

Time Course of Vestibuloocular Reflex Suppression During Gaze Shifts

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Cullen, Kathleen E., Marko Huterer, Danielle A. Braidwood, and Pierre A. Sylvestre. Time course of vestibuloocular reflex suppression during gaze shifts. *J Neurophysiol* 92: 3408–3422, 2004. First published June 22, 2004; doi:10.1152/jn.01156.2003. Although numerous investigations have probed the status of the vestibuloocular (VOR) during gaze shifts, its exact status remains strangely elusive. The goal of the present study was to precisely evaluate the dynamics of VOR suppression immediately before, throughout, and just after gaze shifts. A torque motor was used to apply rapid (100°/s), short-duration (20–30 ms) horizontal head perturbations in three Rhesus monkeys. The status of the VOR elicited by this transient head perturbation was first compared during 15, 40, and 60° gaze shifts. The level of VOR suppression just after gaze-shift onset (40 ms) increased with gaze-shift amplitude in two monkeys, approaching values of 80 and 35%. In contrast, in the third monkey, the VOR was not significantly attenuated for all gaze-shift amplitudes. The time course of VOR attenuation was then studied in greater detail for all three monkeys by imposing the same short-duration head perturbations 40, 100, and 150 ms after the onset of 60° gaze shifts. Overall we found a consistent trend, in which VOR suppression was maximal early in the gaze shift and progressively recovered to reach normal values near gaze-shift end. However, the high variability across subjects prevented establishing a unifying description of the absolute level and time course of VOR suppression during gaze shifts. We propose that differences in behavioral strategies may account, at least in part, for these differences between subjects.

INTRODUCTION

The vestibuloocular reflex (VOR) operates to stabilize the visual world on our retina by producing compensatory eye movements of equal and opposite amplitudes to the head movements that we make or experience during our daily activities. Without a functional VOR, clear vision would be highly compromised when our head is moving, as for example in a car or when walking. However, in certain behavioral situations, the eye movements generated by the VOR can be counterproductive. For example, primates frequently use a combination of rapid eye and head movements (gaze shifts) to voluntarily redirect their visual axis in space. During such combined eye-head gaze shifts, the eye-movement command produced by the VOR would be counterproductive; an intact drive from the VOR pathway would oppose that from the gaze-shift pathway and generate an eye-movement command in the direction opposite to that of the intended shift in gaze.

Although numerous groups have probed the VOR during gaze shifts, its exact status remains controversial. On the one hand, it had been originally proposed by Bizzi and colleagues that the VOR remains fully functional throughout a gaze shift (Bizzi et al. 1971; Dichgans et al. 1973; Morasso et al. 1973).

Indeed, more recent experiments have provided some additional support for this idea by showing that the VOR can be fully operational (Freedman et al. 1998; Guitton and Volle 1987). On the other hand, most more-recent studies have shown that the gain of the VOR is attenuated during gaze shifts (Guitton and Volle 1987; Laurutis and Robinson 1986; Péliesson and Prablanc 1986; Péliesson et al. 1988; Tabak et al. 1996; Tomlinson and Bahra 1986; Tomlinson 1990). Furthermore, recordings from position-vestibular-pause (PVP) neurons, which are believed to constitute most of the intermediate leg of the direct VOR pathway (Cullen and McCrea 1993; McCrea et al. 1987; Scudder and Fuchs 1992), show that the head-velocity signal they carry is attenuated during large gaze shifts in a manner that mirrors the behavioral results described in the preceding text (McCrea and Gdowski 2003; Roy and Cullen 1998, 2002). Thus these neurophysiological studies are also consistent with the proposal that the VOR is attenuated during gaze shifts.

The conflicting observations described in the preceding text could result from differences in the methodological approaches that have been utilized. For example, perturbation as diverse as electromagnetic clutches to brake the head (Fuller et al. 1983; Guitton and Volle 1987; Guitton et al. 1984), torque motors (Freedman et al. 1998; Tabak et al. 1996; Tomlinson and Bahra 1986) or hammers (Laurutis and Robinson 1986) to “bump” the head, or whole-body rotations (Pelisson and Prablanc 1986; Pelisson et al. 1988) have been employed. Moreover, the temporal resolution of the applied perturbations has varied dramatically across studies. None of the duration of the perturbations, their frequency content, or the time at which they were applied can be easily compared. Such differences in timing could have important implications, given that the status of the VOR most likely has time-varying dynamics during gaze shifts. For instance, it has been proposed that the VOR is completely disconnected (gain = 0) in an “all-or-nothing manner” during gaze shifts (Laurutis and Robinson 1986), the magnitude of VOR suppression decays exponentially during gaze shifts (Péliesson et al. 1988), the VOR gain varies linearly with dynamic gaze error during gaze shifts (Lefèvre et al. 1992), and VOR suppression and subsequent recovery displays a high degree of inter-subject and task-specific variability (Guitton and Volle 1987).

To develop realistic models of gaze control, it is important to evaluate the dynamics of VOR suppression throughout gaze shifts (see recent review by Sparks 1999). Only a single published study has attempted to systematically quantify the time-varying dynamics of the VOR during gaze shifts in humans (Tabak et al. 1996). These investigators probed the

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status of the VOR by applying head oscillations (10–14 Hz) and torque pulses to a helmet during gaze shifts. It was argued that the magnitude of VOR suppression decays exponentially during large gaze shifts and that in the wake of gaze shifts, the VOR gain is consistently elevated to a “supra-normal value,” that is, a gain significantly greater than that measured just prior to gaze-shift onset. However, because of several technical limitations in this study, it was not possible to precisely determine the timing of VOR suppression. First, as noted by these investigators, the analysis technique applied to oscillations blurred the temporal resolution of VOR gain changes. Second, the head perturbations were of long duration (>200 ms) and were applied beginning >100 ms before gaze-shift onset. Accordingly, it is likely that feedback pathways involved in gaze-shift control, as well as the classic VOR pathways, contributed to the observed responses. Finally, head rotation was measured with a search coil mounted within a bite bar, and any slippage would have resulted in an erroneous characterization of the induced responses.

Here our primary goal was to evaluate the time course and dynamic characteristics of VOR suppression throughout gaze shifts. The time course of VOR attenuation was probed by applying very short-duration perturbations to the head (20–30 ms) at precise time intervals before, during, and immediately after gaze shifts. Accurate measurement of head motion was ensured by firmly securing a search coil to the monkey’s skull. In addition, analysis was limited to a very small time window not much longer than the latency of the direct VOR pathways to prevent feedback loop effects from biasing our interpretation. Our results demonstrate that the dynamics of the VOR gain attenuation during gaze shifts can vary between animals but that the VOR gain is consistently restored to normal at gaze-shift end.

METHODS

Surgical preparation and data acquisition

Three healthy Macaque monkeys (*Macaca mulatta*) were prepared for chronic behavioral experiments. All procedures were approved by the McGill University Animal Care Committee and were in compliance with the guidelines of the Canadian Council on Animal Care. The methods for surgical preparation of the monkeys, the experimental setup, and the techniques of data acquisition were identical to those recently described (Huterer and Cullen 2002; Sylvestre and Cullen 1999). Briefly, under general anesthesia, a dental acrylic implant was attached to each animal’s skull using stainless steel screws. A stainless steel post, to which the head coil and torque motor were rigidly coupled, was embedded within the implant. An eye coil (18–19 mm diam, 3 loops of Teflon-coated stainless steel wire) was implanted behind the conjunctiva.

During the experiment, the monkeys were comfortably seated in a primate chair. Gaze and head movements were recorded inside a magnetic field (CNC Engineering), using the magnetic search coil technique (Fuchs and Robinson 1966). The head coil was mounted within a clear plastic mold located within 2 cm of the eye coil. Timing of behavioral paradigms, target motion, torque motor triggering, and data storage were controlled by a QNX-based real-time data-acquisition system (REX) (Hayes et al. 1982). Gaze and head position signals were low-pass filtered at 250 Hz (8 pole Bessel filter), sampled at 1,000 Hz, and stored on a hard drive for later analysis. Eye position was calculated from the difference between recorded gaze- and head-position signals.

Behavioral paradigms

The monkeys were allowed complete freedom of head motion (in the pitch, roll, and yaw planes of head movement). Passive horizontal head perturbations were generated using a torque motor (Animatics No. 2320), which was securely coupled, through precision universal joints, to a specially designed lightweight aluminum head-holder. A spring system offloaded the weight of the apparatus. Monkeys were trained to track a visual target (HeNe laser, projected onto a cylindrical screen 60 cm from the center of their head) for a juice reward. Horizontal and vertical gaze shifts of variable magnitude were elicited by having the monkeys fixate a stationary target that was then stepped across the horizontal (amplitudes: 15, 40 and 60°) or vertical (amplitude: 40°) plane. To minimize the occurrence of anticipatory gaze shifts, the interval of fixation prior to target stepping was randomly varied between 800 and 1,500 ms.

Passive horizontal head perturbations

High-frequency, passive horizontal head perturbations were applied at intervals before, during, and immediately after horizontal gaze shifts. Perturbations were identical to the *very short* perturbation applied by Huterer and Cullen (2002). They had a duration of 20–30 ms, a peak head velocity of $\sim 100^\circ/\text{s}$, and a peak acceleration of $10,000\text{--}20,000^\circ/\text{s}^2$ and generated total head displacements $\sim 2\text{--}4^\circ$. Figure 1 shows the gaze, eye, and head profiles (position and velocity) for representative 15° (Fig. 1A), 40° (B), and 60° (C) gaze shifts; the shaded areas indicate the different intervals over which head perturbations were applied in this study.

For 15 and 40° horizontal gaze shifts the onset of head perturbation was programmed to occur at one of three different intervals as is illustrated in Fig. 1, A and B: ~ 30 ms prior to gaze-shift onset, 40 ms after gaze-shift initiation, and < 50 ms after target acquisition, during which time gaze was stable (gaze velocity: $< 20^\circ/\text{s}$), but the head was often still moving. For 60° horizontal gaze shifts, the onset of head perturbation was timed to occur at one of five different intervals as is illustrated in Fig. 1C. In addition to the three perturbation intervals listed in the preceding text (-30 , 40, +50 ms), the head was also perturbed 100 and 150 ms after gaze-shift initiation. Note, to program the motor to perturb the head prior to gaze-shift initiation, we first determined, for each monkey, the mean latency from target stepping to gaze-shift onset ($\text{latency}_{\text{mean}}$, in milliseconds). By triggering motor perturbation onset after a fixed delay from target stepping (e.g., $\text{latency}_{\text{mean}} - 30$ ms), the head could be perturbed prior to gaze-shift initiation. In contrast, perturbations applied > 40 ms after gaze-shift onset were triggered after a fixed latency from when gaze velocity exceeded a threshold value ($20^\circ/\text{s}$). The head was perturbed in the direction of the ongoing gaze shift (“with” direction) or in the direction opposite to the ongoing gaze shift (“against” direction). Passive horizontal head perturbations were also applied during 40° vertical gaze shifts, 40 ms after vertical gaze-shift onset. For vertical gaze shifts, only rightward horizontal head perturbations were applied.

We refer to trials during which the head was perturbed as *perturbed gaze shifts*. During a given experimental session, monkeys made gaze shifts of each amplitude. However, perturbations were applied for only one condition (e.g., 40° gaze shifts, perturbation “with,” 40 ms after gaze-shift initiation). For horizontal and vertical gaze shifts, head perturbations were randomly applied in 20–25% of the trials in which a gaze shift of a given amplitude and direction was elicited. Thus the remaining 75–80% of the gaze shifts of this amplitude and direction were unperturbed and are referred to as *control gaze shifts*. For each perturbation condition, as many as 70, but never fewer than 15, trials were collected. By comparing control gaze shifts with perturbed gaze shifts, we were able to isolate the VOR evoked by the perturbation during the gaze shift.

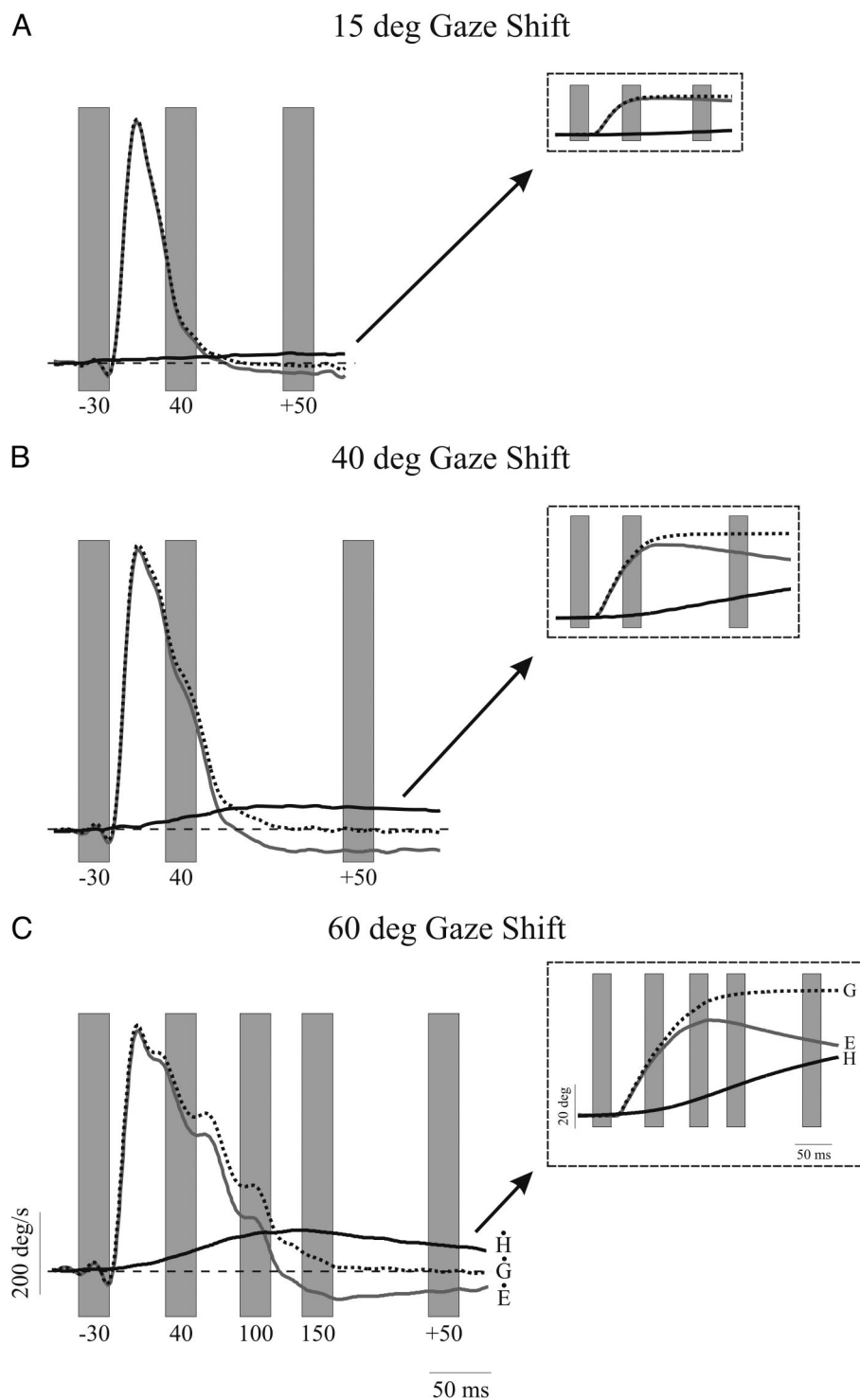


FIG. 1. A–C: velocity profiles of eye (gray curve), head (black curve), and gaze (dotted curve) movements during representative 15, 40, and 60° control gaze shifts. Insets: corresponding position traces. The shaded areas indicate the intervals over which head perturbations were applied in this study. Upward directed traces are in the rightward direction. Dashed horizontal lines indicate velocities of 0°/s. H and \dot{H} , horizontal head position and velocity; E and \dot{E} , horizontal eye position and velocity; G and \dot{G} , horizontal gaze position and velocity.

During each experimental session, passive horizontal head perturbations were also randomly applied while the monkey stabilized gaze by actively fixating an earth stationary target (hence referred to as *control perturbations*). Control perturbations were applied while the monkey's head was stationary in space to evaluate the baseline VOR response on each day. Within each experimental session, as many as 40, but never fewer than 20, trials were collected. By comparing the VOR response to head perturbations applied during gaze shifts with the VOR response to control perturbations, we were able to investigate and characterize the dynamics of VOR suppression.

Data analysis

Horizontal and vertical gaze-, eye-, and head-position data were imported into the Matlab (The MathWorks) programming environment for analysis. These position signals were digitally filtered using a 51st-order finite-impulse-response (FIR) filter with a cutoff frequency of 125 Hz and differentiated to produce velocity and acceleration traces. A custom algorithm calculated the onset (T_{onset}) and endpoint (T_{end}) of each gaze shift. T_{onset} was determined using a gaze velocity criterion of 20°/s. To evaluate the endpoint of a gaze shift, we

searched for the first interval >20 ms in duration for which gaze velocity was consistently $<20^\circ/\text{s}$; T_{end} was defined as the first point of that interval. The amplitude (in degrees) and duration (in milliseconds) of each gaze shift was measured. Student's t -tests were then used to compare gaze-shift amplitudes and durations for perturbed versus control gaze shifts. Within each experimental session, average gaze, eye, and head profiles (position and velocity) were compiled for each condition.

ANALYZING PERTURBATIONS DURING GAZE STABILIZATION. The gain of the control VOR response was determined as described by Huterer and Cullen (2002). For this analysis, we used the VOR evoked by control perturbations (i.e., those that were applied during gaze stabilization, see preceding text). Briefly, for each trial during which the head was perturbed, the gain was calculated as the absolute value of the peak eye velocity divided by the peak head velocity. The analysis was constrained to trials in which peak eye velocity occurred in a window 7 ms after peak head velocity. Typically, peak eye velocity lagged peak head velocity by ~ 5 –6 ms in agreement with our previous estimate of VOR latency (Huterer and Cullen 2002).

ANALYZING PERTURBED GAZE SHIFTS. Passive horizontal head perturbations applied during a horizontal gaze shift occurred while gaze was already rapidly moving, often at velocities $>500^\circ/\text{s}$. Furthermore, for large-amplitude gaze shifts, the head was most often already moving (with velocity $>100^\circ/\text{s}$) prior to head perturbation. Thus to determine the components of the gaze-, eye-, and head-velocity profiles that resulted from perturbations applied during horizontal gaze shifts, we used a technique similar to the matching method employed by Tabak et al. (1996). For every individual perturbed gaze shift, we searched the set of unperturbed control gaze shifts for the trial for which the gaze velocity profile best matched that of the perturbed trial over an interval which began 10 ms prior to gaze-shift onset and ended 2–3 ms prior to perturbation onset. The “best-match” control gaze shift was obtained using a least-squared algorithm and was visually verified by the experimenter. The control gaze shift was then subtracted from the perturbed gaze shift to provide an estimate of the change in head velocity produced by the perturbation ($\Delta\dot{H}$) as well as the resultant eye and gaze velocities ($\Delta\dot{E}$ and $\Delta\dot{G}$, respectively) evoked by the VOR. The VOR gain was then calculated by dividing peak $\Delta\dot{E}$ by peak $\Delta\dot{H}$, similar to the method used for control perturbations. To verify the robustness of this approach, we also subtracted the second best match trial for a subset of trials in each condition and confirmed that the results were comparable.

Use of the matching method was only required when analyzing the response to head perturbations applied during horizontal gaze shifts. In contrast, transient head perturbations which were applied prior to horizontal gaze-shift onset, shortly after horizontal gaze-shift target acquisition, and during vertical gaze shifts, occurred while horizontal gaze velocity was essentially stable. Accordingly, the VOR gain could be calculated as was done for control perturbations (see preceding text).

CALCULATING VOR SUPPRESSION. The mean control VOR gain was calculated for each day of experimentation (mean \pm SE). Student's t -tests were used to determine whether the VOR gain in response to perturbations applied before, during, and immediately after gaze shifts was significantly different from the mean control VOR gain. A repeated-measures linear regression analysis was used to determine whether the percent attenuation of the VOR during a specific perturbation interval varied as a function of gaze-shift amplitude and the interval during which the gaze shift was perturbed.

RESULTS

The VOR responses evoked by short-duration, passive horizontal head perturbations applied during fixation and at intervals before, during, and immediately after gaze shifts of dif-

ferent amplitudes were compared. Figure 2 shows representative individual head-velocity profiles in response to rightward and leftward head perturbations that were applied during fixation of an earth stationary target with the head stationary in space. The shaded areas indicate the duration of each perturbation (between 20 and 30 ms, after which time head velocity returned to $\sim 0^\circ/\text{s}$). As shown in Huterer and Cullen (2002), this method resulted in very stereotyped head-velocity profiles. The velocity profile of the head perturbation had frequency content approaching 80 Hz, peak head velocity $\sim 100^\circ/\text{s}$, and peak accelerations between 10,000 and 20,000 $^\circ/\text{s}^2$ (see Fig. 9 in Huterer and Cullen 2002).

During large-amplitude gaze shifts, all three monkeys utilized coordinated movements of both their eyes and their head. Figure 3 shows example gaze-, eye-, and head-velocity profiles generated during 60° horizontal gaze shifts (gray traces, $n = 80$ individual trials; black traces, averages; A–C, monkeys B, C, and J, respectively). While each monkey utilized a slightly different behavioral strategy, with monkey C typically generating faster eye movements and smaller head movements than monkeys B and J (Table 1), all three subjects generated significant head movements. In general, similar observations were made for smaller-amplitude gaze shifts. Note that monkey C tended to undershoot the target. However, a small catch-up movement was made several milliseconds after the original gaze shift, indicating that the monkey was indeed attentive.

Figure 4 illustrates the head-velocity trajectories that were evoked by passive horizontal head perturbations (shown in Fig. 2) which were applied 40 ms after the onset of 60° horizontal gaze shifts (shown in Fig. 3). Perturbations resulted in very stereotyped responses for all three monkeys. This is illustrated in Fig. 4 where the perturbations were applied in the direction of (“with”) the head motion. Similarly stereotyped responses were evoked for perturbations in the direction opposite to (“against”) the head motion. Thus regardless of the direction, the perturbation was easily discernible relative to the initial voluntary head motion and the head continued to move after the perturbation.

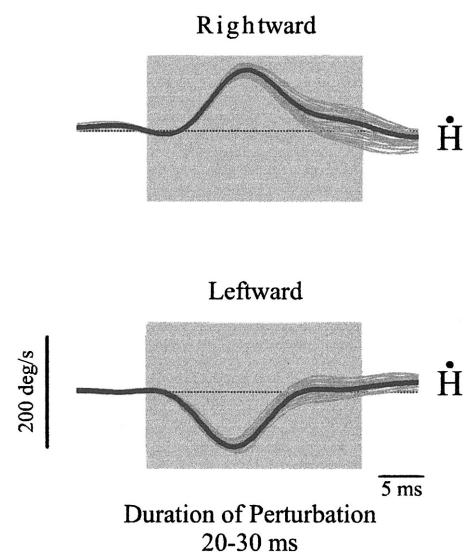


FIG. 2. Representative head-velocity profiles in response to rightward and leftward control head perturbations applied in monkey C. The shaded interval indicates the short-duration of head perturbation (between 20 and 30 ms), after which head velocity returns to $\sim 0^\circ/\text{s}$.

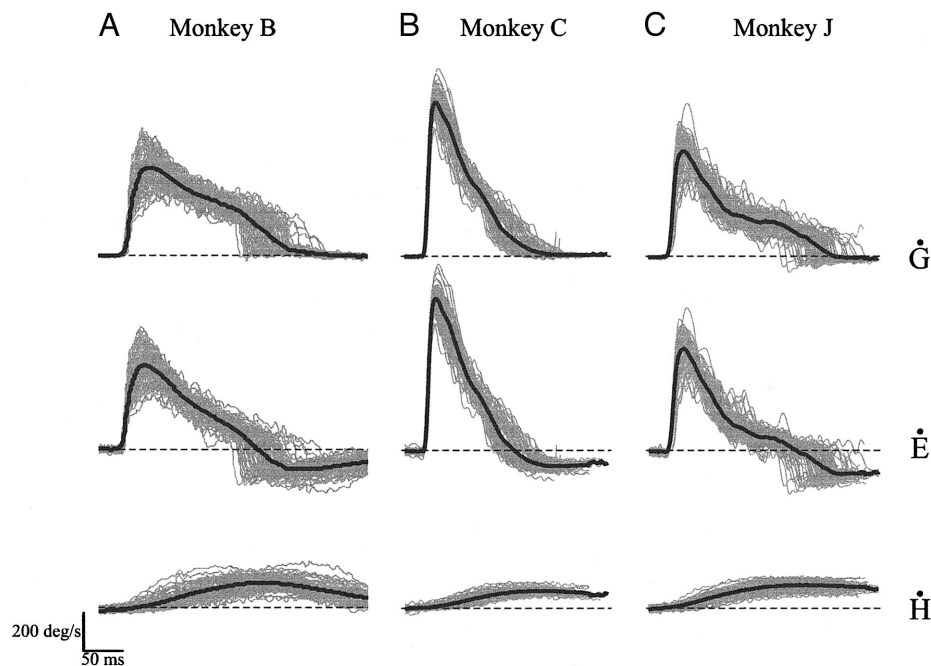


FIG. 3. Representative velocity profiles during 60° gaze shifts for *monkey B* (A), *monkey C* (B), and *monkey J* (C). Gray curves are individual trials ($n = 80$), and thick black curves are averages.

VOR attenuation during gaze shifts

To characterize the time course of VOR attenuation during horizontal gaze shifts, we isolated the gaze, eye, and head signals associated with the response to the imposed head perturbation. To do so, we used a technique similar to the matching method employed by Tabak and colleagues (see METHODS). Representative pairs of matched perturbed and control gaze shifts are shown in Fig. 5 for all three monkeys. Gaze-, eye-, and head-velocity profiles (gray traces, Fig. 5, A–C, respectively) are plotted for 60° horizontal gaze shifts, perturbed with the direction of gaze, 40 ms after gaze-shift onset. Velocity profiles for the control gaze shift that best matched it over the matching interval are superimposed for each example (dashed traces). After the onset of the head perturbation, which began 3 ms after the matching interval ended, the velocity traces for the perturbed and control gaze shift began to diverge. By subtracting the control gaze shift from the perturbed gaze shift, the response to the passive head perturbation was isolated. Black traces represent the perturbation-induced changes in head (Fig. 5A), eye (B), and gaze (C) velocity.

In Fig. 6, $\Delta\dot{G}$, $\Delta\dot{E}$, and $\Delta\dot{H}$ profiles from Fig. 5 are replotted on the same axis for each monkey; the $\Delta\dot{H}$ trace has been inverted to facilitate comparison between head velocity and

induced eye velocity. Prior to head perturbation, the isolated $\Delta\dot{G}$, $\Delta\dot{E}$, and $-\Delta\dot{H}$ traces approximate 0°/s, which confirms that the control and perturbed trials were comparable over the matching interval. After the onset of the head perturbation (illustrated by the arrows in Fig. 6A), the eye began to counter-rotate after a delay of ~5–6 ms, equivalent to our previous estimate of VOR latency during fixation (Huterer and Cullen 2002). For comparison, Fig. 6B shows representative gaze-, eye-, and head-velocity profiles in response to a control perturbation applied while the monkey was holding its gaze stable relative to space. The head-velocity profiles induced by control perturbations (Fig. 6B) closely resemble the head-velocity traces isolated from perturbed gaze shifts (Fig. 6A) and were comparable in duration (20–30 ms) and peak velocity (~100°/s). However, for *monkeys B* and *C*, the peak-to-peak gain of the compensatory eye movement induced by the applied head motion in the control condition was greater than that induced by head perturbation 40 ms into a 60° gaze shift. In contrast, for *monkey J*, there was little difference in these two conditions. For the head perturbation applied during these example gaze shifts, the peak gain of the compensatory eye movement was 0.62 for *monkey B*, 0.57 for *monkey C*, and 0.82 for *monkey J*. In contrast, control gains in response to these high acceleration perturbations were greater than unity for most animals (see also Huterer and Cullen 2002).

TABLE 1. Gaze shift metrics (60° target)

	Head			Eye			<i>n</i>
	% Cont.	Disp.	Peak	% Cont.	Disp.	Peak	
<i>Monkey B</i>	51 ± 13	30.3 ± 10.8	177 ± 54	49 ± 13	29.7 ± 6.0	459 ± 98	262
<i>Monkey C</i>	18 ± 7	9.5 ± 4.2	100 ± 21	82 ± 7	42.0 ± 3.9	774 ± 70	213
<i>Monkey J</i>	34 ± 8	20.4 ± 5.3	144 ± 29	66 ± 9	39.3 ± 5.0	600 ± 81	324
Average	34 ± 16	20.1 ± 10.4	140 ± 39	66 ± 16	37.0 ± 6.5	611 ± 158	799

Values are means ± SE. % Cont., percent contribution to the gaze shift; Disp., total displacement measured at gaze shift end; Peak, peak velocity; *n*, number of gaze shifts.

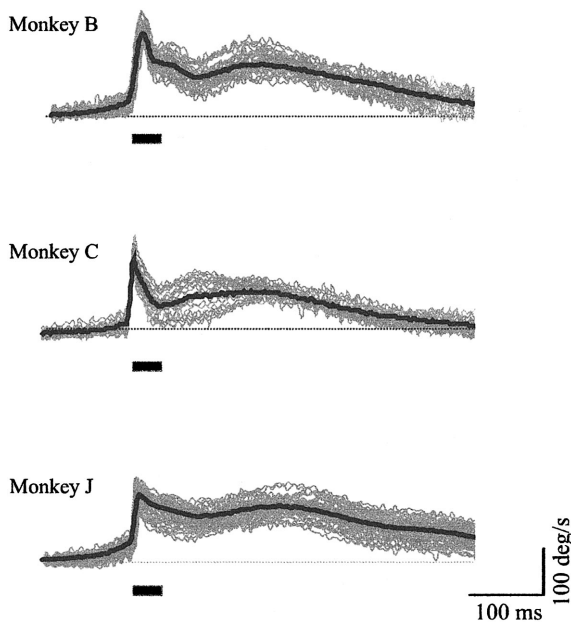


FIG. 4. Head-velocity trajectories when passive horizontal head perturbations were applied 40 ms after the onset of 60° gaze shifts. Average head velocities are plotted in black, the individual trials that contribute to the average are plotted in gray. Perturbation applied in the direction of the ongoing gaze shift (i.e., “with”) for monkey B (top), monkey C (middle), and monkey J (bottom). The intervals over which the perturbations were applied are denoted by the horizontal bars.

By comparing the gain of eye movements induced by head perturbations during gaze shifts with the gain of eye movements evoked by the control perturbations, we calculated the percent attenuation of VOR gain using the equation

$$\% \text{Atten} = [1 - (\text{Gain}_{\text{perturbed trial}}) / (\text{Mean gain}_{\text{control perturbations}})] \times 100 \quad (1)$$

For example, for the data shown in Fig. 6A, the %Atten was 46, 68, and 18% for monkeys B, C, and J, respectively. The mean percent attenuation of the VOR was calculated for each gaze-shift amplitude, perturbation epoch, and perturbation condition across individual trials. In the following text, we consider each perturbation epoch in sequence, beginning with perturbations applied prior to gaze-shift onset.

PERTURBATIONS APPLIED ~30 MS PRIOR TO HORIZONTAL GAZE SHIFTS. The dynamics of the VOR were first characterized in response to perturbations applied 30 ms prior to horizontal gaze shifts. In general, the gain of the VOR response to head perturbations in this interval did not differ from the gain of the VOR induced by control perturbations. This is clearly illustrated by the histograms in Fig. 7, A–C, which show the percent attenuation of the VOR across all gaze-shift magnitudes tested for monkeys B, C, and J, respectively. The response to perturbations applied with versus against the gaze shift are plotted separately (□ vs. ■, respectively). Regardless of the amplitude of the gaze shift or direction of head perturbation, the VOR was not significantly suppressed ($P > 0.05$), with two exceptions for 60° gaze shifts ($P < 0.05$).

PERTURBATIONS 40 MS AFTER HORIZONTAL GAZE-SHIFT ONSET. In contrast to passive head perturbations applied prior to gaze-shift onset, perturbations delivered 40 ms after gaze-shift initiation

occur when gaze and the eyes are moving rapidly, often in excess of 500°/s. To characterize the VOR evoked during this interval, perturbations were applied during 15, 40, and 60° gaze shifts. Histograms quantifying the attenuation of the VOR 40 ms after gaze-shift onset, for all gaze-shift magnitudes and perturbation directions tested, are plotted in Fig. 8. In general, attenuation reached significant levels in monkeys B and C but not in monkey J. For monkey C (Fig. 8B), the gain of the VOR 40 ms into 60° gaze shifts was dramatically attenuated, with the maximum percent attenuation approaching 80%. As gaze-shift amplitude decreased, VOR attenuation also decreased such that passive head perturbations applied 40 ms into 15° gaze shifts resulted in nonsignificant attenuation. In addition, for this monkey, the magnitude of VOR suppression was greater in response to perturbations of the head against the concurrent gaze shift than for perturbations applied in the same direction as (with) the ongoing gaze shift ($P < 0.01$, compare ■ vs. □). Monkey B (Fig. 8A) exhibited attenuation that was intermediate between monkeys C and J; attenuation was generally significant and was greater for 60 than 15° gaze shifts, but the levels of attenuation were not as striking as those seen in monkey C. Finally, for monkey J, the VOR was only slightly attenuated (between 4 and 16%) across all gaze-shift magnitudes tested, but attenuation never reached significance (Fig. 8C). Interestingly, the VOR suppression in monkeys B and J did not consistently differ for perturbations applied with versus against the ongoing gaze redirection, as was the case for monkey C.

PERTURBATIONS 100 AND 150 MS AFTER HORIZONTAL GAZE-SHIFT ONSET. For horizontal gaze shifts 60° in amplitude, the head was perturbed during two additional intra-gaze-shift intervals, beginning 100 and 150 ms after gaze-shift onset. Note that perturbations 100 and 150 ms after gaze-shift onset were always applied before gaze-shift completion, where gaze velocity remained $>20^\circ/\text{s}$. In general, greater attenuation was observed during both intervals for monkeys B and C than for monkey J. In monkey B (Fig. 9A), the VOR was significantly attenuated in both the with (38%) and against (41%) directions when the perturbation was applied 100 ms after gaze-shift onset. The VOR elicited by perturbations applied 150 ms after gaze-shift onset was only attenuated in the against direction (18%). In monkey C, the magnitude of intra-gaze-shift VOR suppression was highly dependent on the direction of the head perturbation (Fig. 9B). When perturbations were applied in the against direction 100 and 150 ms into the gaze shift, the VOR was significantly attenuated by 55 and 44%, respectively. In contrast, when perturbations were applied in the with direction, attenuation did not reach significant levels during either interval. Thus consistent with the results of perturbing 40 ms after gaze-shift onset (see Fig. 8B), the magnitude of VOR attenuation was greater in response to perturbations against than with the gaze shift ($P < 0.05$, compare ■ with □). In monkey J, VOR responses to head perturbations applied 100 ms after gaze-shift initiation were less attenuated for both perturbation directions (on average between 15 and 17%: Fig. 9C) when compared with either monkeys B or C. Furthermore, head perturbations timed to occur 150 ms after gaze-shift onset elicited a VOR that was not significantly attenuated, regardless of the perturbation direction.

PERTURBATIONS <50 MS AFTER GAZE-SHIFT END. The final epoch over which we characterized the VOR response to head pertur-

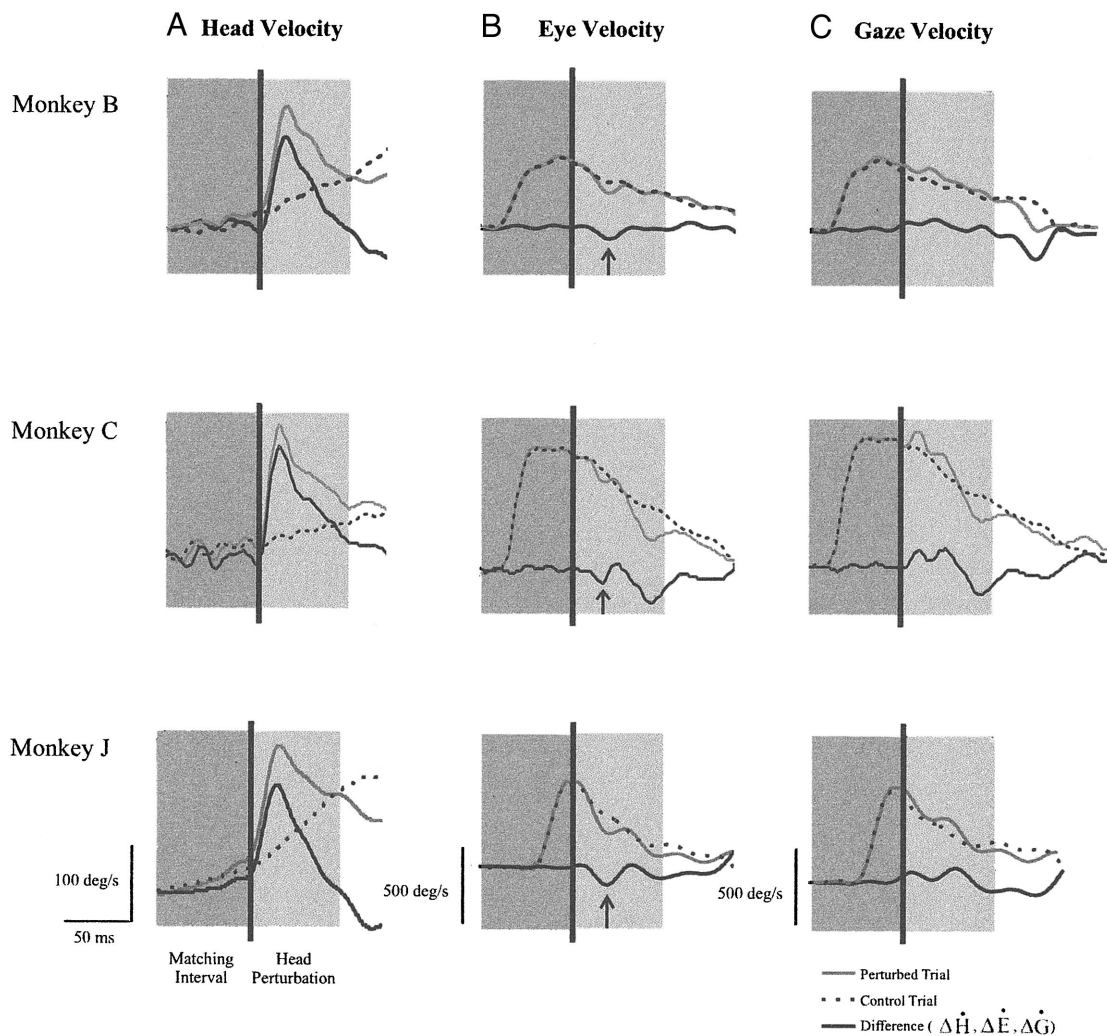


FIG. 5. Head (A)-, eye (B)-, and gaze (C)-velocity profiles are plotted for a 60° gaze shift, perturbed in the with direction 40 ms after gaze-shift onset. Velocity profiles for the control gaze shift that best matched the perturbed gaze shift over the matching interval are superimposed (dashed lines). The differences between control and perturbed velocity profiles (black curves, $\Delta\dot{H}$, $\Delta\dot{E}$, and $\Delta\dot{G}$; A–C, respectively) provide the isolated response to the head perturbation. The eye response to the perturbation is indicated by the arrow in B.

bations was immediately after the termination of the gaze shift, where gaze had acquired target, but the eye and head often continued to move in opposite directions. When the head was perturbed <50 ms after gaze-shift target acquisition, the percent attenuation of VOR gain was near 0%. The histograms in Fig. 10, A–C, show the responses of *monkeys B, C, and J*, respectively. In general, the VOR response was not consistently attenuated in comparison to that elicited by control perturbations. We observed significant ($P < 0.05$) attenuation only in three isolated cases: for one condition in *monkey B* and two in *monkey C*, when perturbations were applied with the ongoing gaze shifts. Moreover, surprisingly *monkey B* showed a small but significant enhancement of the VOR when perturbations were applied immediately after larger (i.e., 40 and 60°) gaze shifts.

Time course of VOR suppression for 60° gaze shifts

To characterize the time course of VOR suppression, we plotted the percent attenuation of VOR gain versus time from gaze-shift onset for 60° gaze shifts (Fig. 11); included for

comparison is the percent attenuation of VOR gain 30 ms before gaze-shift onset, typically $\sim 0\%$. The results for perturbations with and against are plotted separately. In each monkey, the attenuation of VOR gain generally decreased with time from gaze-shift onset. First looking at *monkey C*, for whom the trend was most clear, the gain of the VOR was dramatically attenuated (81 and 35% for perturbations against and with, respectively) 40 ms after gaze-shift onset. The attenuation of VOR gain decreased with time from gaze-shift onset ($P < 0.05$) such that in the terminal interval after gaze-shift completion, the VOR was no longer suppressed. In *monkey B*, attenuation peaked later than in *monkey C*, at 100 ms after gaze-shift onset, and then similarly decreased with time. In *monkey J*, the attenuation of the VOR generally decreased with time from gaze-shift onset; however, the attenuation only reached statistical significance in one condition. Note that VOR suppression peaks earliest for *monkey C*. This may be due to the relatively faster gaze movement dynamics observed in *monkey C* (see DISCUSSION). Nevertheless, the general trend is similar for all three monkeys.

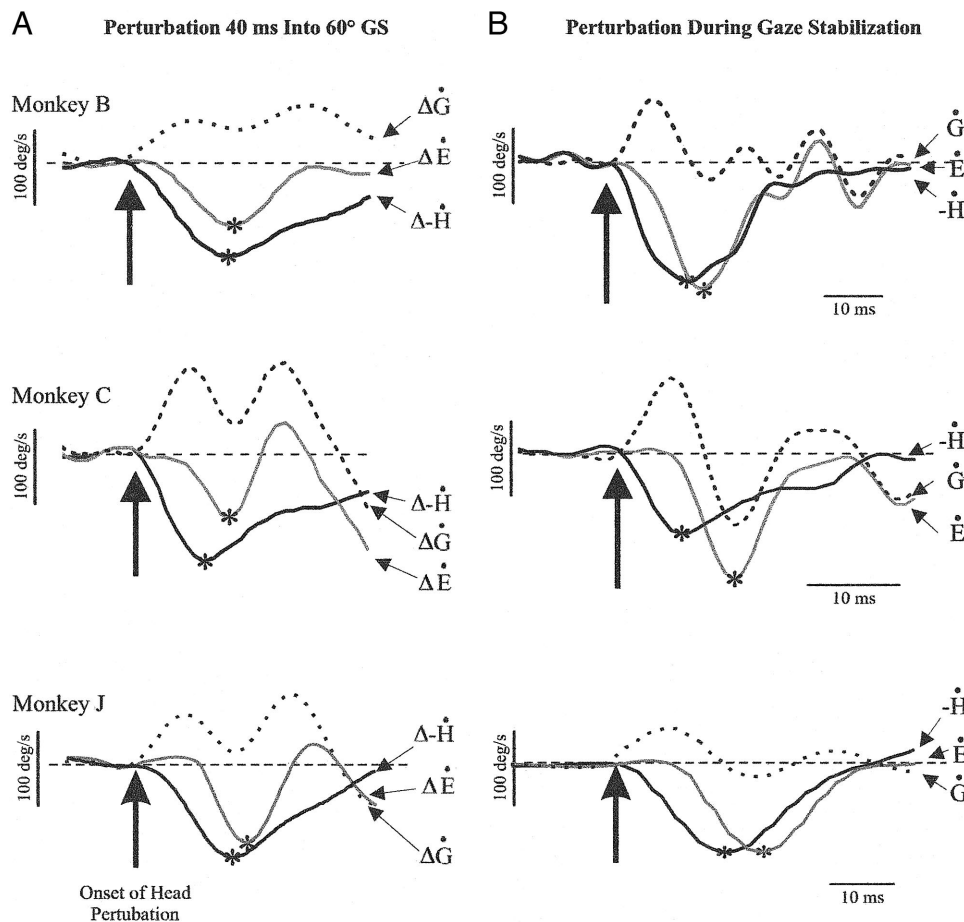


FIG. 6. *A*: representative $\Delta\dot{G}$, $\Delta\dot{E}$, and $\Delta\dot{H}$ profiles from Fig. 5 are replotted on the same axis; the $\Delta\dot{H}$ profile has been inverted to facilitate comparison between head velocity and induced eye velocity. \uparrow , head-perturbation onset, after which the eye began to counter-rotate with a latency of ~ 5 – 6 ms. The gain of the evoked vestibuloocular reflex (VOR) is movement is 0.62 for monkey *B*, 0.57 for monkey *C*, and 0.82 for monkey *J*. *B*: control head perturbations applied during gaze stabilization. *, peak eye and head movements. Mean gain_{control perturbations} is 1.2 for monkey *B*, 1.8 for monkey *C*, and 1.0 for monkey *J*. The values for the control gains for monkeys *C* and *J* were consistent with those reported in Huterer and Cullen (2002).

Influence of head perturbation on gaze-shift amplitude and duration

In addition to evaluating the gain and percent attenuation of the VOR at different epochs during horizontal gaze shifts, we determined whether passive head perturbations affected gaze-shift amplitude (in degrees) and gaze-shift duration (in milliseconds). Recall that the total head displacement resulting from these perturbations was ~ 2 – 4° (see METHODS). Transient head perturbations applied before or during 15, 40, and 60° gaze shifts in monkeys *B* and *J* did not have a consistent effect on gaze-shift amplitude. For monkey *C*, perturbations in the against direction for all gaze-shift amplitudes and perturbations in the with direction for 60° gaze shifts typically influenced amplitude ($P < 0.05$). However, the direction of the effect differed for perturbations that occurred before (decrease) versus during (increase) the gaze shift. Moreover, for all monkeys, regardless of the direction of head perturbation (with or against), perturbed gaze shifts were generally of longer duration compared with unperturbed gaze shifts ($P < 0.001$). The increase in duration was less pronounced when perturbations were applied immediately prior to gaze shifts (monkey *B*: 4 ± 4 and 26 ± 4 ms; monkey *C*: 41 ± 21 and 47 ± 22 ms; monkey *J*: 35 ± 14 and 41 ± 19 ms, with and against directions, respectively), than when perturbations were applied during gaze shifts (monkey *B*: 7 ± 3 and 34 ± 4 ms; monkey *C*: 69 ± 17 and 62 ± 23 ms; monkey *J*: 41 ± 17 and 55 ± 23 ms, with and against directions, respectively).

Horizontal head perturbations applied during vertical gaze shifts

To determine whether intra-gaze-shift VOR suppression was specific to the axis of gaze redirection, passive horizontal head perturbations were also applied 40 ms after the onset of 40° vertical gaze shifts. We observed that head perturbations applied in a direction orthogonal to the axis of gaze redirection elicited a robust VOR that was negligibly attenuated in all animals tested. These results are illustrated in Fig. 12, in which histograms show a near 0% attenuation of the horizontal VOR. Thus our results are in agreement with those of Tomlinson and Bahra (1986), who also found no evidence for intra-gaze-shift VOR suppression in rhesus monkeys under similar conditions; the VOR consistently remained intact for perturbations made in the direction orthogonal to gaze shift.

Influence of head perturbation on subsequent head-movement dynamics

Passive head perturbations applied during horizontal gaze shifts resulted not only in a transient head deflection (coinciding with the period of time during which the motor was actively engaged) but also altered the subsequent head-velocity profile in a manner that persisted throughout the duration of the gaze shift. This is illustrated for monkey *C* in Fig. 13. The average head-velocity profiles obtained during 60° control gaze shifts (gray lines) were compared with the average head-velocity profiles obtained during 60° gaze shifts that were

30 ms Before Onset

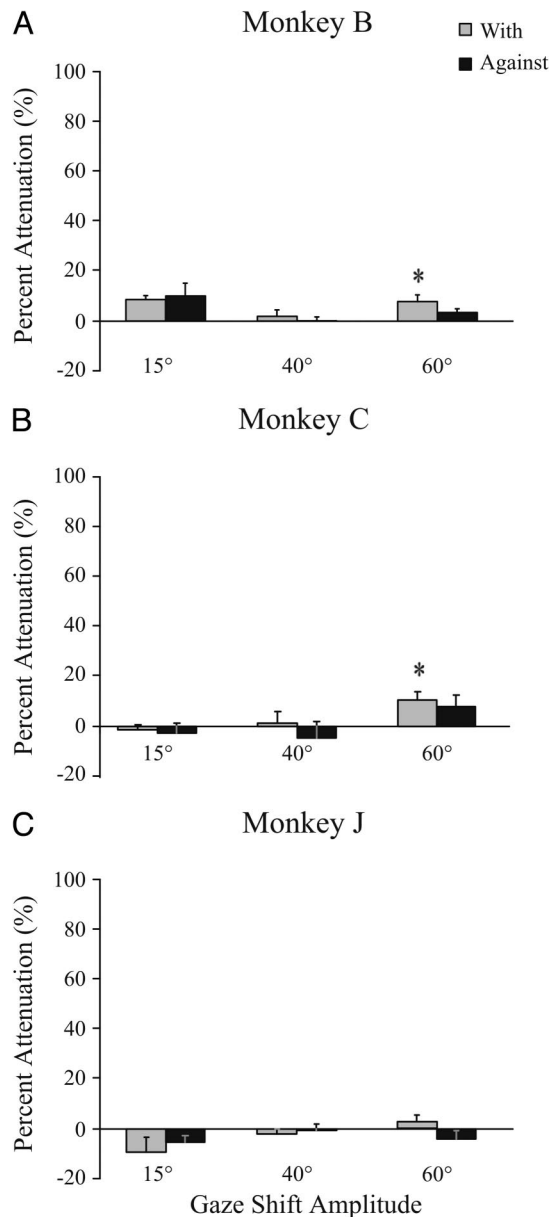


FIG. 7. A–C: the percent attenuation of the VOR in monkeys B, C, and J, respectively. *, significant attenuation relative to control response ($P < 0.05$). The VOR gain was generally not attenuated 30 ms prior to gaze-shift onset. The error bars represent SE.

perturbed with and against 40 ms into the gaze shift (Fig. 13A), 100 ms into the gaze shift (Fig. 13B), 150 ms into the gaze shift (Fig. 13C), and <50 ms after the gaze shift (Fig. 13D). We considered the head velocity profiles for perturbed versus control gaze shifts to significantly differ (gray shaded boxes) when the SE across trials did not overlap for a period of ≥ 25 ms (Crane and Demer 2000).

When the head perturbation was applied in the with direction, 40 ms after gaze shift initiation, we observed that subsequent to torque motor deactivation, the head velocity significantly decreased compared with head velocity during the unperturbed control gaze shift (compare black with gray line in

Fig. 13A, left). Similarly, when monkey C's head was perturbed in the against direction (Fig. 13A, right), there was initially a sudden transient decrease in head velocity, after which the head accelerated such that the instantaneous head velocity for the remainder of the perturbed gaze shift was significantly greater than the head velocity observed during the control gaze shift (gray shaded box). Significant compensatory adjustments in head velocity were also observed after the head was perturbed later during a gaze shift; 100 ms (Fig. 13B) and 150 ms (Fig. 13C) after gaze-shift onset. Analogous adjustments in head velocity were observed when the head was perturbed immediately after gaze-shift completion—50 ms after target acquisition (Fig. 13D), thus compensatory head responses were

40 ms After Onset

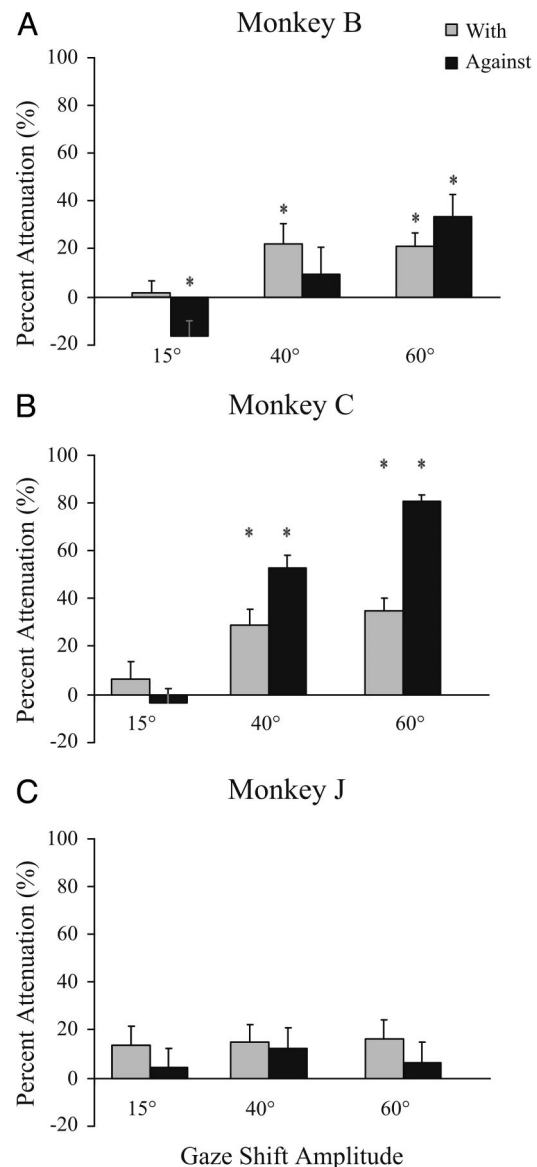


FIG. 8. A–C: the percent attenuation of the VOR in monkeys B, C, and J, respectively. VOR attenuation 40 ms into the gaze shift increased with gaze-shift magnitude in monkeys B and C, whereas for monkey J, the VOR was not significantly attenuated for all gaze-shift magnitudes. The error bars represent SE.

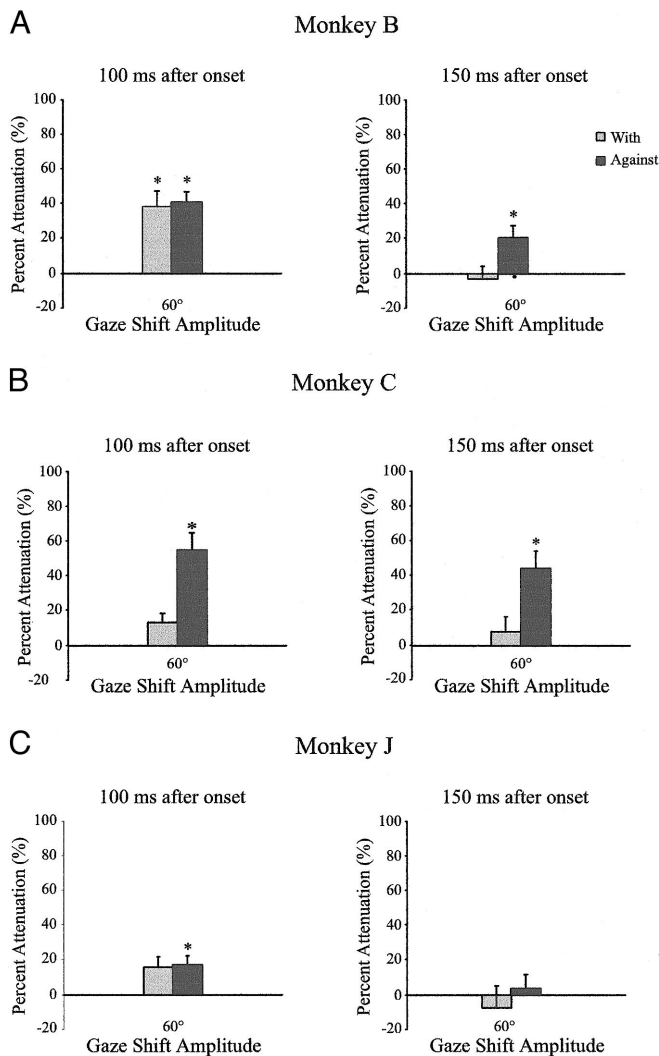


FIG. 9. A–C: the percent attenuation of the VOR in *monkeys B, C, and J*, respectively. VOR response to perturbations that were applied 100 and 150 ms after 60° gaze-shift onset. The error bars represent SE.

not limited to perturbations applied during the gaze shift. Qualitatively similar observations were made in *monkeys B* and *J* (not shown).

DISCUSSION

The primary goal of the present study was to evaluate the time course of intra-gaze-shift VOR suppression. The status of the VOR was compared during 15, 40, and 60° gaze shifts. The amplitude of VOR suppression measured 40 ms after gaze-shift onset increased with gaze-shift magnitude in two monkeys and remained fairly constant and nonsignificant across all gaze-shift magnitudes in a third monkey (Fig. 8). In contrast, passive horizontal head perturbations applied prior to gaze-shift onset (e.g., 30 ms before), as well as perturbations applied after gaze-shift completion (e.g., <50 ms after), elicited a robust VOR in all monkeys (Figs. 7 and 10, respectively). The time course of VOR gain change was studied in more detail by perturbing the head during two additional intra-gaze-shift intervals for 60° gaze shifts (beginning 100 and 150 ms after onset). We found that VOR gain was consistently most atten-

uated shortly after gaze-shift onset and was gradually restored to ~0% attenuation at gaze-shift end. However, the high variability across subjects prevented establishing a unifying description of the absolute level and time course of VOR suppression during gaze shifts.

Status of the VOR during gaze shifts

It is generally considered that the VOR is suppressed during large gaze shifts. Our results generally support this conclusion but show significant subject-to-subject variability in the level of suppression. Indeed, many behavioral perturbation studies,

50 ms Following Gaze Shift

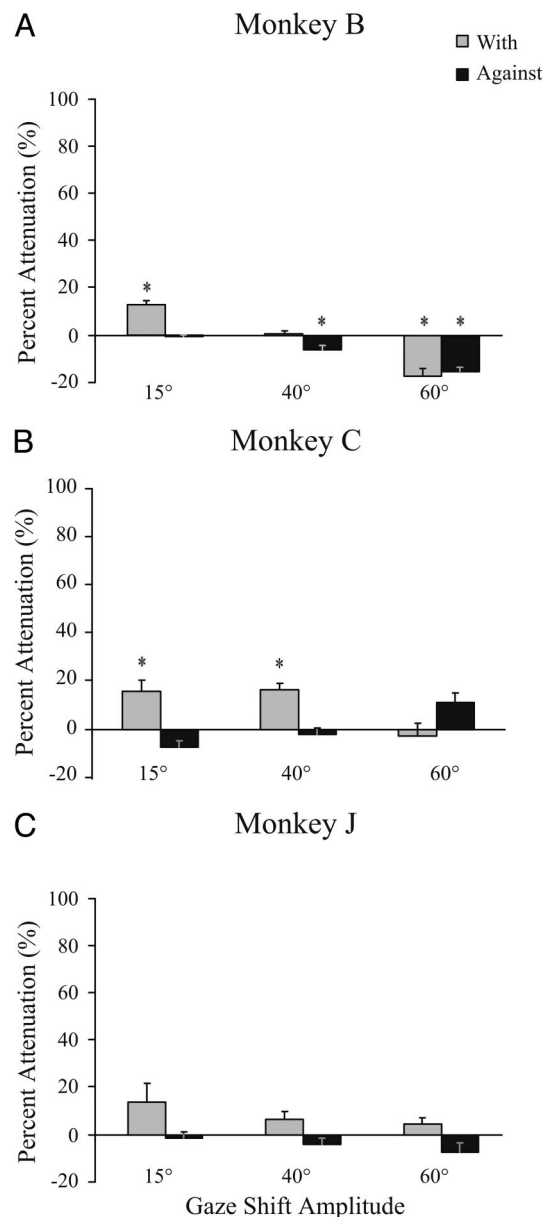


FIG. 10. A–C: the percent attenuation of the VOR in *monkeys B, C, and J*, respectively. When the head was perturbed 50 ms after target acquisition, the resultant VOR was not consistently attenuated in comparison to control perturbations for any of the 3 monkeys. The error bars represent SE.

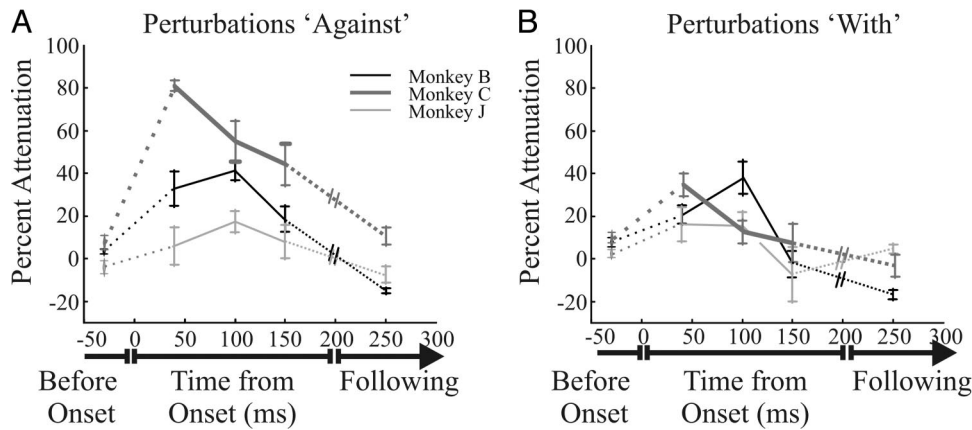


FIG. 11. To characterize the time course of VOR suppression, the percent attenuation of VOR gain vs. time from gaze-shift onset is plotted for 60° gaze shifts when perturbations were applied with (A) and against (B) the ongoing gaze shift. The attenuation of VOR gain generally decreased with time from gaze-shift onset although the magnitude of attenuation varied considerably among monkeys B, C, and J. The error bars represent SE.

which have been carried out over the past three decades (reviewed in Guitton 1992), have clearly shown that the passive application of head movement during gaze shifts *can* modify the profile of the gaze movement. Accordingly, it has been argued that the VOR is not intact during gaze shifts. In the present study, the amplitude of VOR suppression just after gaze-shift onset (40 ms) increased with gaze-shift magnitude in two monkeys (*monkeys B and C*), approaching 80% attenuation in one case. In contrast, the results from a third monkey (*monkey J*) were somewhat unexpected. For this monkey, the VOR was not significantly attenuated for all gaze-shift magnitudes. Thus at first glance, data from *monkeys B and C* appear to confirm and extend the results of these prior studies, while data from *monkey J* appear to contradict them.

A more critical analysis of this prior body of behavioral work, however, provides a far more temperate view of VOR modulation during gaze shifts. First, and most importantly, the results of prior behavioral studies are themselves not without controversy. The studies by Bizzi and colleagues (Morasso et al. 1973) originally suggested that VOR gain remained intact during gaze shifts; however, these investigators only tested gaze shifts <40° in amplitude. Controversy soon followed

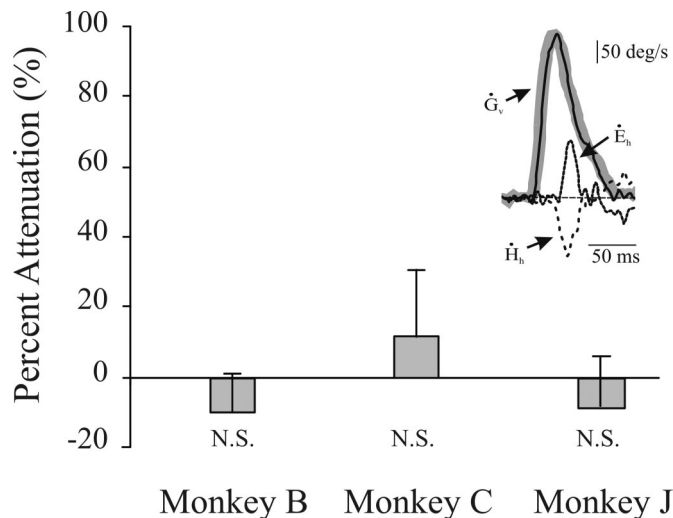


FIG. 12. Horizontal head perturbations were applied 40 ms after onset of 40° vertical gaze shifts. Perturbations applied in a direction orthogonal to the axis of gaze redirection elicited a robust VOR that was negligibly attenuated in *monkeys B, C, and J*, respectively. The error bars represent SE. *Inset*: representative traces of vertical gaze velocity (G_v), horizontal eye velocity (E_h), and horizontal head velocity (H_h). □, a control vertical gaze shift.

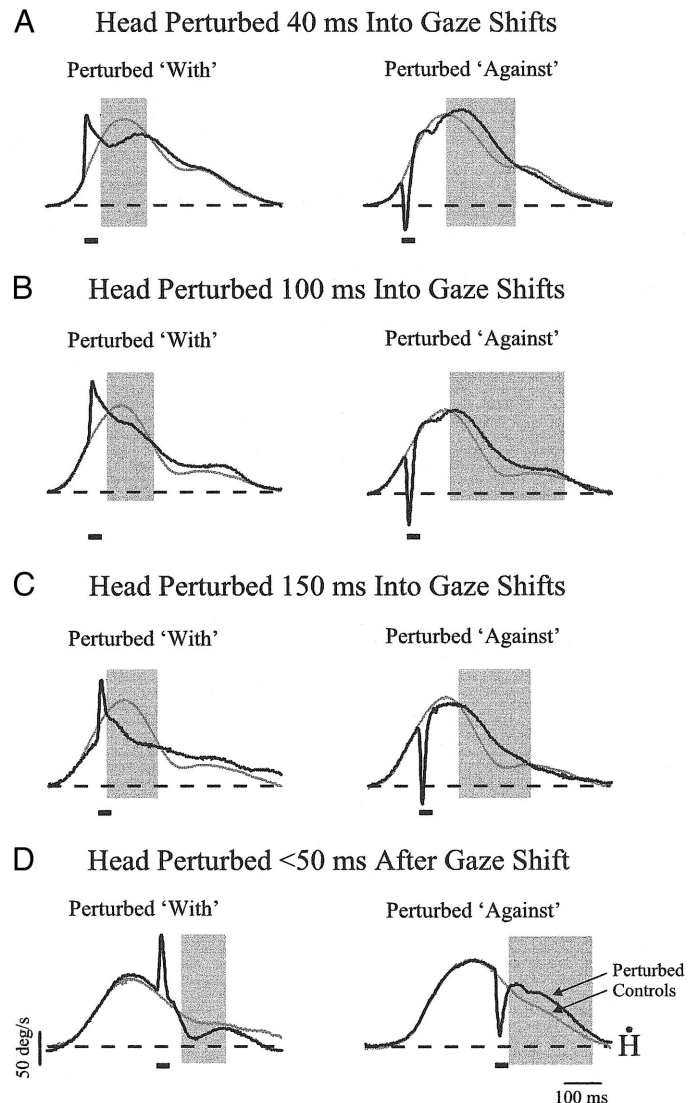


FIG. 13. Average head-velocity profiles (for *monkey C*) obtained during 60° control gaze shifts (gray lines) were compared with average head-velocity profiles obtained during 60° gaze shifts that were perturbed in the with and against directions. Perturbations were applied 40 ms after gaze-shift onset (A), 100 ms after gaze-shift onset (B), 150 ms after gaze-shift onset (C), and in the terminal interval of a gaze shift (D). Head perturbations altered head-velocity profile in a manner that persisted throughout the remaining head movement (gray shaded boxes). The thick horizontal bars indicate the interval during which the head perturbation was applied.

when larger gaze shifts were probed. Guitton et al. (1984) reported VOR-like eye movements in response to head brakes, but Fuller et al. (1983) reported the absence of a compensatory response. Lauritis and Robinson (1986) and Tomlinson and Bahra (1986) then found that in primates, the VOR was completely suppressed only when transient perturbations were applied during larger ($>40^\circ$) gaze shifts. However, more recently other laboratories have reported far more variable levels of VOR attenuation for gaze shifts in this range (Freedman et al. 1998; Guitton and Volle 1987; Tabak et al. 1996).

There are several possible explanations for the large variability in the results obtained across prior perturbation studies, such as important methodological differences in the type of perturbation applied (see INTRODUCTION). A first implication of this heterogeneity is that during braking and sudden perturbation studies, the frequency content of the perturbation would be significantly higher than during constant velocity rotations. Because the gain of the VOR was shown to differ from unity during high-frequency stimulation (reviewed in Huterer and Cullen 2002; Minor et al. 1999), the interpretation of any data from perturbation experiments therefore requires a robust estimate of the "intact" gain of the VOR in response to the test stimuli. A limitation of most previous studies (the study of Tabak et al. 1996 is the notable exception), but not of the present one, was the inherent assumption that the default gain of the VOR in response to the applied perturbation is unity.

A second major methodological limitation that hinders comparison across prior perturbation studies is that there was no attempt to standardize the contribution of the head motion to the gaze shifts. Furthermore, the experimental apparatus employed in many studies often interfered with the subject's ability to perform natural head rotations during gaze shifts by imparting significant inertia to the head and limiting head motion to a single axis of rotation (see for example Tabak et al. 1996; Tomlinson and Bahra 1986). Thus it is probable that in some studies head perturbations were primarily applied during gaze shifts for which head movements were relatively small, whereas in other studies, they were applied during gaze shifts with large head movements. This is a very likely scenario because eye-head coordination can vary greatly as a function of experimental protocol (e.g., Zangemeister and Stark 1982). Differences in head-movement strategies could provide an explanation for the differences between subjects that was seen in the present study as well as across previous studies. On the one hand, many studies (Lauritis and Robinson 1986; Pelisson and Prablanc 1986; Pelisson et al. 1988) have applied head perturbations during both eye-only saccades and combined eye-head gaze shifts and have shown that the attenuation of the VOR is comparable in both conditions. This issue was further explored by Lefevre et al. (1992), who compared the gaze trajectories during gaze shifts with different head-movement contributions and concluded that VOR gain is independent of head velocity. On the other hand, Tabak et al. (1996) argued that VOR suppression was well correlated with maximum head velocity, but even in this study, head movement was not necessary for VOR suppression. This point is further addressed in the following text with respect to our own data.

When compared with previous investigations, the approach used here was most similar to that employed by Tomlinson and Bahra (1986), Tabak et al. (1996), and Freedman et al. (1998). Specifically, our perturbations were most similar in type and

by extension in frequency content, to the torque motor perturbations utilized in these studies. However, all four studies support very different conclusions regarding the status of the VOR during gaze shifts. Tomlinson and Bahra (1986) used perturbations that were 100 ms in duration and reached maximum displacement within 40–50 ms and found complete VOR suppression for large gaze shifts. In contrast, Tabak et al. (1996) used longer perturbations that were >200 ms in duration and began 100 ms preceding saccades and found 30–40% residual VOR function. Finally, Freedman et al. (1998) observed intact VOR responses when more transient perturbations (i.e., 30-ms duration) were used. The perturbations in the present study were of comparable duration (20–30 ms) and thus best matched those used in this latter study. Accordingly, when viewed from this perspective, our data from *monkey J* could be considered to be more consistent with the literature than are those from *monkey B* or *C*. However, it is important to note that to date, Freedman and colleagues have only published a preliminary report of these findings.

Time course of VOR suppression

Our findings regarding the time course of VOR suppression during large gaze shifts (Fig. 11) do not support prior hypotheses that the VOR gain is completely disconnected throughout large gaze shifts (Lauritis and Robinson 1986; Tomlinson 1990), the VOR gain decays exponentially during large gaze shifts (Pélisson et al. 1988; Tabak et al. 1996), or the VOR gain varies linearly as a function of instantaneous gaze motor error (Lefevre et al. 1992). In fact, our results are most consistent with the view presented by Guitton and Volle (1987), who reported considerable inter-subject and task-specific variability in the interaction between the VOR and gaze shifts. In addition, we found that the VOR gain returned to control levels immediately after gaze-shift completion in two monkeys (*monkeys C* and *J*). However, in the third animal (*monkey B*), we found that the VOR gain was actually greater during this interval than for control perturbations. This result is noteworthy, because it is consistent with the findings of Tabak et al. (1996), who reported that human VOR gains are consistently elevated to a supra-normal value in the wake of gaze shifts.

As noted in the preceding text and in the INTRODUCTION, the difference between our results and those of other studies might also result from important technical and analytical limitations in these previous approaches. We addressed this latter consideration by designing a torque motor assembly that did not impede natural head motion and that allowed us to apply very short-duration (20–30 ms), high-acceleration head perturbations at precisely timed epochs. Moreover, to isolate the VOR response to head perturbations applied during gaze shifts, we modified the matching method technique developed by Tabak et al. (1996). In the approach originally used by these investigators, long matching intervals (beginning 50 ms before and ending 500 ms after gaze-shift onset) were used, and as a result matched pairs were rare. Head perturbations were also applied before the gaze shift was underway, and thus the perturbed portion of the gaze shift was utilized in their matching algorithm. In the present study, because we used much shorter duration perturbations, we were able to match trials over a much shorter interval (i.e., beginning 10 ms prior to gaze-shift onset and ending 2–3 ms prior to perturbation onset) so as to

ensure that our matching interval ended before the onset of the head perturbation. Thus because the matches were computed using the interval before the head perturbation, the control and perturbed gaze shifts essentially did not differ until the perturbation was initiated.

These methodological differences, and especially the temporal properties of the perturbations/analysis, have other important implications. For example, using model simulations, Lauritis and Robinson (1986) and Galiana and Guitton (1992) have shown that through the use of feedback loops, it is possible to generate VOR-like behaviors (i.e., compensatory eye-movement responses) during gaze shifts even in situations where the direct VOR pathways are deliberately disconnected. Such VOR-like responses could have confounded the conclusions of previous studies in which the status of the VOR during gaze shifts was investigated using long duration head perturbations or analyzed over long time intervals. In our experiments, the peak head velocity induced by head perturbation occurred ~10 ms after the onset of head perturbation, and the compensatory eye movements induced by the VOR began after a very short latency (5–6 ms). Therefore we were able to limit our analysis of the VOR response to a time interval not much longer than the latency of the direct three-neuron VOR pathway. Hence, we conclude that the short latency responses to head perturbations that we observed were primarily mediated through classical VOR pathways via interactions with the saccadic burst generator.

Neural substrate of VOR attenuation

In previous experiments (Roy and Cullen 1998, 2002), we have recorded from individual VOR interneurons [position vestibular pause (PVP) neurons] in alert Macaque monkeys during gaze shifts. We observed that the gain of the head-velocity signals transmitted by PVP neurons is reduced during gaze shifts in an amplitude-dependent manner that is consistent with previous behavioral reports of VOR attenuation in humans and monkeys. Data from one of the monkeys tested in the present experiments (*monkey C*) comprised most the sample of PVP neurons included in these previous studies. PVP modulation in this animal was dramatically reduced immediately after gaze-shift onset, gradually resumed throughout the movement, and was no longer attenuated immediately after the gaze shift. Thus there is a striking concurrence between PVP neuronal responses and time course of behavioral VOR suppression during gaze shifts (e.g., Fig. 11) in this monkey. This observation is consistent with the hypothesis that an attenuation in the activity of the direct VOR pathways during gaze shifts underlies, at least in part, the VOR suppression observed in the present study.

This hypothesis is not a new idea. We and others have previously proposed a mechanism in which the attenuation of PVP neuron discharges during gaze shifts results from inhibitory connections with the brain stem burst generator (reviewed in Roy and Cullen 1998). Here we propose that this pathway may account for some of the behavioral differences that were observed between monkeys. For example, we have documented in RESULTS that *monkey C* generated 60° gaze shifts that were much faster (often in excess by 200°/s) than those generated by either *monkeys B* or *J*. Because saccadic burst neurons during gaze shifts have discharge patterns that are

roughly correlated with the gaze velocity (Cullen and Guitton 1997a,b), we can presume that *monkey C*'s saccadic burst neurons discharged at higher rates than those of the other monkeys. Moreover, since saccadic burst neurons inhibit, albeit indirectly through type II neurons, PVP neuron discharges during gaze shifts (Sasaki and Shimazu 1981; Nakao et al. 1982), it follows that *monkey C*'s PVP neurons were more inhibited than either *monkey B* or *J*'s during large gaze shifts. Thus if the suppressed responses of PVPs contribute to behavioral suppression, it is not surprising that *monkey C*'s VOR was the most attenuated during gaze shifts.

GAZE-SHIFTS METRICS. Prior studies have also shown that perturbed gaze shifts are generally as accurate as unperturbed gaze shifts (Lauritis and Robinson 1986; Guitton and Volle 1987; Tomlinson 1990; Tabak et al. 1996). Our results similarly showed no consistent effect on gaze-shift accuracy. Moreover, it has been shown that the effect of head perturbations on gaze-shift duration is direction-dependent: head perturbations in the direction of the ongoing gaze shift shorten gaze-shift duration, whereas head perturbations in the direction opposite to the ongoing gaze shift increase gaze-shift duration (Lauritis and Robinson 1986; Tabak et al. 1996; Tomlinson 1990). In contrast to these findings, we observed that transiently perturbed gaze shifts were consistently longer in duration than control gaze shifts, regardless of the direction of head perturbation. This discrepancy could arise due to the more transient nature of the perturbations in this present study compared with previous studies or to the fact that different criteria have been used to establish the time of gaze-shift completion. Although a clear criterion for determining the timing of gaze-shift offset was not described in prior studies, investigators generally use a strict velocity threshold (e.g., 1st point where gaze velocity is <20°/s) to mark gaze-shift offset. In our study, the use of such a criterion would have been misleading because a low velocity tail was often observed during the terminal portion of perturbed gaze shifts. Thus gaze-shift offset was defined by the first point of a 20-ms interval where gaze velocity was constantly <20°/s (see METHODS).

PLANE-SPECIFIC ATTENUATION. The VOR consistently remained intact for perturbations made in the direction orthogonal to gaze shift. Overall, our results confirm and extend those of Tomlinson and Bahra (1986), who found no evidence for intra-gaze-shift VOR suppression in rhesus monkeys when passive horizontal head perturbations were applied during vertical gaze shifts. In contrast, the human experiments of Tabak et al. (1996) reported the existence of VOR suppression for perturbations that were delivered in the plane orthogonal to saccades. Nevertheless, these latter investigators found that their results were compatible with some degree of plane specificity because the attenuation was significantly decreased in the orthogonal plane. As noted in the preceding text, of these two prior studies our test stimulus was more similar to, albeit still more transient than, that employed by Tomlinson and Bahra (1986), and thus it is encouraging that our results are in agreement with those of this previous investigation. Interestingly, the head perturbations used in the experiments of Tabak et al. (1996) were substantially longer (>200 ms) and started >100 ms before the saccade. Thus it is possible that subjects were able to integrate information about this perturbation into their responses in this latter study. Moreover, the lack of VOR

attenuation reported in this study and that of Tomlinson and Bahra is probably not due to the fact that the head-movement contribution to vertical gaze shifts is generally less than that of horizontal gaze shifts (see Freedman and Sparks 1997). As was noted in the preceding text, prior studies have shown significant VOR attenuation for saccades made with no head movements (e.g., Laurutis and Robinson 1986).

General conclusions

The results of the present study suggest that the level of VOR attenuation during large eye-head gaze shifts varies across subjects. We used a programmable torque motor to apply the most precise temporal resolution to date and found that VOR gain was highly attenuated in one animal, rather robust in another animal, and reached intermediate levels of attenuation in a third animal. Overall VOR suppression was maximal early in the gaze shift and progressively recovered to normal control values near gaze-shift end. However, we observed considerable variability across subjects, which precluded defining a common function that could describe VOR suppression during gaze shifts. It is likely that differences in behavioral strategies used during gaze shifts could account, at least in part, for the variations in time courses of VOR attenuation that we observed.

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