-to-position integrator (Crawford et al. 1991; Fukushima et al. 1990; King et al. 1981). This structure receives inputs from the rostral interstitial nucleus of the medial longitudinal fascicule where short-lead burst neurons are located that generate torsional and vertical eye position signals (King and Fuchs 1979; Vilis et al. 1989). It is a common understanding that these structures are organized in head-fixed coordinates (Büttner et al. 1977; Robinson and Zee 1981; Crawford and Vilis 1992). Based on our behavioral findings, one could speculate that these neurons are in fact organized in a reference system that is modulated by static and dynamic oto-lith input. Interestingly, lesions of these neuronal populations result not only in oculo-motor deficits but also in changes of head posture, indicating that these structures may be involved more generally in gaze control (for a recent review, see Fukushima 1987).

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