Integration of Vestibular and Head Movement Signals in the Vestibular Nuclei During Whole-Body Rotation

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Introduction

The vestibular labyrinths are embedded in the temporal bones of the head and detect the position and movement of the head in space. This sensory information contributes to spatial perception of the head and body in space and has a role in mediating reflexes that stabilize gaze and the posture of the head and body (Flourens 1842). The head-referenced spatial coordinates of the signals carried by the vestibular nerves are sufficient for controlling movements that are made with respect to the head, such as eye movements, as well as for perception of head orientation and movement in space. The results of several studies suggest that the control of posture, perception of the orientation of the body, and the location of objects in extrapersonal space requires an integration of proprioceptive, visual, and vestibular signals as well as internally generated signals related to intended head and body movements (Lackner and DiZio 1993; Lackner and Graybiel 1978; Mergner et al. 1997). However, in most mammals, a multi-articulate neck permits the orientation and movement of the head to be independent of the orientation and movement of the rest of body (Keshner 1994; Keshner et al. 1992; Richmond et al. 1992; Vidal et al. 1986). As a consequence, vestibular nerve signals can be inappropriate or inadequate for the perception of the orientation of the body in space, for the location of objects in extrapersonal space, for adjusting body, limb, and neck posture, and for determining the metrics of postural reflexes that compensate for perturbations of the whole body (Horak et al. 1994; Lackner and DiZio 1993; Mergner et al. 1997).

Vestibular sensory signals play an important role in a variety of reflexes that function to stabilize the position of the head and body in space (Peterson and Goldberg 1982; Peterson et al. 1988; Wilson 1993). In natural circumstances, movements of the limbs, torso, neck, and head all work together to oppose a passive perturbation of the whole body (Horak et al. 1990; Mergner et al. 1997). The vestibulocollic reflex (VCR) is a reflex that functions to stabilize the position of the head in space. Passive angular rotation of the whole body stimulates semicircular canal afferents that reflexively activate neck muscles that produce opposing angular head and neck movements (Baker et al. 1985; Ezure et al. 1978; Goldberg and Peterson 1986; Wilson and Peterson 1981; Wilson et al. 1990). In fact, the VCR activates muscles that can produce compensatory rotation of the head on the neck but also muscles that are capable of changing the orientation of the neck with respect to the body (Keshner et al. 1992). Stabilization of the head in space during rotations of the whole body can be accomplished with head-on-neck rotations, neck-on-trunk rotations, or with trunk-in-space rotations. Recent work by Mergner and colleagues (1997) has suggested that each of these types of movements work synergistically toward stabilizing the head in space.

One problem that arises in coordinating all of the muscular activities that stabilize the head in space is that the movements evoked by the VCR can only rotate the head with respect to the trunk. If head-referenced vestibular signals are used as input for other motor systems that stabilize the head in space, the vestibular afferent input to the pathway must be transformed with respect to a body or trunk reference frame. This transformation could be accomplished by adding signals related to...
neck angular velocity to vestibular signals related to angular head velocity.

The question is not whether but where, how, and under what circumstances neck movement signals are integrated with vestibular signals. Several anatomic and electrophysiological studies suggest that signals related to neck movements combine with vestibular signals throughout the brain, including the vestibular cortex (Akbarian et al. 1988; Grüsser et al. 1990; Mergner et al. 1985), somatosensory cortex (Zarzecki et al. 1983), vestibulocerebellum (Denoth et al. 1980; Wilson et al. 1975), reticular formation (Wilson 1993), perihypoglossal nuclei (Gretskey and Baker 1976), spinal cord (Wilson 1988), and vestibular sensory epithelium (Boyle and Hightstein 1990; Brichta and Goldberg 1996; Goldberg and Fernandez 1980; Hightstein 1991; Highteen and Baker 1985). The functional role of each structure as well as the behavioral context of the situation most likely dictate where, how, and under which circumstances neck movement signals and vestibular signals are combined.

There is considerable electrophysiological evidence that a convergence of neck movement and vestibular inputs occurs in the vestibular nuclei. Neurons involved in the vestibulo-ocular reflex (VOR), the VCR, and lateral vestibulo-spinal pathways all receive neck proprioceptive inputs, which combine with vestibular signals in a variety of ways (Anastasopoulos and Mergner 1982; Boyle and Pompeiano 1981; Fuller 1988; Wilson et al. 1990). Although neck movement signals interact powerfully with vestibular signals within the vestibular nuclei at the earliest stages of central vestibular sensory processing, little is known about how these interactions contribute to the signal processing of vestibular pathways during voluntary and reflexive head movements.

We have carried out a series of studies that were designed to investigate the firing behavior of secondary horizontal semicircular canal-related vestibular neurons in alert squirrel monkeys who were free to generate angular head movements in the plane of the horizontal semicircular canal. Responses were studied during active head movements, which include reflexive compensatory head movements, and voluntary gaze shifts. These were compared with responses during passive rotations of the head, body, or combinations of both. In this paper, the signals generated by horizontal canal-related central vestibular neurons during passive whole-body rotation (WBR) when the head was fixed with respect to the body were compared with the signals during compensatory reflexive head movements evoked during WBR when the head was free to move.

**METHODS**

**Surgical preparation**

Three adult squirrel monkeys were prepared for chronic recording of eye movements and single-unit activity. Surgeries were carried out under sterile conditions with sodium pentobarbital (20 mg/kg ip, initial dose, with supplements of 1–2 mg/kg as necessary). A skull cap constructed of dental acrylic was attached to an exposed portion of the cranium. A small stainless steel keybol was embedded in the acrylic, which was used to attach the animal’s head to the experimental apparatus. A search coil (4 turn, 10-mm diam) constructed of Teflon-coated stainless steel wire was sutured to the sclera of the right eye. Bipolar labyrinthine stimulating electrodes were implanted bilaterally in the middle ear for electrical stimulation of the vestibular nerve.

**Experimental recording conditions**

Figure 1A is a diagram of the experimental recording apparatus. The monkey was seated in a chair on top of a vestibular turntable (a). The back of the chair (b) was shaped to inhibit trunk movement. A harness (c) was placed over the animal’s shoulders and in front of the trunk to inhibit trunk and arm movements. The bolt on the monkey’s head (d) was attached to a rod that allowed the head to move in the plane of the horizontal semicircular canals. The rod rotated within a low-friction ball bearing assembly (e) that was fixed to the table and had a universal joint (f) that permitted small (±5°) pitch-and-roll postural adjustments of the head. The rotational axis of the rod was coincident with the rotational axis of the turntable and was positioned at the level of the external auditory meatus within 5 mm of C1–C2 axis of rotation. The dynamic range of head movements was limited to ±40° with a block (Fig. 1, g) that obstructed the rod’s rotational path. The head could be fixed to the turntable by disabling the universal joint (h, see inset) and by attaching a block (i), which prevented angular rotation of the rod.

Gaze and head positions were measured with a magnetic search-coil system (Neurodata). Head position was measured with a coil (Fig. 1, j) that was attached to the rod below the universal joint. The head position signal was calibrated before experiments by precisely rotating the rod (and coil) with a motor that was mounted on the ceiling. Gaze position was measured with the implanted scleral coil. The gain of the implanted eye coil was determined by fixing the head to the turntable and by assuming that the VOR gain recorded in the light was unity during passive sinusoidal WBR (1.9 Hz, 20°/s) (Chen-Huang and McCrea 1999). The animals were also trained to fixate and pursue targets projected onto a cylindrical screen (k) that was 90 cm away from the monkey. The eye coil calibration was checked periodically by having the monkey fixate or pursue targets. The linearity of the magnetic search-coil system was slightly sigmoidal and underestimated large coil rotations (>40°). Head movements were limited within the system’s linear range (<40°) and were unaffected. A linear approximation was used to measure gaze position, which resulted in <4% error over its dynamic range (±60°). The noise level of the gaze and head position signals was typically less than ±0.2° rms. Eye position in the head was calculated as the difference between gaze and head position.

Smooth-pursuit eye movements were evoked by sinusoidal movement (0.5 Hz, peak velocity 40°/s) of a small visual target (<0.2° diam) that was projected onto the cylindrical screen either from a turntable- or ceiling-mounted laser (Fig. 1A, m and n). A liquid reinforcement of sweetened milk (o) was delivered to the monkey with a feeding tube that was attached to the rod used to hold its head.

Behavioral monitoring, data acquisition, and stimulus generation were all controlled with a personal computer (Compaq). Both table rotation and visual target stimuli were operated under computer control. Turntable, target, gaze, and head signals were low-pass filtered (5–10 kHz) and sampled (2–500 Hz) with A/D converters of a peripheral device (16 bit, Cambridge Electronics) interfaced to the computer.

1 Gravito-inertial forces can play an important role in generating head movements (Goldberg and Peterson 1986). In our experiments, the inertial forces that act on the head during WBR were minimized by positioning it in the center of the axis of rotation. The small rotational torque produced by the mass of the head acting at a radius of <5 cm was estimated to be <1 × 10⁻² Nm. Several observations suggest that the head-on-trunk movements evoked in the head-free WBR condition were primarily produced by active neuromuscular contractions and not by passive inertial forces. 1) The amplitude of the VCR was strongly related to alertness and decreased significantly in sleeping or anesthetized monkeys. 2) No movement was observed immediately postmortem. 3) The detached head of a dead squirrel monkey also remained stationary during turntable rotation at the stimulus frequencies used in this study, presumably because the inertial torque was less than the reactive forces associated with the friction and inertia of the ball-bearing assembly.
Single-unit recording techniques

Single unit recordings were obtained with a lightweight hydraulic microdrive (Fig. 1A, l) that was fixed to the animal’s head. The microelectrode (Tungsten, 4- to 7-MΩ impedance), protected by a guide tube (22 G), was inserted into the cerebellum with respect to a stereotaxic landmark. The microdrive was used to advance the microelectrode into the vestibular nuclei. Isolated single-unit recordings (signal/noise ratio $\geq 2$) were routinely maintained for periods of $\geq 1$ h while the head was free to move.

Action potentials were conventionally amplified, discriminated with a dual-window discriminator (Bak), and time marked with a real time clock (0.1-μs resolution). Unit discharge rates were computed for each A/D sample of eye and head movement (binwidth 2–5 ms) with a time-symmetric algorithm in which discharge rate was computed from the occurrence of spikes immediately before, after, and during the sample (Cullen and McCrea 1993).

Location of single-unit recording sites

All of the units included in this report were presumed to be located in the vestibular nuclei based on the latency and amplitude of field potentials evoked by shocking the ipsilateral vestibular nerve (0.1-ms monophasic perilymphatic cathodal pulses, 50–300 mA). Figure 2A shows the response of a typical unit after electrical stimulation of the vestibular nerve (Fig. 2A). The microelectrode, which was fixed to the head, was used to advance single-unit microelectrodes. The monkey faced a cylindrical screen (k) 90 cm away in a dimly lit room in all conditions. Laser targets were projected from the turntable (m) or the ceiling (n) onto the cylindrical screen. Sweetened milk rewards were delivered to the monkey with a feeding tube (o) connected to the rod. A tone was delivered with a speaker (p) as a secondary reinforcement during behavioral conditioning. Two views illustrate the transition from the head-free (exploded view) to the head-fixed condition (unexploded view). In the head-fixed condition, the head was fixed with respect to the table with a keyed block (i) that prevented rotation of the rod and attachment of the sleeve (h) that disabled the universal joint.

Fig. 1. A: experimental setup. Squirrel monkeys were seated on a Plexiglas chair on a vestibular turntable (a). Movements of the animal’s trunk were prevented by shaping the back of the chair (b) and by placing a harness (c) over the animal’s head, which extended over its trunk. All head movements, except yaw-axis rotations about the C1–C2 axis, were minimized by connecting a rod assembly to a bolt (d) on the animal’s head that rotated within a ball-bearing hub (e). A universal joint (f) allowed slight positional adjustments that could be blocked by a sleeve (h). Range of yaw-axis rotations was limited ($\pm 40^\circ$) by a block (g). Head position was measured with a search coil (j) mounted on the vertical rod. A hydraulic microdrive (l), which was fixed to the head, was used to advance single-unit microelectrodes. The monkey faced a cylindrical screen (k) 90 cm away in a dimly lit room in all conditions. Laser targets were projected from the turntable (m) or the ceiling (n) onto the cylindrical screen. Sweetened milk rewards were delivered to the monkey with a feeding tube (o) connected to the rod. A tone was delivered with a speaker (p) as a secondary reinforcement during behavioral conditioning. Two views illustrate the transition from the head-free (exploded view) to the head-fixed condition (unexploded view). In the head-fixed condition, the head was fixed with respect to the table with a keyed block (i) that prevented rotation of the rod and attachment of the sleeve (h) that disabled the universal joint.
The estimated location of electrode tracks and units in the vestibular nuclei is illustrated diagrammatically in Fig. 2, B and C. The diagrams are dorsal views of the vestibular nuclei in a plane orthogonal to the orientation of electrode tracks. Stereotaxic reconstructions of recording tracks from all three monkeys are shown superimposed in Fig. 2B. Filled symbols are tracks where vestibular field potentials were observed after shocks of the ipsilateral vestibular nerve, and open symbols are tracks where field potentials were not observed. Reconstructions were aided by locating the lateral border of the vestibular nuclei at the level of the vestibular nerve and by the characteristic firing behavior of neurons or axons in bordering structures (e.g., the abducens nucleus, the prepositus nucleus, external cuneate nucleus, and the facial and vestibular nerves). The track locations in one monkey were confirmed by histological examination of the location of a single deposit of horseradish peroxidase.

Figure 2C shows the location of all of the units included in this study. Units were not recorded on all electrode tracks. The symbol types are based on unit classifications (filled symbols are non-eye-movement units, and open symbols are eye-movement units). All of the units were judged to be located in the vestibular nuclei. Most recordings were obtained from the ventral lateral vestibular nucleus, the inferior vestibular nucleus, and lateral parts of the medial vestibular nucleus. The most rostral parts of the vestibular nuclei, particularly the superior vestibular nucleus, were not explored. The caudal border of the vestibular nuclei was estimated from the absence of vestibular field potentials and the appearance of neck somatosensory and proprioceptive responses (e.g., lateral cuneate nucleus) or autonomic responses (e.g., associated with respiration and blood pressure) of neurons presumably located in the nuclei of the solitary tract.
Experimental protocol

Passive WBR was used as a search stimulus (0.5 Hz, 40°/s and 2.3 Hz, 20°/s) as electrodes were advanced toward the vestibular nuclei. Units that responded to the search stimulus were tested for their response to electrical stimulation of the ipsilateral vestibular nerve (described previously). Different classes of eye-movement units were identified by examining their responses during steady fixation, ocular saccades, smooth-pursuit eye movements, and VOR cancellation (Cullen and McCrea 1993).

The experimental results reported in this paper are based on a comparison of unit responses to WBR when the head was free to move and when the head was fixed to the turntable (Fig. 1B). Unit responses to WBR were typically recorded at two stimulus frequencies (0.5 Hz, 40°/s and 2.3 Hz, 20°/s) in dim light in the absence of a visual target. In the head-fixed condition (Fig. 1B, left panel), head movements were restrained so that the velocity of the monkey’s head in space (HS) was equal to the velocity of the trunk in space (TS). In the head-free condition, compensatory head movements (HT) were usually evoked in the opposite direction (Fig. 1B, arrows). For some units, responses were also recorded while the monkey fixated an earth-stationary target during WBR (0.5 Hz, 40°/s).

Data analysis

Analysis was done on a Macintosh computer with algorithms developed in IGOR (Wavemetrics). The methods used for assessing unit sensitivity to eye position and eye velocity were similar to those previously described (Cullen and McCrea 1993). Unit sensitivity to head position was assessed by linear regression analysis of firing rate during intervals when eye and head position were stable. Unit firing behavior during saccades and smooth pursuit was also quantitatively analyzed. The methods used in this analysis will not be described because in the context of this study it was only used for grouping units into different qualitative categories.

Unit rotational responses were typed on the basis of their response phase and the location of the recording electrode. Units whose responses were in phase with ipsilateral rotation were defined as type I and are reported as positive values in figures and tables. Responses that were in phase with contralateral rotation were defined as type II and are reported as negative values in figures and tables. WBR responses were assessed by averaging selected records with respect to the turntable frequency. Stimulus cycles were not selected if the monkey was judged not to be alert (reduced VOR gain, low frequency of saccades) or if it suppressed its VCR and VOR by looking downward at the reward tube or chair. All records related to saccades were also excluded from analysis. Typically, the A/D samples and records of unit firing rate that occurred ≥30 ms before the onset of the saccadic gaze shift and 40 ms after the end of the gaze shift or the end of the head movement component of the gaze shift were excluded from analysis. To study the contribution of the VCR to unit firing behavior, only cycles that included compensatory head movements were included in the analysis of unit responses.

Selected, desaccaded records were averaged and fit with a fixed-frequency sinusoidal function. Some units were silenced during rotation in their off-direction. In such units, the sinusoidal fit was restricted to epochs in which the unit’s firing rate was greater than a minimum value. This value was equal to the lowest firing rate at which a linear relationship was observed between firing rate and head velocity. The amplitude of the eye movements produced during 2.3 Hz WBR was usually small (±1.4°) and had little effect on the average rotational responses of most eye-movement units. Nevertheless, the WBR responses of units that were sensitive to eye position were analyzed both before and after subtracting eye position signals (Cullen and McCrea 1993). In the head-restrained condition, the gain and phase of the unit’s response were calculated both with respect to head velocity and with respect to trunk velocity in space. The estimates of variance cited in the text and figures are SEs.

Results

The responses of 107 horizontal canal-related vestibular units were studied during WBR. Most of the units tested (61/80) were monosynaptically activated after stimulation of the vestibular nerve. The firing behavior of one-half (55/107) of the units was related to eye position and/or eye velocity. The remaining 52 were classified as non–eye-movement units.

Approximately one-half of the non–eye-movement units were sensitive to ipsilateral head velocity (type I units, n = 25), and one-half were sensitive to contralateral head velocity (type II units, n = 27) during WBR. The gain and phase of the rotational responses of each type of non–eye-movement unit are summarized in Table 1. Most of the type I and type II non–eye-movement units tested (93 and 74%, respectively, Table 1) were activated at monosynaptic latencies after stimulation of the vestibular nerve. A few non–eye-movement units (7/52) were inhibited during ocular saccades in all directions, although their firing rate was not correlated with eye position or with eye velocity during pursuit eye movements.

Eye-movement units were subdivided into conventional subclasses based on their firing behavior during VOR, VOR cancellation, smooth-pursuit eye movements, and fixation (Cullen and McCrea 1993; Miles 1974; Scudder and Fuchs 1992; Tomlinson and Robinson 1984). Most of the eye-movement units were secondary position-vestibular-pause (PVP) units (n = 29), which had discharge rates that were related to contralateral eye position during steady fixation and to ipsilateral head velocity during WBR and paused during most or all saccades. Some eye-head-velocity (EHV) units were sensitive to contralateral head velocity during the VOR, to ipsilateral head velocity during VOR cancellation, and to ipsilateral eye velocity during smooth-pursuit eye movements (n = 5). Other EHV units (n = 4) were sensitive to ipsilateral head velocity.

### Table 1. Summary of unit rotational responses during head-fixed WBR

<table>
<thead>
<tr>
<th>Units, n</th>
<th>Monosynaptically Activated n/tested</th>
<th>2.3-Hz WBR Gain, Phase spikes/s/deg/s deg</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>NEM units</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VI 25</td>
<td>14/15</td>
<td>0.99 ± 0.15 -16.9 ± 3.0</td>
</tr>
<tr>
<td>VII 27</td>
<td>13/19</td>
<td>-0.57 ± 0.06 -21.7 ± 4.3</td>
</tr>
<tr>
<td>Subtotal 52</td>
<td>27/34</td>
<td></td>
</tr>
<tr>
<td><strong>EM units</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PVP 29</td>
<td>20/21</td>
<td>1.33 ± 0.13 -18.6 ± 4.6</td>
</tr>
<tr>
<td>EHV 9</td>
<td>8/9</td>
<td>0.72 ± 0.14 13.5 ± 23.1</td>
</tr>
<tr>
<td>PVI 8</td>
<td>1/7</td>
<td>1.14 ± 0.32 -25.9 ± 6.9</td>
</tr>
<tr>
<td>PVII 5</td>
<td>4/5</td>
<td>-0.54 ± 0.18 -45.8 ± 10.6</td>
</tr>
<tr>
<td>BP 4</td>
<td>1/4</td>
<td>-0.33 ± 0.01 -11.4 ± 20.4</td>
</tr>
<tr>
<td>Subtotal 55</td>
<td>34/46</td>
<td></td>
</tr>
<tr>
<td>Total 107</td>
<td>61/80</td>
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</tr>
</tbody>
</table>

Values are means ± SE. WBR, whole-body rotation; NEM, non–eye movement; VI, type I units; VII, type II units; EM, eye movement; PVP, position-vestibular-pause units; EHV, eye-head-velocity units; PVI, PVII, position-vestibular units; BP, burst position units.
during the VOR, to contralateral head velocity during VOR cancellation, and to contralateral eye velocity during smooth-pursuit eye movements. Some EHV units generated bursts of spikes during ocular saccades. Position-vestibular (PV) units \((n = 13)\) were sensitive to head velocity during WBR and to eye position but not to eye velocity during either saccades or smooth pursuit. They did not pause during saccades. Eight of the PV units were sensitive to contralateral eye position and ipsilateral head velocity during WBR, and five were sensitive to ipsilateral eye position and contralateral head velocity. A few \((n = 4)\) burst-PV units that generated bursts of spikes during contralateral saccades and whose tonic firing rate was related to contralateral eye position were recorded. Most of the eye-movement units tested \((34/46, 74\%\), Table 1) were monosynaptically activated after stimulation of the vestibular nerve.

**Compensatory head movements evoked during WBR**

When the head was free to move, WBR evoked a compensatory VCR (Fig. 3B, arrows). The gain of the VCR was quite variable and tended to be higher at higher frequencies of turntable rotation. The mean gain of the VCR during single-unit recordings was \(0.14 \pm 0.11\) at 0.5 Hz and \(0.33 \pm 0.14\) at 2.3 Hz. The mean phase was \(153 \pm 30°\) at 0.5 Hz and \(173 \pm 19°\) at 2.3 Hz. In some units \((n = 34)\), either the amplitude of the VCR was too small (gain of \(<0.1\)) or the unit’s sensitivity during WBR was too small (gain of \(<0.2\) spikes s\(^{-1}\) deg\(^{-1}\) s\(^{-1}\)) to allow the effect of the VCR on WBR responses to be quantitatively assessed. In the remaining 73 cells, the most reliable estimate of the effect of the VCR was usually obtained from analysis of 2.3 Hz WBR.

The head-on-trunk movement produced by the VCR affected the rotational responses of different vestibular units in different ways. As expected, the compensatory head movements reduced the WBR responses of many cells \((34/73, 47\%)\). However, many other units \((24/73, 33\%)\) exhibited similar responses in the presence and absence of the VCR. Finally, some units \((15/73, 21\%)\) had WBR responses that were significantly larger during the VCR. The effect of the VCR on different classes of vestibular units is summarized in Table 2.

**Units whose WBR responses were reduced by the VCR**

Many eye-movement and non–eye-movement units had WBR responses that were reduced by the VCR. Sample records of the responses of a type I PV unit in the head-fixed and -free conditions are shown in Fig. 3, A and B. The averaged
desaccaded responses are shown in Fig. 3, C and D, respectively. The amplitude of this unit’s response decreased when the head-on-trunk movement produced by the VCR (blue traces labeled HT in Fig. 3, B and D) reduced head velocity in space (red traces labeled HS in Fig. 3, B and D) by 34%. Most (22/35; 63%) of the units whose responses were reduced by the VCR had head velocity sensitivities that were not significantly different in the head-free and -fixed conditions ($P > 0.05$, two-sided $t$-test). For example, the firing rate modulation of the unit in the head-free condition was 12.3 ± 0.3 sp/s (dashed line in Fig. 3D). This was identical to the modulation expected if the unit’s firing rate had been related to head velocity in space (12.3 sp/s, red trace labeled FR$_{hs}$ in Fig. 3D). The remaining 13 units exhibited small but significant ($P < 0.05$, two-sided $t$-test) changes in their sensitivity to head velocity in the head-free condition. Their rotational responses were either more (7/10) or less (6/10) attenuated than would be expected based on their sensitivity to head velocity during head-fixed WBR.

### Table 2. Changes in firing rate during the VCR

<table>
<thead>
<tr>
<th>Units</th>
<th>Decreased by &gt;20%</th>
<th>Same</th>
<th>Increased by &gt;20%</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEM units</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VI</td>
<td>5</td>
<td>8</td>
<td>6</td>
<td>19</td>
</tr>
<tr>
<td>VII</td>
<td>9</td>
<td>9</td>
<td>6</td>
<td>24</td>
</tr>
<tr>
<td>Subtotal</td>
<td>14</td>
<td>17</td>
<td>12</td>
<td>43</td>
</tr>
<tr>
<td>EM units</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PVP</td>
<td>11</td>
<td>4</td>
<td>2</td>
<td>17</td>
</tr>
<tr>
<td>EHV</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>PV</td>
<td>6</td>
<td>0</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>BP</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Subtotal</td>
<td>21</td>
<td>6</td>
<td>3</td>
<td>30</td>
</tr>
<tr>
<td>Total</td>
<td>35</td>
<td>23</td>
<td>15</td>
<td>73</td>
</tr>
</tbody>
</table>

Figure 4 illustrates the firing behavior of a non–eye-movement unit whose response to WBR was not significantly affected by the VCR. The unit was activated at monosynaptic latencies after electrical stimulation of the ipsilateral vestibular nerve (Fig. 2A). Sample records of the unit’s firing behavior when the head was fixed to the turntable and when the head...
was free to move in the yaw plane are shown in Fig. 4, A and B, respectively. The corresponding averaged desaccaded responses from the entire trial are shown in Fig. 4, C and D. The unit’s firing rate modulation was similar in both conditions (horizontal dashed lines in Fig. 4, C and D), although the VCR produced a head-on-trunk movement (HT, blue line in Fig. 4, B and D) that reduced the velocity of the head in space by 40%.

The amplitude of the sinusoidal function fit to unit firing rate (dashed lines labeled Fit in Fig. 4, C and D) was 16.0 sp/s (gain re turntable = 0.81 spikes s\(^{-1}\) deg\(^{-1}\) s\(^{-1}\)) during head-fixed WBR and 16.7 sp/s (gain with respect to turntable = 0.89 spikes s\(^{-1}\) deg\(^{-1}\) s\(^{-1}\)) during head-free WBR. If the unit’s firing behavior had been related to head velocity in space, the amplitude of its response would have decreased to 9.6 sp/s (red line labeled FR\(_{hs}\) in Fig. 4D). On the other hand, if the unit’s response had been related to trunk velocity in space (thick black line labeled FR\(_{ts}\) in Fig. 4D) the modulation would have been expected to be 16.0 sp/s. Clearly, the firing behavior of this vestibular unit was better related to trunk velocity than to head velocity during WBR. Nearly all (21/23, 91%) of the units whose WBR responses were unaffected by the VCR (16 non–eye-movement and 5 eye-movement–related units) had trunk velocity sensitivities that were not statistically different (\(P > 0.05\), two-sided t-test) in the head-free and -fixed conditions.

Units whose WBR responses were enlarged by the VCR

The amplitude of the rotational responses of 15 units was larger by \(\geq 20\%\) in the head-free condition than in the head-fixed condition. Figure 5 illustrates the averaged responses of one of these units. The amplitude of the unit’s modulation increased from 10.7 sp/s in the head-fixed condition to 14.0 sp/s in the head-free condition, although the VCR reduced head velocity by \(\geq 30\%\). The head-free WBR responses of these units were poorly correlated with both head velocity and trunk velocity in space.

Effect of the VCR on the WBR responses of non–eye-movement vestibular units

The WBR responses of most (29/43) non–eye-movement units were either unaffected by the VCR or increased in amplitude in the head-free condition. In Fig. 6, the gain of the WBR responses of non–eye-movement units during the head-free condition is plotted as a function of their gain the head-fixed condition. In Fig. 6A, the response gain in the head-free condition was computed with respect to trunk velocity, whereas in Fig. 6B the gain was computed with respect to head velocity.

Units plotted near the center diagonal line (blue shaded region) in Fig. 6A had rotational responses that were similar in the head-free and -fixed conditions. Units plotted near the center diagonal line in Fig. 6B had signals that were related to head velocity in the head-free condition. The yellow and white stars in each plot are the units illustrated in Figs. 4 and 5, respectively. The dashed diagonal lines above the center solid unity diagonal line in each plot represent two- and fourfold increases in response gain in the head-free condition. Units plotted below the unity lines had response gains that were attenuated by the VCR in the head-free condition.

Although the sensitivity of many cells to head velocity was essentially unchanged by the VCR, the population of units was better related to trunk velocity in space (Fig. 6A) than to head velocity in space (Fig. 6B). The mean ratio of the non–eye-movement unit gains in the head-free and -fixed conditions re trunk velocity was 1.06 ± 0.05 compared with a mean response gain ratio of 1.52 ± 0.1 re head velocity. The histograms in Fig. 6 show the distribution of unit gain ratios re trunk and head velocity. Non–eye-movement units were roughly normally distributed around the unity line in Fig. 6A, which represents responses related to trunk velocity in space. The distributions of type I and type II units were similar. In contrast, non–eye-movement units were asymmetrically distributed above the unity line in Fig. 6B, which represents...
responses related to head velocity in space. Thus the propensity to code trunk velocity during the VCR was evident in the population as well as in individual non-eye-movement units.

**Effect of the VCR on the WBR responses of eye-movement vestibular units**

Eye movements are generated in head coordinates, and the VOR is a reflex that functions to stabilize images on the retina during head movements. Therefore a reasonable expectation was that eye-movement vestibular units would have signals that were related to head velocity in space, regardless of whether the head was moving with respect to the body. The result of our experiments generally confirm this expectation, although some eye-movement units were not equally sensitive to head velocity in the head-fixed and -free conditions.

The comparison of head-fixed and -free responses in eye-movement neurons was complicated by the eye-movement signals they carried. This complication was partly addressed by eliminating segments of cycles related to saccades from analysis. In addition, an estimate of each unit’s sensitivity to eye position was determined with a linear regression analysis of unit firing rate versus eye position during periods of steady fixation in the absence of turntable rotation. This eye position signal was then subtracted from the WBR responses before averaging. The 2.3-Hz WBR stimulus typically evoked a VOR eye movement whose amplitude was $<1.2^\circ$ and whose velocity was $\sim20^\circ/s$. In most units, the small modulation in eye position contributed little to the sinusoidal modulation in firing rate during WBR. However, the potential contribution of eye velocity signals to unit responses made the interpretation of head-free WBR responses somewhat problematic because the compensatory head movement reduced both the vestibular input to units and the velocity of the VOR. No attempt was made to correct unit WBR responses for the changes in eye velocity that accompanied the VCR.

The gain of the head-free and -fixed WBR responses of eye-movement units with respect to trunk velocity and head velocity is plotted in Fig. 7, A and B, respectively. The majority (21/30) of eye-movement units had WBR gains that were smaller in the head-free condition, i.e., their data lie below the solid unity line in Fig. 7A. On the other hand, their gains were more equally distributed around the unity line in Fig. 7B, which indicates equal gains relative to head velocity whether the head was fixed or free. Six of the eye-movement units that were more closely related to trunk velocity than to head velocity were PVP units, and three were EHV units.

**Effects of stimulus frequency on WBR responses**

As noted previously, the gain of the VCR tended to increase as a function of frequency. In some units (14 eye-movement units and 16 non–eye-movement units), the VCR gain at low frequencies was large enough (gain $>0.15$) to determine the effect of the VCR at two or more stimulus frequencies. Units whose responses were reduced, unchanged, or enlarged by the VCR at 2.3 Hz exhibited similar changes at other stimulus frequencies. Figure 8 plots the gain of the WBR responses of a non–eye-movement unit in the head-fixed and -free conditions at four stimulus frequencies. The unit’s WBR response in
the head-free condition was similar to its response in the head-fixed condition at each frequency. Thus the unit’s WBR response gain re trunk velocity (blue symbols and line in Fig. 8) was comparable with its head-fixed WBR response (black triangles and line), whereas the unit’s response gain re head velocity (red circles and line) was consistently higher in the head-free condition. The phase of the units response was also unaffected by stimulus frequency, although the VCR head movement phase lag increased with stimulus frequency.

**Fixation of earth-stationary targets during WBR**

In the presence of an earth-stationary visual target, the squirrel monkeys produced smooth head-on-trunk movements during WBR that were usually larger than those produced in the absence of a target. These large smooth head-on-trunk movements reduced the head velocity by $\geq 50\%$ during 0.5-Hz WBR. Units whose rotational responses were related to trunk velocity during the VCR were also related to trunk velocity when the monkey stabilized gaze with smooth head-on-trunk movements.

Figure 9, A and B, shows the effects of target fixation on the WBR responses of a non–eye-movement vestibular neuron whose rotational responses in the absence of a target were related to trunk velocity. The monkey fixated the earth-stationary target (Fig. 9B) had little effect on the unit’s rotational response ($FR_\alpha$). Similar responses were observed at higher stimulus frequencies. Figure 9, C and D, shows the effects of target fixation on the WBR responses of a secondary PV unit whose rotational responses in the absence of a target were related to head velocity. The large head-on-trunk movements that the monkey generated during fixation of the earth-stationary target proportionally reduced this unit’s response. Similar experiments were carried out in 13 other units (8 non–eye-movement...
and 5 eye-movement units). In each case, the relationship of unit responses to head or trunk velocity during smooth head-on-trunk movements in the presence of an earth-stationary target was similar to the relationship during VCR-related head movements in the absence of a target.

DISCUSSION

Passive rotation of the whole body at mid- to high frequencies evokes compensatory head movements in the opposite direction that effectively reduce head velocity in space. This VCR stabilizes the head with respect to the trunk (reviewed in Goldberg 1982; Goldberg and Peterson 1986; Peterson and Wilson et al. 1990; Wilson and Peterson 1981), and is thought to work synergistically with the VOR to stabilize gaze. However, the head movement produced by the VCR causes the vestibular signal transduced by the horizontal semicircular canal during WBR to no longer be an accurate estimate of the movement of the body in space. Because the vestibular system plays an important role in stabilizing body posture and in the perception of the orientation of the body in space, an estimate of the VCR-related head velocity needs to be added to vestibular nerve signals at some point to construct a vestibular estimate of body velocity in space. The results of this study suggest that this necessary addition of VCR-related head movement signals with vestibular signals is reflected in the firing behavior of many secondary vestibular neurons in the vestibular nuclei. Specifically, we found that most of the secondary vestibular neurons whose firing behavior was not related to eye movement control were better related to the velocity of the body in space than to the velocity of the head in space during passive WBR.

We briefly discuss why some units may be more sensitive to VCR head movements than others, why vestibular nerve signals are modified by the VCR at such an early stage of central processing, and how different afferent inputs to the vestibular nuclei may play a role in modifying vestibular signals. Finally, we speculate on the function of the VCR and the nature of its central control.

VCR-related signals on different classes of central vestibular neurons

Neurons in the vestibular nuclei are heterogeneous with respect to their afferent and efferent connections and with
respect to the signals they generate during head movements. All of the units in this study were sensitive to rotation in the plane of the horizontal semicircular canal, and most of them received monosynaptic inputs from the vestibular nerve. However, these horizontal canal units were distributed throughout the vestibular nuclei, and different neurons were likely involved in different vestibular functions.

We segregated vestibular neurons into eye-movement and non–eye-movement classes. There is evidence that each subtype of eye-movement units included in this study contributes to pathways from the vestibular nuclei to extraocular motoneurons (Chen-Huang and McCrea 1999; McCrea et al. 1980, 1987; Scudder and Fuchs 1992; Tomlinson and Robinson 1984). One would expect that vestibular neurons involved in producing rotation of the eye in the head carry vestibular signals that are referenced with respect to the head. On the other hand, non–eye-movement units contribute to pathways from the vestibular nuclei to the thalamus (Büttner and Lang 1979; Magnin and Fuchs 1977), vestibular cortex (Akbarian et al. 1988; Grüsser et al. 1990), and spinal cord (Boyle 1993) that may carry self-motion signals that are not exclusively related to the head. Both eye-movement and non–eye-movement unit classes probably contain units with quite different functions. Therefore it is perhaps not surprising that some eye-movement units were sensitive to VCR head movements and some non–eye-movement units were not.

Transformation of vestibular signals on secondary vestibular neurons to body coordinates

It has often been observed that vestibular signals and head-on-trunk movement signals need to be integrated in the CNS for proper postural control and self-motion perception (Lackner and Dizio 1993; Mergner et al. 1991–1993, 1997; von Holst and Mittelstaedt 1950). However, the observation that vestibular sensory signals were modified at such an early stage of sensory processing is remarkable. Why is it necessary to convert the signals of many non–eye-movement neurons to trunk or body coordinates? One obvious reason could be that many secondary vestibular neurons participate in direct premotor pathways to motoneurons, and they are as important in motor control as they are in sensory processing. The sensory signals they carry have to be modified to fit the behavioral context in which they arise and the requirements of the motor system that they are involved in controlling.

Vestibular reflexes are essential for stabilizing gaze and posture when the whole body is perturbed (WBR in Fig. 10A). The spatial coordinates of the signals carried by VOR pathway do not need to be transformed because eye movements are generated in head coordinates (red in Fig. 10A). However, postural reflexes that help stabilize the head and body may require an estimate of the angular rotation of the body or center of gravity in space (green in Fig. 10A) because the limbs, head, and spinal column are rarely symmetrically distributed about the center of gravity.

One way to construct a central estimate of body motion in space is to add an estimate of the motion of the head with respect to the body (orange pathway in Fig. 10A) to the vestibular and visual estimates of head motion in space (green in Fig. 10A). Perhaps the most convenient place to construct this estimate is the vestibular nuclei. Neurons there have both visual and vestibular estimates of head motion in space and cerebellar inputs that constantly calibrate that estimate based on visual feedback (Lisberger et al. 1984, 1994). Finally, the vestibular nuclei have direct projections to motoneurons that can produce rapid movements of the tail, limbs, and trunk if the center of gravity shifts (Wilson 1988). The appropriate signals for controlling different postural reflexes may vary, depending on the specific mechanical requirements and the muscles and joints involved, which may explain why there was variability in the effect of the VCR on the WBR responses of different vestibular units.

Vestibular signals are also used for perceiving the orientation and movement of both the head and body in space (Horak et al. 1994; Lackner and Dizio 1993; Mergner et al. 1997). Most of the neurons in the thalamus and cortex that receive vestibular inputs are not related to eye movements (Büttner and Lang 1979; Grüsser et al. 1990; Magnin and Fuchs 1977), are sensitive to horizontal WBR, and are also modulated during

\[ \text{A: transformation of signals in the vestibular nuclei during WBR. Passive WBR produces trunk velocity in space. Compensatory head-on-trunk rotation (HT) produced by the VCR reduces head velocity in space (HS). Semicircular canals (SCC) transmit a HS signal (red arrows) that is used to produce an estimate of head velocity in space that is used by reflexes such as the vestibulo-ocular reflex (VOR), which require a head referenced signal. Vestibular nuclei also construct a central estimate of TS by adding a signal related to HT to the vestibular nerve HS signal. This TS signal may be used for central perception of body motion in space and for controlling postural reflexes, including the VCR. B: scheme by which the VCR could be transformed from a closed-loop to an open-loop control system by addition of a HT signal to a HS signal in the vestibular nuclei.} \]
produces vestibular drive (Fig. 10). Closed-loop versus open-loop control of the VCR movement units. VCR neck movement signals observed in most non-eye-proprioceptive inputs are more important for producing the signals observed during the VCR. It seems likely that other, powerful enough to produce the neck movement-related signals observed during the VCR. The results of our study indicate that these neck proprioceptive inputs were, in most cases, not sufficient to prevent the VCR head movement from reducing the unit’s response during head-free WBR (Fig. 10).

In the squirrel monkey most, if not all, secondary vestibular neurons are sensitive to passive neck rotation (Gdowski and McCrea, unpublished observation). A quantitative analysis of the contribution of neck proprioceptive inputs to the rotational responses of different classes of secondary vestibular units will be described in detail elsewhere (Gdowski and McCrea, in preparation). In the context of this study, it is sufficient to note that these neck proprioceptive inputs were, in most cases, not powerful enough to produce the neck movement-related signals observed during the VCR. It seems likely that other, nonproprioceptive inputs are more important for producing the VCR neck movement signals observed in most non-eye-movement units.

Closed-loop versus open-loop control of the VCR

The VCR is often described as a closed-looped reflex (Goldberg and Peterson 1986; Peterson et al. 1988) because the vestibular input produces a reflexive head movement that reduces vestibular drive (Fig. 10B). The feedback loop is inherent because the inputs (perturbations of the trunk or body in space, TS) are transduced by the semicircular canals as movements of the head in space (HS). Vestibulospinal pathways receive primary afferent input and project to cervical motor nuclei that produce VCR head movements. If these pathways receive inputs related to head-on-trunk rotation that sum with vestibular signals (blue line, Fig. 10B), the VCR would operate as an open-loop control system that produces compensatory head movements in response to perturbations of the whole body. Local cervicocervical stretch reflexes could function to prevent overextension of the neck during large-amplitude rotations of the body and help compensate for movements produced by the inertial mass of the head.

The medial vestibulospinal tract projects not only to the upper cervical segments that innervate muscles that produce rotation of the head around the C1–C2 axis but also to its caudal segments that innervate muscles that produce movement of the neck vertebrae and movements of the neck on the trunk (Boyle et al. 1992; Minor et al. 1990; Shinoda et al. 1989). Individual vestibulospinal units send collaterals to several levels of the cervical spinal cord and are thus in a position to contribute to all three types of head movement (Shinoda et al. 1992). Thus the anatomic evidence suggests that the VCR is organized to produce coordinated movements of the head and neck on the trunk. The signals carried by this pathway may be more closely related to the motor coordinates in which the VCR is produced than to vestibular sensory coordinates.

Conclusion

During passive WBR at mid- to high frequencies, the VCR produces a compensatory head-on-trunk movement that affects the processing of vestibular information in the vestibular nuclei. In many vestibular nucleus neurons, sensory signals related to head rotation in space are transformed into signals that are related to rotation of the body in space. This coordinate transformation is presumably important for controlling postural reflexes and constructing a central percept of body orientation and movement in space.

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