Primate Translational Vestibuloocular Reflexes. I. High-Frequency Dynamics and Three-Dimensional Properties During Lateral Motion

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INTRODUCTION

Head movements generally consist of combinations of rotational and translational motion components. Depending on these components, reflexes must comply with many different geometric and dynamic conditions that can be studied easily in the vestibuloocular reflexes (VORs). A rotational disturbance can be compensated, in a first approximation, by a simple reflex organization that generates an eye rotation equal and opposite to the imposed head rotation. A translational disturbance, on the other hand, that displaces the head (and eyes) relative to the target also must be compensated by an appropriate rotation of the eye. This requires a more sophisticated reflex machinery where the underlying computations can be quite involved, particularly when the gaze direction is not perpendicular to the head displacement. Moreover, because the gaze directions of the two eyes are usually not parallel unless for fixation of far targets, the required eye movement for maintaining binocular fixation will have, in general, to move the two eyes through different angles. Because of these complex geometric properties, quantitative studies of the translational VORs (trVORs) in three-dimensions (3-D) have been limited.

One of the few well-established properties of the reflex is its dependence on viewing distance and vergence angle (Bush and Miles 1996; Gianna et al. 1997; Paige 1989; Paige and Tomko 1991a,b; Schwarz and Miles 1991; Shelhamer and Young 1991; Telford et al. 1997). For simple kinematic reasons, the eye movement amplitude should be inversely proportional to viewing distance (Paige and Tomko 1991a; Schwarz and Miles 1991; Schwarz et al. 1989; Telford et al. 1997). Viewing distance is, however, only one of the parameters that should shape the properties of the translational VORs. Other factors, such as horizontal and vertical gaze eccentricities, are equally important in determining the reflex performance when movement direction is not necessary perpendicular to gaze direction.

Another, less-characterized, property is the reflex dynamics. Even though it is well established that trVOR sensitivities increase with increasing frequency, most experimental studies have been limited to frequencies \( \leq 4 – 5 \) Hz (Paige and Tomko 1991a,b; Telford et al. 1997). The VORs, however, also would need to elicit compensatory eye movements during more dynamic stimuli. Head movements during running, for example, have been shown to have substantial energy in the power spectrum of 15–20 Hz (Grossman et al. 1988). Indeed, rotational VOR gain has been shown to be high for frequencies \( \leq 15 – 30 \) Hz (Gauthier et al. 1984; Minor et al. 1999; Skavenski et al. 1979; Tabak and Collewijn 1994; Tabak et al. 1997). Because of the posterior location of the axis of rotation relative to the vestibular apparatus, active head movements always would include a translational component. Furthermore transient translational accelerations with a substantial high-frequency content are likely to be encountered during either passive (e.g., in a vehicle) or active (e.g., forward-directed eye-head-hand coordination tasks) movements. Such high-frequency transient movements elicit robust compensatory eye movements at very short latencies (Angelaki and McHenry 1999). Consistent with these short-latency responses during abrupt transient motion, horizontal trVOR sensitivities, even when tested in darkness, have been shown to increase with frequency (Angelaki 1998).

Finally, there is currently little and incomplete data on the 3-D properties of the trVOR. Lateral motion has been shown to generate ocular torsion in addition to the functionally compensatory horizontal eye movements (Angelaki 1998; Lichtenberg et al. 1982; Merfeld et al. 1996; Paige and Tomko 1991a; Telford et al. 1997). These torsional eye movements have been described as “tilt” responses and portrayed to be due to an
imperfection of the otolith-ocular system because the peripheral vestibular system cannot distinguish gravity from translational components of acceleration (Paige and Tomko 1991a; Telford et al. 1997). Even though a functional interpretation of the small translation-induced torsional eye movements as tilt responses might be possible for very low frequencies (<<0.1 Hz), this concept does not generalize to higher frequencies for several reasons. First, the vestibulocular system has been shown to appropriately discriminate tilts from translations at frequencies above 0.16 Hz (Angelaki et al. 1999; Hess and Angelaki 1999). Second, a recent examination of the torsional responses during translation has shown that large phase lags are being introduced at frequencies higher than ~0.1 Hz (Angelaki 1998; see also Lichtenberg et al. 1982). Within only a decade (from 0.1 to 1 Hz), torsional response phase reverses. As a result, responses that could be considered compensatory to tilt at frequencies <0.1 Hz become anticompensatory to the "apparent tilt" at high frequencies (Angelaki 1998). In contrast to the nearly 180° shift in phase, torsional sensitivity increases versus frequency similarly as the horizontal component (see Fig. 5 in Angelaki 1998).

On the basis of these data, we have proposed that two different functional bandwidths might exist for torsional eye movements during translation. For very low frequencies (<0.1 Hz) when VOR is not critical for maintaining visual acuity, the functional requirement for appropriate tilt/translational discrimination in complete darkness is relaxed and the small torsional slow phases evoked might be considered to represent erroneous tilt responses. At frequencies higher than ~0.1 Hz, however, when the brain can rely on veridical information from the semicircular canals to discriminate linear accelerations (Angelaki et al. 1999), the argument of tilt/translational ambiguity collapses. If the tilt interpretation proposed by Paige and colleagues (Paige and Tomko 1991a; Telford et al. 1997) does not hold true for frequencies above 0.16 Hz, what is then the functional explanation for the presence of torsional eye movements during high-frequency translation? Because most previous high-frequency trVOR studies measuring torsion have focused on the tilt theory (Paige and Tomko 1991a; Telford et al. 1997), no alternative has been proposed or investigated.

The present study has the following aims. First, to extend characterization of the trVOR dynamics at high frequencies. Second, to quantify the reflex dependence on gaze eccentricity. Finally and most importantly, we were interested in quantitatively characterizing the torsional components of the response by examining their dependence on gaze parameters that potentially could shed light into their function.

METHODS

Animal preparation and eye movement recording/calibration

Five juvenile rhesus monkeys were chronically implanted with a circular molded, lightweight dental acrylic ring that was anchored to the skull by stainless steel screws (for more details, see Angelaki 1998). Dual eye coils designed for recording binocular 3-D eye movements were implanted under the conjunctiva at ~3–5 mm from the limbus corneae and anterior to all eye muscle insertions (Hess 1990). Coils were sutured securely to the globe with at least four silk stitches. The lead wires were passed out of the orbit, under the muscle and skin to the head holder where they were soldered to connectors and secured to the head ring with dental acrylic. When animals were in their cages, the implanted delrin ring was covered with a cap to protect the eye coil plugs. All surgical procedures were performed under sterile conditions in accordance to institutional guidelines. The animals initially were anesthetized with an intramuscular injection of ketamine (10 mg/kg), followed by administration of an inhalative anesthesia that consisted of an O2/isoflurane mixture. Respiration, body temperature, and heart rate were monitored continuously during all surgical procedures. Each animal was treated prophylactically with antibiotics and analgesics after the completion of each surgery.

The dual eye coil assembly that was implanted on each eye consisted of two serially interconnected miniature coils (Sokymat, Switzerland) that were attached at diagonal points along the circumference of a large three-turn coil (Cooner wire, ~15 mm diam). The exact orientation of the two coils relative to one another, as well as the orientation of the dual search coil on the eye were determined based on both preimplantation and daily calibration procedures (see also Hess et al. 1992). Before implantation, each dual eye coil was calibrated using a calibration jig. Using rotations about all three axes, this calibration yielded the horizontal and vertical angular orientations of the two coil sensitivity vectors as well as the angle between them. Because of the stable geometry of the dual coil assembly, these parameters were assumed to remain unchanged before and after implantation. On each experimental session and before the experimental protocols, pretrained animals performed a visual fixation task (targets at a distance of 1.5 m). The voltages measured during visual fixation along with the precalibrated values for the sensitivity vector of the torsion coil and the angle between the two coils were used to calculate the orientation of the dual coil on the eye, as well as offset voltages. As a consistency check, the direction coil sensitivity vector estimated from the preimplantation calibration (which was not used in the daily calibration calculations) was compared with the respective magnitude computed on the basis of the fixation task. In all experiments, the difference between the two values was <10%.

Experimental set-up and protocols

During experimental testing, the monkeys were seated in a primate chair with their heads statically positioned such that the horizontal stereotaxic plane was tilted 18° nose-down. The animal’s body was secured with shoulder and lap belts, while the extremities were loosely restrained to the chair. The primate chair then was secured inside the inner frame of a vestibular turntable consisting of a 3-D rotator on top of a linear sled (Acutronics). The two inner frames of the turntable and the associated gimbal structures were manufactured by nonmetallic composite materials to minimize interference with the magnetic fields. In addition, the whole rotator assembly and gimbal structure were constructed specially to provide rigid coupling between the motion generator and the animal. For these experiments, animals were maintained upright and were translated laterally during stimulation. Before experimental sessions, animals were sometimes given a small dose of d-amphetamine (1.0 mg orally) to maintain a constant level of alertness.

All animals participating in these experiments were pretrained using juice rewards to fixate targets paired with auditory cues for variable time periods (300–1000 ms), then to maintain fixation after the target was turned off for as long as the auditory tone was present (~1 s). During all fixations, the room was illuminated (through small red lights) such that the animals could easily establish relative distance estimates of the targets. Adequate fixation was defined when both eyes were within behavioral windows (separate for each eye) of less than ±1.0° (for far and near central targets) or ±2.0° (for near eccentric targets with eye position >20°). Usually animals were trained 5 days/wk with free access to water during the weekend.

Binocular 3-D eye movements were recorded using the magnetic search coil technique (0.01° resolution). The driver coils, which generated horizontal and vertical magnetic fields (100 and 66 kHz, respectively) in phase and space quadrature were mounted on a
fiberglass cubic frame of 16-in side length (CNC Engineering). The heavy fiberglass coil frame was mounted on the inner gimbal of the rotator and was constructed specifically to avoid deformation or bending during the high-frequency motion.

During experimental testing, animals were oscillated sinusoidally at different frequencies between 4 and 12 Hz (0.3–0.4 g; Table 1) under the following fixation tasks: while fixating on a center (i.e., ~0 horizontal eccentricity relative to a point midway between the two eyes) space-fixed target placed at distances of 3.1, 2.1, and 1.1 m, as well as 87, 60, 40, and 20 cm from the eyes and while fixating on one of several head-fixed target light-emitting diodes (LEDs) at different horizontal and vertical eccentricities (the largest horizontal/vertical eccentricity was ±12 cm), all lying on a vertical surface 20 cm away from the eyes (e.g., Fig. 8A). Whereas all five animals were tested for the second task, only two animals were tested for the first one. Intermingled between days of experimental sessions were additional training sessions that were identical to the pretraining sessions (with animals stationary), as defined in the preceding text.

Each trial was initiated under computer control when the animal had satisfactorily fixated the target light in a dimly illuminated environment for a random period of ~300–1000 ms. After successful fixation had been obtained, the sled was commanded to deliver 3–25 cycles of sinusoidal linear displacements lasting ~1 s (the exact number of cycles depended on frequency). During the motion, the target was maintained on but the background lights were turned off. Illumination of the target during motion ascertained maintenance of vigilance for the entire 1 s of recording. Because the goal was to study the properties of trVORs as a function of gaze direction, only data where gaze was maintained and not redirected by a saccade during stimulus presentation were of interest. To facilitate data analysis, a behavioral constraint was usually placed during motion: Either an eye-position window of ±3–4° was imposed during motion or eye velocity and acceleration were computed on-line such that a trial was aborted if eye acceleration exceeded a certain value (usually set to ~1,000–1,400°/s²) before the end of the stimulus. Because of the small eye-position changes required to maintain fixation during these high-frequency motion stimuli (Table 1), these behavioral constraints had no baring on slow phase eye velocity (catch-up saccades are evoked only at low frequencies) (e.g., Israel and Berthoz 1989). This was verified by comparing data with and without the behavioral constraint. trVOR sensitivity was independent of the existence of the position or acceleration window during motion [F(1,378) = 0.05, P ≫ 0.05]. The same was true for response dynamics [F(8,378) = 0.52, P ≫ 0.05]. At the high frequencies tested here, saccades were only elicited when the animal lost interest in the target and redirected its gaze elsewhere in the oculomotor field.

For each recording session, the eight voltage signals of the two eye coil assemblies (or 4 right eye voltages and 4 head voltages; see following text), the three output signals of a 3-D linear accelerometer (mounted on fiberglass members that firmly attached the animal’s head ring to the inner gimbal of the rotator), as well as linear velocity and position feedback signals from the linear sled were low-pass filtered (200 Hz, 6-pole Bessel), digitized at a rate of 833.33 Hz (Cambridge Electronics Design, model 1401, initially 12- and later 16-bit resolution) and stored for off-line analysis.

### Data analyses

All data analyses were performed on microcomputers off-line using a combination of computer software written to perform specific tasks. Calibrated 3-D eye positions were expressed either as Fick angles or as rotation vectors, \( \mathbf{E} \) (Haustein 1989; van Opstall 1993). The eye angular velocity vector, \( \mathbf{\Omega} \), subsequently was computed (Hepp 1990). Both eye position and angular eye velocity vectors were expressed relative to a head-fixed right-handed coordinate system, as defined in the 18° nose-down position (standard position of the animals inside the magnetic field system; see following text). Torsional, vertical, and horizontal eye position and velocity were the components of the eye position and eye velocity vectors along the nasooccipital, interaural, and vertical head axes, respectively. Positive directions were clockwise (i.e., rotation of the upper pole of the eye toward the right ear), downward and leftward for the torsional, vertical, and horizontal components, respectively. For the majority of analyses, the reference position was straight ahead. To investigate the origin of the torsional sensitivity, however, selected runs also were expressed in Listing’s coordinates, as previously described (e.g., Hess and Angelaki 1997a,b). For this, Listing’s plane was computed daily from spontaneous eye movements with the head upright and stationary while looking around in the laboratory (potential targets at 1.5–3.0 m). On average, Listing’s plane was tilted downward through 5.3 ± 8.9° (right eye; mean ± SD) and 3.9 ± 4.8° (left eye) and rotated about the head-vertical axis through −1.7 ± 3.4° (right eye) and 3.7 ± 3.6° (left eye).

The horizontal, vertical, and torsional components of the calibrated eye position vectors were smoothed and differentiated with a Savitzky-Golay quadratic polynomial filter with a 15-point forward and backward window (Press et al. 1988; Savitzky and Golay 1964). This filter did not alter phase characteristics but did cause a frequency-dependent gain attenuation of response magnitude that was negligible (<5%) <6 Hz but was significant at higher frequencies. Sensitivity values have been multiplied by the appropriate correction factor that reverses the gain attenuation of the filter. The adequacy of this procedure was verified in selective experimental runs by comparing eye velocity computed as described in the preceding text with that computed from the same set of data, which were now processed by two cascade notch filters (60 and 120 Hz) instead of the polynomial filter. An ANOVA on selected runs that were analyzed with both procedures showed no difference in the gain estimates [dependent variables: horizontal, vertical and torsional response sensitivities; independent variables: frequency and filtering; F(3,93) = 0.97, P ≫ 0.1].

Average response cycles from a custom-selected saccade-free steady-state portion of the response were computed for each component (i.e., horizontal, vertical, and torsional) of the right eye and left eye (or head signal). For each of these average response cycles, response amplitude and phase were calculated by fitting a sinusoidal

### TABLE 1. Stimulus parameters and ideal (i.e., compensatory) response

<table>
<thead>
<tr>
<th>Frequency, Hz</th>
<th>Acceleration, g</th>
<th>Head velocity, cm/s</th>
<th>Harmonic distortion</th>
<th>Eye velocity, °/s</th>
<th>Eye position, °</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>0.43</td>
<td>5.6</td>
<td>0.10</td>
<td>15.8</td>
<td>0.21</td>
</tr>
<tr>
<td>10</td>
<td>0.32</td>
<td>5.1</td>
<td>0.15</td>
<td>14.4</td>
<td>0.23</td>
</tr>
<tr>
<td>8</td>
<td>0.37</td>
<td>7.3</td>
<td>0.09</td>
<td>20.7</td>
<td>0.41</td>
</tr>
<tr>
<td>6</td>
<td>0.38</td>
<td>9.8</td>
<td>0.10</td>
<td>28.0</td>
<td>0.74</td>
</tr>
<tr>
<td>5</td>
<td>0.41</td>
<td>12.8</td>
<td>0.08</td>
<td>36.5</td>
<td>1.16</td>
</tr>
<tr>
<td>4</td>
<td>0.44</td>
<td>17.2</td>
<td>0.08</td>
<td>49.1</td>
<td>1.95</td>
</tr>
</tbody>
</table>

Stimulus parameters are for each frequency. Peak ideal eye position and velocity computed from Eqs. 1–4 for a centered target at a distance of 20 cm.
function (first and second harmonic, as well as a DC offset) to both eye velocity and stimulus (output of linear accelerometer mounted on the animal’s head) using a nonlinear least squares algorithm based on the Levenberg-Marquardt method. The ratio of the second over the fundamental component was <10% for horizontal and <22% for torsional eye velocity. These higher harmonic components could be due to the 8–15% harmonic distortion of the stimulus (Table 1). The second harmonic component of both the horizontal and torsional responses was independent of frequency \[ F(5.231) = 1.5 \quad \text{and} \quad F(5.231) = 0.80, \text{respectively} \quad P > 0.05. \] The analyses here focus only on the fundamental response component.

Response sensitivity was expressed as the ratio of peak eye velocity over peak stimulus velocity and expressed in degrees per centimeter. Peak stimulus linear velocity was computed from the linear acceleration amplitude fits. Phase was expressed as the difference (in °) between peak eye velocity and peak head velocity, such that a phase of 0° corresponds to a compensatory nVOR. Right and left eye responses were also expressed as gains, i.e., as ratios of peak eye velocity amplitude and the respective “ideal” (i.e., compensatory) velocity.

For each stimulus condition (i.e., frequency and fixation target), the latter was computed from simple trigonometric relationships between translational displacement, interocular distance, as well as target distance and eccentricity (see following text). “Target” distance and horizontal/vertical eccentricity were estimated from horizontal and vertical eye position during the fixation period prior to the stimulus (see Eq. 4). Even though responses from both eyes were always processed, only right eye data have been included in most figures.

**Potential artifacts and control experiments**

Because the present study employed high-frequency stimulation, the possibility for artifact in the recordings has been a main concern. We have addressed this problem with the following steps. First, we constructed a high-rigidity gimbal and coil frames as well as head attachment couplings. Second, we monitored a head coil securely fastened on the animal’s head and measured the elicited “eye” movements immediately after an animal had been euthanized. Each of these steps is described in more detail in the following text. Finally, we have limited our quantitative analyses to data where the estimated error in measurement was judged to be <10% (usually <5%).

Special care was taken to tightly and securely fasten the animal’s head to the magnetic coils and to the stiff inner gimbal of the 3-D turntable. In addition, the eye coil leads were taped securely to the superstructure. The following control experiments were conducted to quantify the errors in our eye movement measurements.

**SUPERSTRUCTURE WOBBLING AND FLEXING.** We mounted a 3-D accelerometer and rate sensor exactly where the animal’s head was plugged (Angelaki 1998).

**COUPLING BETWEEN THE HEAD COIL AND THE SKULL.** To investigate the possibility that the head coil did not accurately reflect the movement of the head (i.e., through incomplete coupling or loose head-holder), the following test was performed. Within less than an hour after an animal was euthanized and perfused, the head was put into the superstructure in exactly the same position and was mounted exactly the same way as during experiments. The measured eye and head movements have been plotted in Fig. 1. For the horizontal component, the eye and head values differed by <0.05°/cm (i.e., <5% of the smallest eye movement recorded). For the torsional component, the difference was slightly larger (but still ≤0.05°/cm).

On the basis of the controls described in the preceding text, the following two measures were adopted. First, quantitative analyses were only obtained at frequencies ≤12 Hz (originally data ≤25 Hz were collected). Second, all data were corrected for the small head movement. For this, an average sensitivity and phase were computed at each frequency for each of the torsional, vertical, and horizontal components of the velocity detected by the head coil. These values were subsequently subtracted vectorially from each component of the sensitivity and phase of the right and left eye velocity signals. With the correction for head movement, we feel confident that the worst case error in the quantitative data presented here was always kept <5%. Moreover, these small errors, if present, would only apply to the response dynamics analyses. In contrast, differences as a function of target distance and eccentricity are immune to these errors since they are common to all target conditions.

**Computation of ideal translational VOR responses during lateral motion**

Let \( \theta_R, \phi_L, \varphi_{R_t}, \varphi_{L_t}, \text{and } \psi_{R}, \psi_{L} \) be the horizontal, vertical, and torsional Fick angles of the right and left eye, defined as rotations about axes \( e_x, e_y, \text{and } e_z \) (in this sequence), respectively (Fig. 2). Let also \( d_{inc} \) be the interocular distance. Assuming a fixation point on a flat screen at a perpendicular distance \( D \), with \( H \) and \( V \) the horizontal and vertical eccentricities relative to the right eye (positive values to the left and downward, respectively; see Fig. 2), and a lateral displacement through \( \Delta y \), the new eye position required to maintain fixation is easily calculated to be

\[
\theta_R = \tan^{-1} \left( \frac{H + \Delta y}{D} \right), \quad \varphi_L = \tan^{-1} \left( \frac{V}{(H + \Delta y)^2 + D^2} \right)
\]

and \( \psi_e = 0 \) (1a)
\[ \theta_h = \tan^{-1} \left( \frac{H + \Delta y - d_{in}}{D} \right), \quad \varphi_h = \tan^{-1} \left( \frac{V}{\sqrt{(H + \Delta y - d_{in})^2 + D^2}} \right) \]

and \( \psi_h = 0 \) \( (1b) \)

Under the assumption that \( \Delta y \ll D \), it is easily computed that the ideal (i.e., compensatory) sensitivity (defined as eye velocity/linear velocity) is

\[ \left( \frac{d\theta_{h,L}}{d\Delta y/dt} \right) = (1/D) \cos^2 \theta_{h,L} \quad \text{and} \quad \left( \frac{d\varphi_{h,L}}{d\Delta y/dt} \right) = (-1/4D) \sin(2\theta_{h,L}) \sin(2\varphi_{h,L}) \] \( (2) \)

For small eye-position angles (\( \theta, \varphi < 20^\circ \)), these equations are simplified to

\[ \left( \frac{d\theta_{h,L}}{d\Delta y/dt} \right) \approx 1/D \quad \text{and} \quad \left( \frac{d\varphi_{h,L}}{d\Delta y/dt} \right) \approx -(\theta \varphi)/D \] \( (3) \)

For this analysis and computation of ideal responses, Eq. 2 (rather than the simplified approximation Eq. 3) were used. In addition, to avoid the difficulties associated with measuring the exact target eccentricity relative to the monkey’s eyes, the parameters \( H \) and \( V \) were computed from the prestimulus fixation angles, \( \theta_h \) and \( \varphi_h \), as follows:

\[ H = D \tan (\theta_h) \quad \text{and} \quad V = D \tan (\varphi_h)/\cos (\theta_h) \] \( (4) \)

For each eye, the Fick eye positions described by Eq. 1 were converted into rotation vectors, \( \mathbf{E} \), according to the equation (Haustein 1989; Hepp 1990):

\[ \mathbf{E}_{\text{ideal}} = \mathbf{E}(e_1, \theta) \circ \mathbf{E}(e_2, \varphi) \circ \mathbf{E}(e_3, \psi) \]

\[ = \frac{1}{1 + \tan (\theta/2)^* \tan (\varphi/2)^* \tan (\psi/2)} \times \frac{\tan (\psi/2) - \tan (\varphi/2)^* \tan (\theta/2)}{\tan (\varphi/2) + \tan (\theta/2)^* \tan (\psi/2)} \times \frac{\tan (\theta/2) - \tan (\varphi/2)^* \tan (\psi/2)}{\tan (\theta/2) + \tan (\varphi/2)^* \tan (\psi/2)} \] \( (5) \)

where, for example, \( \mathbf{E}(e_1, \theta) \) is a rotation about an axis \( e_1 \) through an angle \( \theta \) and \( \circ \) defines the composition of rotation vectors (Haustein 1989; Hepp 1990). Rotation vectors describing the ideal right and left eye positions required to maintain binocular fixation onto the target (assuming \( \psi = 0 \)) were also used to compute the ideal (i.e., compensatory) angular eye velocity, as (Hepp 1990)

\[ \Omega_{\text{ideal}} = \frac{2(\mathbf{dE}/dt \times \mathbf{E} \times \mathbf{dE}/dt)}{(1 + |\mathbf{E}|^2)} \] \( (6) \)

Translational VOR gain (defined as measured eye velocity amplitude/ideal eye velocity amplitude) was computed for each component as \( \Omega/\Omega_{\text{ideal}} \). \n
**RESULTS**

Sinusoidal lateral motion elicited translational VORs with robust horizontal eye velocity modulation, as shown in Fig. 3. As expected based on the kinematic requirements of the reflex and in accordance with previous descriptions of primate and human trVORs, horizontal response sensitivity increased proportionally to the inverse of viewing distance (Table 2).
Based on the equation $S(f, D) = S_0(f) + S_D f / D$ (with $S_0$ in °/cm, $S_D$ in ° and $D$ in cm). For an ideal (i.e., compensatory) translational vestibuloocular reflex (trVOR), the equation that describes the dependence of response sensitivity on the inverse of viewing distance is $y = 0.0 + 0.57(1/D)$. Viewing distances of 20 cm to 3.1 m (space-fixed targets).

### Dependence of horizontal response gain on target eccentricity

For appropriate gaze stabilization, horizontal trVOR gain (computed as outlined in the preceding text) should be independent of both horizontal and vertical eye eccentricities. Such ideal performance was only partially observed. Horizontal trVOR gain depended on both horizontal and vertical target eccentricities (Fig. 4, Table 3A). The larger the horizontal target eccentricity, the larger the horizontal trVOR gain, and this difference was more pronounced at high frequencies. In addition, the larger the vertical target eccentricity, the lower the horizontal trVOR gain (Fig. 4, Table 3A).

The differential effects of horizontal and vertical target eccentricities on horizontal trVOR gain at different frequencies suggested that response dynamics depended on target eccentricity (see Table 3A, bottom, for statistical comparisons). Because the effects were symmetric for up/down and left/right targets (see Fig. 4), horizontal response gain and phase were averaged according to target eccentricity rather than absolute eye position. That is, those with zero elevation and maximum azimuth (H ecc; a total of 2 targets located at ±12 cm leftward and rightward), those with maximum elevation and zero azimuth (V ecc; a total of 2 targets located at ±12 cm up and down) and those with maximum elevation and azimuth (HV ecc; a total of 4 targets located eccentrically at the 4 corners of the target array) were compared with data while fixating at the center target (Fig. 5). Fixation at eccentric compared with center targets resulted in steeper gain increases and larger phase leads (Fig. 5, compare thick with thin lines). Both effects were statistically significant (see Table 3).

### Three-dimensional response properties

Ideally there should be no vertical and torsional response components when fixating a center target during translation. Indeed, vertical sensitivities were typically <10% of the horizontal and characterized by considerable variability in both response amplitude and phase. However, the torsional sensitivities were larger than vertical and exhibited a systematic phase relationship to the horizontal response component (20–60° lead) during center target fixation (Fig. 6). That is, translation to the right that elicited a positive (leftward) horizontal eye velocity, also generated a positive (clockwise as viewed from the animal’s viewpoint) torsional velocity. Such a torsional eye movement would not be compensatory to an apparent tilt (see DISCUSSION). Also, torsional eye velocity exhibited a consistent, albeit weak, correlation with the inverse of viewing distance (slopes: 0.02 – 0.03°, $R^2 = 0.5–0.9$). This dependence of torsional eye velocity on the inverse of viewing distance was smaller than the respective dependence of horizontal eye velocity. As a result, the closer the target, the smaller the torsional tilt of eye velocity (i.e., the smaller the

### Table 2. Dependence of response sensitivity on the inverse of viewing distance, $D$

<table>
<thead>
<tr>
<th>Frequency, Hz</th>
<th>Regression Equation $y$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>$y = 0.36 + 0.16(1/D)$</td>
<td>0.97</td>
</tr>
<tr>
<td>10</td>
<td>$y = 0.42 + 0.17(1/D)$</td>
<td>0.99</td>
</tr>
<tr>
<td>8</td>
<td>$y = 0.25 + 0.12(1/D)$</td>
<td>0.98</td>
</tr>
<tr>
<td>6</td>
<td>$y = 0.14 + 0.23(1/D)$</td>
<td>0.99</td>
</tr>
<tr>
<td>5</td>
<td>$y = 0.02 + 0.25(1/D)$</td>
<td>0.98</td>
</tr>
<tr>
<td>4</td>
<td>$y = -0.01 + 0.23(1/D)$</td>
<td>0.98</td>
</tr>
</tbody>
</table>

Linear regression parameters computed from average data in two animals based on the equation $S(f, D) = S_0(f) + S_D f / D$ (with $S_0$ in °/cm, $S_D$ in ° and $D$ in cm). For an ideal (i.e., compensatory) translational vestibuloocular reflex (trVOR), the equation that describes the dependence of response sensitivity on the inverse of viewing distance is $y = 0.0 + 0.57(1/D)$. Viewing distances of 20 cm to 3.1 m (space-fixed targets).

### Table 3. Dependence on target eccentricity

<table>
<thead>
<tr>
<th>Frequency, Hz</th>
<th>Horizontal Target Eccentricity</th>
<th>Vertical Target Eccentricity</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 (gain)</td>
<td>$F(4,282) = 2.59$*</td>
<td>$F(4,282) = 2.95$*</td>
</tr>
<tr>
<td>10 (gain)</td>
<td>$F(4,452) = 2.73$*</td>
<td>$F(4,452) = 2.73$*</td>
</tr>
<tr>
<td>8 (gain)</td>
<td>$F(4,282) = 1.44$*</td>
<td>$F(4,282) = 1.46$*</td>
</tr>
<tr>
<td>6 (gain)</td>
<td>$F(4,282) = 1.44$*</td>
<td>$F(4,282) = 1.46$*</td>
</tr>
<tr>
<td>5 (gain)</td>
<td>$F(4,282) = 1.44$*</td>
<td>$F(4,282) = 1.46$*</td>
</tr>
<tr>
<td>4 (gain)</td>
<td>$F(4,282) = 1.44$*</td>
<td>$F(4,282) = 1.46$*</td>
</tr>
</tbody>
</table>

Statistical $F$ values (analyses of variance). Asterisks (*) mark statistically significant results ($P < 0.05$). For all dependent variables (i.e., horizontal gain/phase and torsional sensitivity), the independent variables were horizontal and/or vertical target eccentricity, each with five levels (2 upward/downward elevations, 2 leftward/rightward azimuths, and center targets) and frequency.

![Gain vs eccentricity](image)

**Fig. 4.** Dependence of horizontal translational vestibuloocular reflex (trVOR) gain on horizontal and vertical eye eccentricity. Average horizontal response gains (right eye) from all animals during fixation at different targets have been plotted versus the horizontal position of the right eye. Data are plotted separately for each of 5 × 5 targets placed 6 cm (inner ring) or 12 cm (outer ring) horizontally and vertically relative to a central target which was in the midsagittal plane 20 cm in front of the animal. Different symbols have been used for targets at different vertical eccentricities. Data have been plotted separately for 4 and 10 Hz.
The angle of deviation from a purely horizontal eye movement; Fig. 7). Finally, the torsional tilt of eye velocity was frequency dependent. The closer the target, the larger the frequency range in which this tilt was minimal (\(\sim 10^\circ\); Fig. 7).

The consistent presence of a torsional response component was not due to a misalignment of Listing’s plane with the coordinate axes in which eye position and velocity were expressed (see METHODS). To address this possibility, we recomputed trVOR responses in Listing’s coordinates. The recomputed torsional sensitivities decreased by only \(\sim 30\%\).

Interestingly, the torsional component and the resulting tilt of the eye velocity vector exhibited a strong and significant dependence on target (and, thus eye) position (Table 3B). This is illustrated in Fig. 8 where frontal views of the eye velocity vectors during 4- to 6-Hz oscillations have been plotted separately for each of 25 different targets. Each dot corresponds to the tip of a vector, where the abscissa represents the torsional (clockwise is to the right and counterclockwise to the left) and the ordinate the horizontal component of eye velocity (leftward is up and rightward is down). The center plot shows responses obtained during fixation of the center target, plots to the right, left, up, and down exhibit responses obtained during fixation of targets located 6 cm (inner ring) and 12 cm (outer ring) from the center target (all at a distance of 20 cm from the eyes). Even though the torsional tilt of eye velocity was relatively independent of horizontal target eccentricity, it was strongly dependent on vertical target (and eye) position. For downward eye positions, torsional components were generally closely in phase with the horizontal trVOR component, similarly as for center targets. Nevertheless, the magnitude of torsional sensitivity and the corresponding tilt of the eye velocity vector increased with downward target (and eye) eccentricity. For upward eye positions, the torsional response components reversed polarity such that the corresponding torsional tilt of the eye velocity vectors was opposite (Fig. 8).

The amount of torsional tilt of eye velocity was computed for each target as the angle between a line connecting the average of the corresponding data points from all animals with the coordinate zero and the horizontal eye velocity axis. The torsional tilt angles of the eye velocity vector at 4 and 10 Hz, estimated separately for the right and left eyes, have been plotted as a function of vertical eye position in Fig. 9. Data at all frequencies are summarized in Table 4. In addition to a nonzero tilt at zero vertical eccentricity (which corresponded to the eye velocity vector misalignment for a center target), the characteristic vertical eye position dependency was linear (\(R^2 > 0.90\)) with a slope that was much larger than 0.5 (Fig. 9, \(\cdots\); see DISCUSSION).
DISCUSSION

High-frequency (4–12 Hz) lateral oscillations have been used in the present study to quantify the properties of the translational VOR in rhesus monkeys. In addition to quantifying response dynamics in a higher frequency range than previous studies, the present work has particularly focused on two issues that have not been previously addressed: First, on the tuning of the horizontal response gain on target (and eye) eccentricity; Second, on the properties and functional significance of the torsional eye movements that are robust and consistent during high-frequency translations.

Role of vestibular signals in gaze stabilization during high-frequency head translation

An important finding of this study was that trVOR sensitivity continues to increase for frequencies up to ≥12 Hz. An important issue to address is whether trVOR responses at the high frequencies reported here is of physiological significance. There are at least three arguments in support of this. First, high-frequency stimuli represent a constituent of rapid transient movements. Such motions are often encountered in everyday life and can be either passive (e.g., on a vehicle) or active (e.g., head-free gaze shifts). Second, motion of images on the retina at velocities >2°/s can produce oscillopsia (Demer et al. 1994). Even at the highest frequencies used here, a ~15°/s peak eye velocity would be required to maintain gaze on a close target (Table 1). Therefore the motion stimuli used in these studies would behaviorally require an eye movement compensation for maintenance of visual acuity. Finally, it should be added that afferent transduction of linear acceleration also operates in an expanded high-frequency bandwidth. For example, hair cells in the mammalian otolith neuroepithelia have been shown to respond to high-frequency stimulation (Holt et al. 1999). Primate primary otolith afferents also exhibit a large discharge modulation at frequencies at least up to 10 Hz (A. Haque, D. E. Angelaki, and J. D. Dickman, unpublished observations). Therefore it is likely that these high-frequency responses are of physiological significance.

One of the issues investigated here was the compliance with which the elicited eye movement follows the required kinematic dependence as a function of gaze eccentricity. We found that the geometric dependence on target (and eye) eccentricity is not ideal. As a result, horizontal response gains depend on
Torsional eye movements during translation

A second goal of this study was to investigate the properties of high-frequency torsion. Ideally, only horizontal eye movements are needed to maintain binocular fixation on targets in the horizontal gaze plane during lateral motion. Any dynamic change in torsional eye velocity potentially would be visually destructive and noncompensatory to the motion, particularly for peripheral vision. Nevertheless, large torsional eye velocity components were consistently generated during lateral sinusoidal head displacements during center target fixation (Fig. 6). Torsional eye movements have been reported previously during lateral translation (Angelaki 1998; Lichtenberg et al. 1982; Merfeld et al. 1996; Paige and Tomko 1991a; Telford et al. 1997). These torsional eye movements have been interpreted generally as tilt responses, primarily due to the lack of any obvious compensatory function during head translation (Paige and Tomko 1991a; Telford et al. 1997). At low frequencies (<0.1 Hz), torsional response characteristics (including phase) are indeed consistent with a response to “an apparent tilt” of the head (Angelaki 1998; Lichtenberg et al. 1982; Merfeld et al. 1996). For example, when the head is displaced maximally to the right during low-frequency sinusoidal motion (mimicking a roll tilt to the right in terms of linear acceleration along the interaural axis), counterclockwise (negative) torsional eye movements are generated (Angelaki 1998). As frequency increases, however, the dynamics of these torsional eye movements change. Specifically, phase lags are introduced progressively as frequency increases beyond ~0.1 Hz (Angelaki 1998; Lichtenberg et al. 1982). At frequencies higher than ~1 Hz, response phase differs by nearly 180° from that at low frequencies (Angelaki 1998). Therefore even though robust torsional eye velocity responses are also elicited during lateral motion at high frequencies, the reversed phase makes these responses anticompen-satory to the apparent tilt. Accordingly, we previously had raised the possibility that the torsional eye movements elicited during high-frequency translation are not tilt responses but rather arise because of some, yet unknown, functionality associated with head translation (Angelaki 1998).

Quantification of the 3-D characteristics of the trVORs as a function of eye eccentricity in the present study has revealed additional properties of these torsional eye movements. The most relevant observation is that there is a consistent and very systematic dependence of torsional eye velocity on vertical eye position (Figs. 8 and 9). Clockwise (positive) torsion is elicited for straight ahead and downward gaze during translation to the right. The further downward the gaze, the larger the torsional component of eye velocity and the larger the associated posi-tive torsional (i.e., forward tilt) of the eye velocity vector. For upward gaze, torsional eye velocity reverses polarity. The further upward the gaze, the larger the associated negative torsional (i.e., backward) tilt of the eye velocity vector (Fig. 9). In fact, there is a systematic linear relationship between the torsional tilt of the trVOR eye velocity vector and vertical eye position (Fig. 9). Slopes are between 0.55 and 0.93° of torsional tilt per 1° change in vertical eye position, whereas zero intersections are between 8 and 17° (Table 4). That is, there is a consistent positive tilt of the trVOR eye velocity vector at zero vertical eye (and target) eccentricity.

Torsional eye velocity components also were reported during high-frequency oscillations in a recent study in squirrel monkeys (Telford et al. 1997). Similar to our results, a small but consistent dependence on vergence angle also was reported for squirrel monkeys. The torsional response phase, however, was reported to be highly variable with some in phase and others out of phase with head velocity (Telford et al. 1997). This variability is not surprising, in view of the fact that torsional eye velocity is strongly correlated with vertical eye velocity components also were reported during high-frequency oscillations in a recent study in squirrel monkeys (Telford et al. 1997). Similar to our results, a small but consistent dependence on vergence angle also was reported for squirrel monkeys. The torsional response phase, however, was reported to be highly variable with some in phase and others out of phase with head velocity (Telford et al. 1997). This variability is not surprising, in view of the fact that torsional eye velocity is strongly correlated with vertical eye velocity.

TABLE 4. Dependence of torsional tilt of trVOR eye velocity vector on vertical eye position

<table>
<thead>
<tr>
<th>Frequency, Hz</th>
<th>Regression Equation</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 Right eye</td>
<td>$y = 0.5x + 17.0$</td>
<td>0.99</td>
</tr>
<tr>
<td>Left eye</td>
<td>$y = 0.9x + 10.2$</td>
<td>0.92</td>
</tr>
<tr>
<td>10 Right eye</td>
<td>$y = 0.6x + 15.3$</td>
<td>0.99</td>
</tr>
<tr>
<td>Left eye</td>
<td>$y = 0.7x + 13.5$</td>
<td>0.99</td>
</tr>
<tr>
<td>8 Right eye</td>
<td>$y = 0.5x + 14.8$</td>
<td>0.99</td>
</tr>
<tr>
<td>Left eye</td>
<td>$y = 0.8x + 9.2$</td>
<td>0.90</td>
</tr>
<tr>
<td>6 Right eye</td>
<td>$y = 0.5x + 13.6$</td>
<td>0.99</td>
</tr>
<tr>
<td>Left eye</td>
<td>$y = 0.8x + 9.1$</td>
<td>0.94</td>
</tr>
<tr>
<td>5 Right eye</td>
<td>$y = 0.5x + 12.6$</td>
<td>0.99</td>
</tr>
<tr>
<td>Left eye</td>
<td>$y = 0.8x + 9.1$</td>
<td>0.96</td>
</tr>
<tr>
<td>4 Right eye</td>
<td>$y = 0.7x + 8.4$</td>
<td>0.99</td>
</tr>
<tr>
<td>Left eye</td>
<td>$y = 0.8x + 8.2$</td>
<td>0.98</td>
</tr>
</tbody>
</table>

Parameters of $y = ax + b$ with $a$ in units of [° per °] and $b$ in [°].

FIG. 9. Dependence of the torsional tilt of the eye velocity vectors on vertical eye position. Data are plotted separately for each eye. Linear regression lines are included in Table 4. Only data from targets with zero azimuth have been included. ∙ ∙ ∙, predicted according to the half angle rule.
position (a relationship that was not examined by the authors). As shown here, torsional eye velocity is very consistent and often quite large (e.g., for large vertical eccentricities).

**Three-dimensional kinematic constraints: is Listing’s law preserved during trVOR?**

In several recent studies, visually guided eye movements have been shown to be subject to robust kinematic constraints whereby they remain primarily two-dimensional by minimizing ocular rotations about a unique gaze direction defined as primary position (Listing’s law) (see Hepp 1990; Tweed and Vilis 1987; Tweed et al. 1990, 1992). The requirement of gaze stabilization during head movements can be incompatible with these kinematic constraints. Rotational VORs, for example, have been shown to follow a compromised strategy whereby these kinematic constraints are overruled by mechanisms that optimize gaze stabilization during rotations (Crawford and Vilis 1992; Hess and Angelaki 1997a,b; Misslisch et al. 1994).

To satisfy Listing’s law during a lateral displacement, trVOR response vectors should tilt downwards for downward gaze and upwards for upward gaze. Thus rather than a purely horizontal velocity, a combination of torsional and horizontal slow phase velocity components is predicted (Haustein 1989; Misslisch et al. 1994; Tweed and Vilis 1987, 1990; Tweed et al. 1992). Therefore, if the kinematic constraints of visually guided eye movements also are to be satisfied during head translation, the direction of the elicited eye movement would be determined not only by the requirements for binocular gaze stabilization but also by the 3-D kinematic constraints of Listing’s law. The dependence of torsional eye velocity on vertical eye eccentricity suggests the latter.

During sinusoidal lateral translation, two effects were observed that bear on Listing’s law and its interaction with vergence (Mok et al. 1992). First, as outlined in the preceding text, sinusoidal lateral translation during center target fixation induced a mean positive torsional tilt of eye velocity. This tilt averaged ~10° at 4 Hz and ~15° at 10 Hz for a vergence of ~9–10° (5 MA). There could be at least two explanations for the presence of this torsional component: it could be due to the difference between the straight ahead coordinates used to express eye velocity and Listing’s coordinates. However, when expressing trVOR responses in Listing’s coordinates, we found that this could only account for ~30% of the observed torsion. This decrease was in line with a ~5° downward tilt of primary eye position relative to straight ahead (see METHODS). Such a downward tilt could be responsible for half as much torsional tilt of the eye velocity vector, but could certainly not explain the 10–30° tilts observed (Fig. 7). It also could be due to the temporal shift of Listing’s plane during convergence. On the basis of previous work during static (i.e., no movement) near target fixation, for example, there is a rotation of Listing’s plane and primary eye position outwards/inwards for convergence/divergence, respectively (Minken and van Gisbergen 1994, 1996; Mok et al. 1992; van Rijn and van den Berg 1993). However, the eccentricity of the central targets relative to primary gaze direction was small and, therefore the vergence induced by fixation of closer targets along this direction should induce little or no cyclorotation of the eyes. Nonetheless, during translation, a positive torsional velocity signal emerged consistently during center target fixation as if primary gaze direction would have shifted downward relative to its orientation at rest (and zero vergence). This effect clearly depended on both the stimulus frequency and the distance to the target, being greater at high frequencies and far targets (Fig. 7).

A second related observation was that eye velocity tilted by almost the same angle as the gaze line during fixation of close targets at different vertical eccentricities (Fig. 9). As summarized in the preceding text, Listing’s law (for far target viewing) dictates that eye velocity should tilt by half the gaze angle. This apparent discrepancy could be explained by the changes in the kinematics of 3-D eye movements during near target fixation and large vergence angles (Minken and van Gisbergen 1994, 1996; Mok et al. 1992; van Rijn and van den Berg 1993). For pure vergence movements, for example, a full angle tilt has been observed during visually guided eye movements (Minken and van Gisbergen 1996). Because the trVOR responses during fixation of close targets are mixed vergence-version responses, slopes between 0.5 and 1 might indeed be expected, similar as described for vergence-version gaze shifts (Minken and van Gisbergen 1996).

In summary, the systematic torsional eye velocity components elicited during lateral translation at high frequencies (i.e., >1 Hz) (see Angelaki 1998; present results) do not represent tilt responses, but might be rather related to the kinematics of 3-D eye movements and their interaction with vergence. The systematic torsional tilt of the trVOR eye velocity vector as a function of vertical eye position is in line with the hypothesis that trVOR might follow a similar 3-D kinematic organization as visually guided eye movements. Such a difference in the 3-D kinematic properties between the rotational and translational VORs would be in line with the view that trVORs are important for maintaining visual acuity on the fovea and have evolved in parallel with foveal vision and stereopsis (e.g., Miles 1998). The nonzero torsional velocity during straight-ahead gaze, however, is more puzzling. It might represent a downward shift of primary eye position during lateral translation, albeit the functional significance of such an effect is at present elusive.

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