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Behavior and Physiology of the Macaque Vestibulo-Ocular Reflex Response to Sudden Off-Axis Rotation: Computing Eye Translation

L. H. SNYDER[1] AND W. M. KING

Division of Biology, 216-76, Caltech, Pasadena, CA 91125 USA
Departments of Neurology and Anatomy, University of Mississippi Medical Center, Jackson, MS 39216 USA

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ABSTRACT: The vestibulo-ocular reflex (VOR) has historically been considered a computationally simple reflex: to stabilize images on the retina against imposed head rotation, the eyes must be counterrotated by an equal amount in the opposite direction. During almost any head rotation, however, the eyes are also translated. We show that the VOR compensates for 90% of this translation, and suggest a computational scheme by which this is done, based on a temporal dissection of the VOR response to sudden head rotation. An initial response that corrects only for imposed rotation is refined by a series of three temporally delayed corrections of increasing complexity. The first correction takes only head rotation and viewing distance into account; the second, head rotation, viewing distance, and otolith translation; and the third, head rotation, viewing distance, otolith translation, and translation of the eyes relative to the otoliths. Responses of type I gaze velocity Purkinje (GVP) cells in the cerebellar flocculus and ventral paraflocculus of rhesus monkeys were recorded during sudden head rotation. We show that cell discharge was modulated both by axis location and by viewing distance, suggesting that GVP cells play a role in the VOR response to rotation-induced eye translation.

KEY WORDS: Linear translation, Vergence, VOR, Flocculus, Purkinje cell.

INTRODUCTION

Our eyes are mounted in our head, and, therefore, head movement relative to a visual target causes the image of that target to move on our retinas, degrading high acuity vision. The vestibulo-ocular reflex (VOR) acts to preserve high acuity vision by rotating the eyes in their orbits so as to minimize image motion on the retina. The vestibular apparatus, located in the inner ear, provides short-latency information on head movement. The function of the VOR is to compute from this signal an eye movement that will minimize gaze deviation from the current visual target. For head rotations, this is relatively simple. The VOR merely counterrotates the eyes an equal amount in the opposite direction. However, because the axes of head and eye rotation are generally not the same, head rotation almost always also causes the eyes to translate in space. When viewing a distant object, eye translation can be ignored, because it results in vanishingly small image motion on the retina. However, when viewing a near object, uncompensated eye translation can cause significant visual image motion. For example, when threading a needle 8 inches from the eyes, image slip resulting from rotation-induced eye translation is 50% as large as the slip produced by the rotation itself.

The VOR does respond to rotation-induced translation, although the computational problems it faces in doing so are formidable [1,2,4–6,14,15,20,21]. First and foremost, the VOR must act quickly. Visual stabilization mechanisms have latencies of 100 ms (but see [17]). To be of most use, the VOR must act more quickly than this. Second, the VOR must compute eye translation in space. The vestibular otolith organs, located in the inner ear, sense head translation. Because the eyes and otoliths lie at different distances from the center of head rotation, eye translation can be different from otolith translation. For example, head pitch about the interaural axis does not translate the otoliths at all, but produces significant up–down motion of the eyes. Third, the translational VOR, unlike the rotational VOR, must take viewing distance and viewing eccentricity into account. It is not the translation itself that is important, but rather the effect of translation on viewing angle. As a result, near targets require more compensation than far targets (as discussed above), and midline targets require more compensation than eccentric targets. Because the eccentricities of targets off the midline differ for each eye, the effect of translation is not the same and, ideally, separate compensatory responses should be computed for each eye. We will show that most of these computational challenges are met, and that the VOR response is refined in several successive approximations, with each successive approximation affecting eye velocity at a different latency.

Much previous work has focussed on the role of the cerebellar flocculus in VOR performance (see [3] for review). Stimulation, lesion and single unit studies provide evidence that the cerebellar flocculus is involved in the VOR response to head rotation. The discharge of a subclass of Purkinje cells (gaze velocity Purkinje or GVP cells) are modulated with the sum of eye velocity in the orbit and rotational head velocity in space [8,12]. No study has addressed whether this structure might also be involved in the response to translation. We will show that GVP cells modulate

[1] Requests for reprints should be addressed to Lawrence Snyder, Division of Biology, 216-76, Caltech, Pasadena, CA 91125.

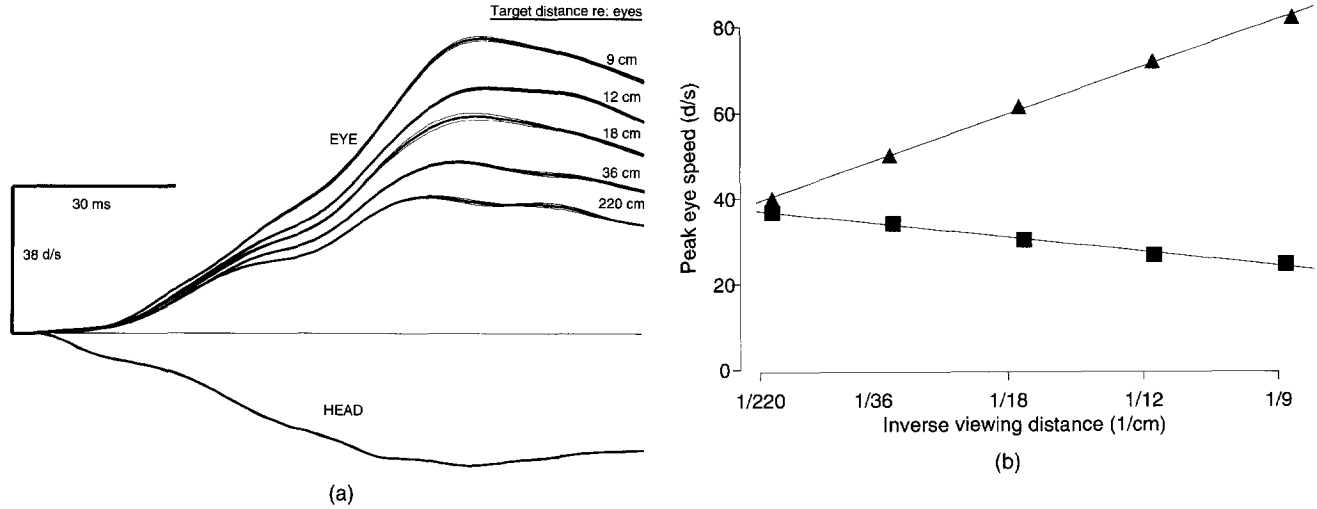

FIG. 1. Effect of viewing distance and axis location on the VOR. (A) Mean eye velocity (± 1 SEM) evoked by a sudden head rotation (± 1 SEM, five overlaid traces) increased with near viewing (e.g., 9 vs. 220 cm, indicated on far right). With distant viewing, eye velocity was comparable to head velocity; with nearest viewing, eye velocity was twice head velocity. Rotation was about an axis 12.5 cm behind the eyes. Conjugate eye velocity (average of right and left) is shown. (B) Peak evoked eye velocity (ordinate) varied linearly with inverse viewing distance (abscissa). Two axes of head rotation are shown (14 cm behind the eyes: triangles; 3 cm in front of the eyes: squares). Least square regression lines show linear relationship. Standard errors are smaller than plotting symbols. (Modified from Figs. 1 and 3 of Snyder and King 1992, with permission.)

with the translation that accompanies off-axis head rotation, and that a component of this modulation is dependent on viewing distance.

METHOD

Details of the behavioral task have been previously published [20]. Briefly, eye velocity responses to sudden head rotations were obtained from three rhesus monkeys. Animal care and procedures were in accord with the standards of the National Institutes of Health Guide. An earth-vertical axis of head rotation was positioned on the midline and between 4 cm in front and 15 cm behind the eyes by displacing the animal forward or backward on a vestibular turntable (Contraves-Goertz). At the start of each trial, an earth-fixed fixation target 9, 12, 18, 36, or 220 cm distant was turned on in an otherwise dark room. After a fixation interval of random duration (520–936 ms), the LED was extinguished, and 30 ms later the turntable was accelerated (500°/s/s) to 25–30°/s. This speed was maintained for 190 ms, and then the LED was relit and the rate table slowly decelerated (100 deg/s/s). Animals received a liquid reward for rapid refixation of the relit target. Viewing distances and directions of rotation were randomly interleaved within blocks of trials employing a single axis of head rotation. Left and right eye positions, obtained using the scleral search coil technique (CNC engineering), were low-pass filtered (−3 dB at 80 Hz) and recorded, along with turntable position and velocity, at 1000 Hz. Great care was taken to precisely calibrate the eye position signals. An 11/23 computer running custom software controlled LEDs, the turntable and the room lights, monitored the animal's performance and aborted trials when fixation became inadequate. Off-line, eye position records from multiple trials were differentiated to obtain left and right eye velocity. Eye velocities and turntable velocities were averaged across similar trials to produce mean ± 1 standard error of the mean (SEM) responses for each combination of viewing distance and axis location (Figs. 1A and 4). Peak eye velocity (Fig. 1B) or eye velocity during a specified interval (Figs. 2 and 5) was obtained from these averaged records.

In some sessions, type I [8] horizontal GVP cell activity was recorded along with behavioral data. Extracellular recordings were made using glass-insulated Pt-Ir electrodes, inserted stereotaxically through skull-mounted stainless steel chambers into the flocculus and ventral paraflocculus of two rhesus monkeys. Signals were amplified and filtered (100–10,000 Hz bandpass), and action potentials were discriminated using a Bak window discriminator. Spike times were recorded with 10 μs resolution. Units were isolated while the monkey performed smooth pursuit eye movements. Purkinje cells were identified by their discharge properties (complex spikes, broad negative then positive potentials, isolated over > 100 μm of electrode travel) and then characterized using horizontal and vertical smooth pursuit and VOR cancellation tasks. Purkinje cells which increased firing with ipsilateral eye movement and with ipsilateral head movement, and were more strongly modulated by horizontal than by vertical eye movement, were considered horizontal type I GVP cells and tested during abrupt head rotation. Off-line, spike times were converted to continuous frequency records using the modified interspike interval method of Lisberger [9], sorted, and averaged by trial type to obtain mean ± 1 SEM firing for each viewing distance and axis location (Fig. 6).

RESULTS

Eye Movement Responses to Off-Axis Head Rotation

The VOR response to off-axis head rotation was very close to the geometrically ideal response. Figure 1A shows a family of eye velocity responses to steps of head velocity as viewing distance is varied. With an axis behind the head, the eyes are translated in the same direction that they are rotated, and as a result, the evoked eye speed is greater than that which would be produced by the pure VOR alone. With far viewing (220 cm), the VOR response was similar to the rotational speed of the head ("Head"). With nearer viewing, the evoked eye speed was greater. When viewing distance was 9 cm, evoked eye velocity was roughly twice the rotational head speed. Ideally, eye velocity would vary inversely with viewing distance, and in fact, this was

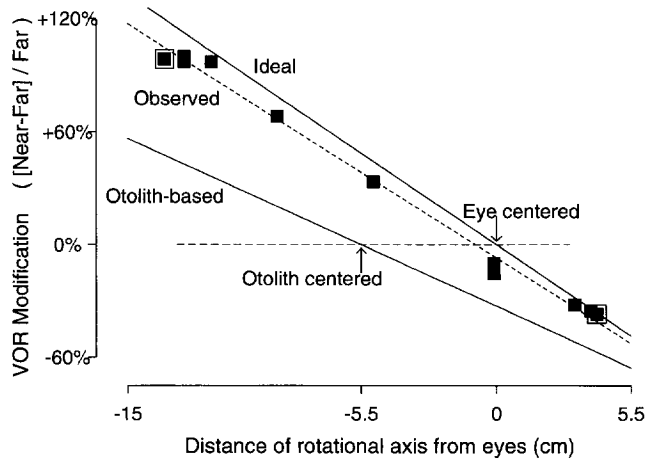

FIG. 2. Compensation for rotation-evoked eye translation was nearly ideal. The effect of near compared to far viewing on the VOR response (ordinate) is shown as a function of the location of the axis of head rotation. Head rotations were all identical. Near and far viewing were defined by vergence angles (20 and 0°, respectively) rather than absolute distance so that values from different animals could be more easily compared (although the data shown was obtained from a single animal.) Data from Fig. 1B are shown as outlined squares. The dashed line represents the least squares regression through the data points. Solid lines represent geometrically ideal and otolith-based models of the VOR (see text). For derivation of model data, see Snyder and King 1992. Arrows indicate positions of the eyes (x = 0) and otolith organs (in this animal, 5.5 cm behind the eyes). (Modified from Fig. 4 of Snyder and King 1992, with permission.)

the case (Fig. 1B). Peak eye velocity scaled precisely with inverse viewing distance for two different axes of rotation, one behind and one in front of the eyes. Peak eye velocity was virtually the same for the two axes at a far viewing distance (220 cm), where no compensation is required for translation. With near viewing, compensation for rotation-induced translation grew inversely with viewing distance, as predicted by the geometrically ideal model. Thus the y-intercept isolates the effect of rotation, while the slopes isolate the effect of translation produced by rotation about a given axis. Focussing on the response to translation, the ideal model can be used to predict slope as a function of axis location. The next figure compares predicted and observed slopes as a function of axis location.

Figure 2 shows that the observed effects of near viewing on eye velocity (squares and dashed line) were very close to those predicted by a geometrically ideal model of the VOR (solid line, "Ideal"). The Y axis represents the effect of near viewing (20° of vergence) compared to far viewing (0° of vergence) on the VOR response. The metric used was percentage change of response between near and far viewing, normalized to the far viewing response. This is equivalent to a measure of slope in Fig. 1B. Axes behind the eyes (left-hand side of abscissa) resulted in an elevated VOR response with near viewing. For example, rotation about an axis 14 cm behind the eyes caused a 104% increase in eye velocity with near compared to far viewing (outlined point on far left, derived from upward sloping line of Fig. 1B). Axes in front of the eyes (right-hand side of abscissa) depressed the VOR response with near viewing. For example, rotation about an axis 3 cm forward of the eyes caused a 31% decrease in eye velocity (outlined point on far right, derived from downward sloping line of Fig. 1B).

The two solid lines in Fig. 2 represent predicted VOR responses for two models of the VOR. The line labeled "Ideal" assumes that eye translation relative to the visual target is completely compensated. For rotation about an axis centered between the eyes ("Eye centered"), the ideal model predicts no effect of near viewing, because there is no rotation-induced lateral eye translation. The line labelled "Otolith-based" assumes compensation for lateral head translation sensed by the otolith organs in the inner ear, 5.5 cm behind the eyes in the animal represented in Fig. 2. During eye-centered rotation, the otoliths are translated in a direction opposite to the direction of rotation, and, therefore, the otolith-based model, unlike the ideal model, predicts decreased eye velocity with near viewing. During rotation about an otolith-centered axis ("Otolith-centered"), there is no lateral otolith translation (even though the eyes are translated), and, therefore, the "Otolith-based" model, again unlike the ideal model, predicts no VOR modification with viewing distance.

The observed responses were very close to those of the ideal model, and were far from those of the otolith-based model. The ratio of the slopes of the observed and ideal lines were 92%, and the offset was minimal. Data from two other animals yielded slope ratios of 83 and 103% and similarly small offsets. The observed VOR compensates on average for just over 90% of the image slip produced by rotation-induced translation. Critically, the VOR compensates for the translation of the eyes in space, and not the translation of the otoliths, despite the fact that otolith and not eye translation is sensed by the vestibular apparatus.

Figure 3 shows the difference between eye and otolith translation. For a head rotation of Θ degrees through an axis a distance D_{oto} from the otoliths, the otoliths are translated a distance equal to Θ times D_{oto}. For the same rotation, the eyes are translated a distance equal to Θ times D_{eye}, where D_{eye} is the distance of the eyes from the axis of rotation. The difference between eye and otolith translation, therefore, equals $(D_{eye} - D_{oto}) \times \Theta$, and the difference in their translational velocity equals angular head velocity times the distance between the eyes and the otoliths. This result is somewhat unexpected: the VOR must use a signal pro-

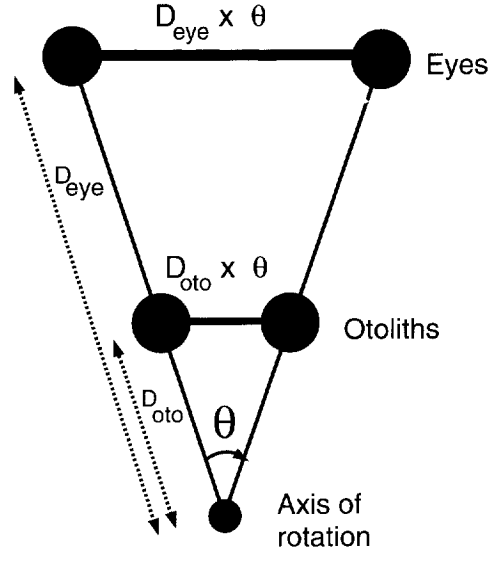

FIG. 3. Head rotation though Θ degrees translates the otolith organs a distance Θ times D_{oto}, where D_{oto} is the distance of the otoliths from the axis of rotation and Θ is a small angle. The eyes are translated Θ times D_{eye}, where D_{eye} is the distance of the eyes from the axis of rotation. Relative eye-otolith translation, produced by head rotation, equals $(D_{eye} - D_{oto}) \times \Theta$. This translation depends only on angular rotation and an anatomical constant (the distance between eyes and otoliths).

portional to head rotation to compute eye translation. [Information about rotation can be derived from the otolith ograns as well as the canals (e.g., [16]). For example, forward translation of the right otolith and an otherwise identical backward translation of the left otolith implies counterclockwise rotation about an axis passing through the interaural line. Other sources of linear translation information are also available [Mittelstaedt and Mittelstaedt, this volume). We know that information about rotation, however derived, must be used to calculate the difference between otolith organ and eye translation. For convenience, however, we will refer to canal and otolith signals as a shorthand for signals encoding rotation and those encoding translation.] Equally surprising is the fact that knowledge of the location of the axis of rotation is not required to compute relative eye–otolith translation. Although the absolute translations of the eyes and otoliths are proportional to the distance of the rotational axis from the interocular and interaural lines, respectively, this dependence on axis location cancels out when relative translation is computed.

Earliest Eye Movement Responses

So far we have considered only the peak VOR response to a transient stimulus. We hypothesized that the responses to rotation, otolith translation, and relative eye–otolith translation might all influence eye velocity with different latencies relative to the start of the head movement. Figure 4 illustrates exactly this. The first 120 ms of eye and head velocities are overlaid, for rotation about an anterior or posterior axis during near or far viewing (monkey head inset). Under all four conditions, angular head velocities (dashed H-dot traces) were virtually identical, but eye velocity traces (solid E-dot traces, mean ± 1 SEM) diverged from one another in a very particular pattern. Notice first that, on the right of the figure, peak and sustained eye speeds were as expected. With far viewing, there was no effect of viewing distance, and so evoked eye velocity traces (Far-Anterior and Far-Posterior) overlap one another. With near viewing, eye speed increased for posterior axis rotation and decreased for anterior axis rotation. Now let us consider what happened before peak eye velocity was reached.

After a ~10 ms latency [relative to head rotation onset (triangles)], a compensatory eye response appeared that was independent of both viewing distance and axis location, and was, therefore, driven solely by head rotation. At 18 ms after rotation onset, the trajectories obtained with near and far viewing diverged abruptly. This period of the VOR response represents a canal signal modified by viewing distance. Finally, 28 ms after rotation onset, head translation finally began to influence eye speed.

The different latencies of canal and otolith inputs on the VOR are not at all surprising. It is surprising that viewing distance should affect the VOR before otolith inputs. Why should a canal signal be influenced by viewing distance? The ideal VOR takes viewing distance into account for translation, not for rotation. In fact, with an anterior axis of rotation, the initial increase in eye speed with near viewing is anticompensatory: eye speed should decrease with nearer viewing, not increase. There are two possible explanations for this paradoxical early modulation of the

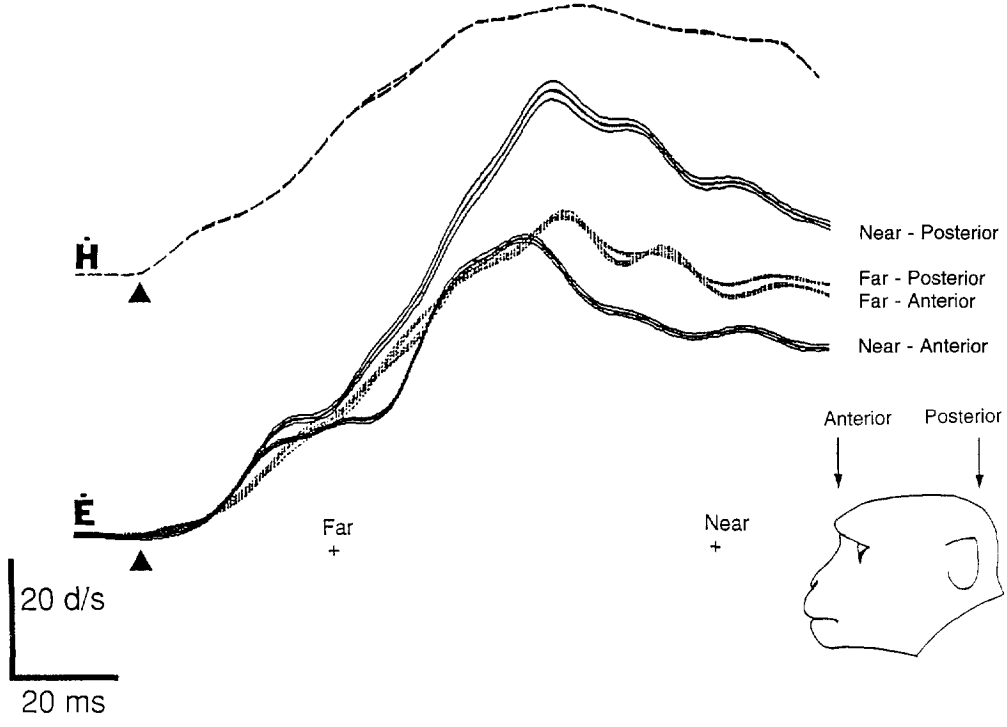

FIG. 4. Eye velocity was modified first by viewing distance, and then by axis location. Mean (± 1 SEM) conjugate eye velocities (E-dot) are shown for rotation about an anterior (+3 cm) or posterior (−14 cm) axis, with near (9 cm) or far (220 cm) viewing (see inset). Mean (± 1 SEM) head velocities (H-dot) from the four conditions overlay one another. Eye velocities initially overlay one another, but after 18 ms, eye velocity recorded during near viewing diverged abruptly from that recorded during far viewing. Eye velocities recorded during near viewing with an anterior or posterior axis of rotation diverge again, after 28 ms. We propose that these divergences represent contributions of discrete VOR channels, sequentially refining the overall response to become closer to the ideal.

canal signal. First, it might represent a "best guess" of the system in the absence of better data. Viewing distance information is available even before head rotation begins. (In fact, the VOR can anticipate future viewing distance by utilizing a central command signal rather than [or in addition to] an afferent or efferent copy of current vergence eye position [19].) The translation signal, on the other hand, has a 30 ms latency before it is available. The VOR may presume a default axis location behind the head, because that is the most common case (as in, e.g., yaw rotation of the head about the top of the spine). As a result, eye speed would be boosted in response to head rotation during near viewing, before the true axis is known. Alternatively, the early modulation of a rotational signal by viewing distance may represent the calculation of rotation-induced eye–otolith translation. A canal signal scaled by inverse viewing distance is exactly what one would expect for such a calculation (Fig. 3), and we know that the calculation is in fact performed (Fig. 2).

Figure 5 suggests that the former explanation is correct. Panels A and B are identical in format to Fig. 2. Panel A shows that, in the interval 18–26 ms after rotation onset, the change in eye speed with near viewing (abscissa) was independent of axis location (ordinate). This confirms the impression from Fig. 4 that early on, the VOR is driven only by a canal signal, conveying rotational (not translational) information, that has been modified by viewing distance. Panel B shows that, 34–44 ms after rotation onset, eye speed depended on axis location, and, therefore, the VOR is now being driven by a viewing-distance modified otolith signal. However, and this is the key point, the observed VOR response now resembles the otolith-based model, not the ideal model. In this early interval, eye velocity is compensating for otolith translation, not eye translation. For example, rotation about an otolith-centered axis resulted, in this early interval, in no modulation of eye speed with viewing distance, stabilizing the visual image with respect to the otolith organs instead of with respect to the eyes.

It could be argued that the slope of the line relating the effect of viewing distance on the VOR as a function of axis location must change continuously, from the near zero value 18–26 ms

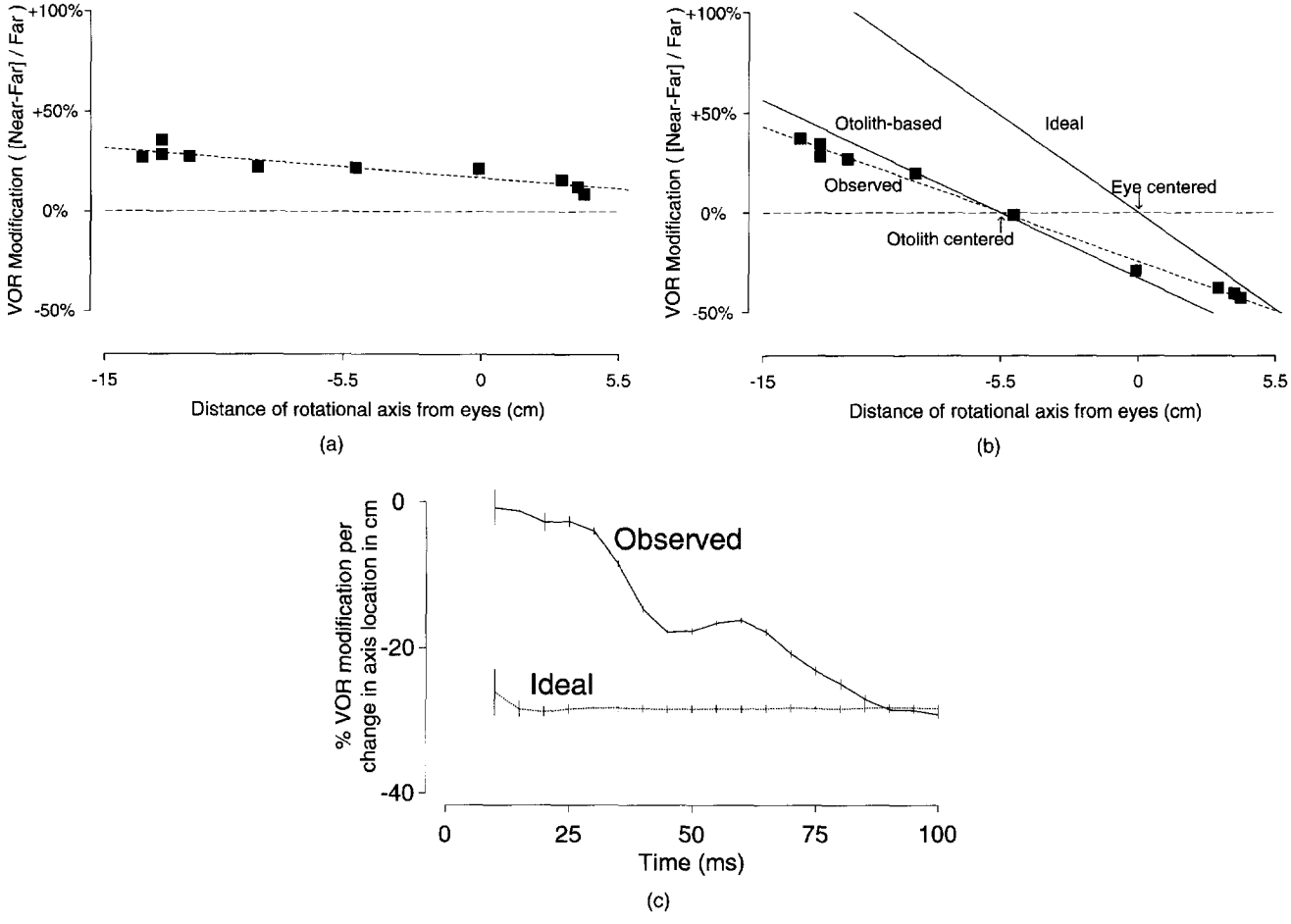

FIG. 5. The VOR response to head rotation consists of several discrete components. Format of A+B the same as Fig. 2. (A) The effect of near viewing was initially almost completely independent of rotational axis location. Data averaged from the interval 18–26 ms after rotation onset (squares) show a 35% increase in eye velocity with near compared to far viewing (ordinate), regardless of axis location (abscissa). This is anticompensatory for rotations about axes in front of the eyes. (B) The early VOR response stabilized images with respect to the otoliths, not the eyes. Data averaged from the interval 34–44 ms after rotation onset (squares) match the prediction of the otolith-based model, not the ideal model (see text). (C) The time course of the slope of the regression line relating effect of near compared to far viewing to axis location (dashed lines in Figs. 2, 5A, and 5B) shows that the character of the response changed abruptly and periodically, not gradually and continuously. The slope was calculated at 5 ms intervals using overlapping 10-ms epochs of data. Error bars indicate the standard error of the regression (Splus statistics package). Because the VOR has a latency of 10 ms, there is no data prior to 10 ms after rotation onset. The line labeled "Ideal" represents the slope of the geometrically ideal VOR response, which does not change as a function of time. (A+B modified from Fig. 9 of Snyder and King 1992, with permission.)

after rotation (Fig. 5A) to the steep slope obtained at peak VOR response (Fig. 2), and that Fig. 5B merely represents the instant in time at which the slope crosses, as it must at some time, the slope predicted by the otolith-based model. Figure 5C supports the existence of a discrete processing stage in which an otolith head translation signal is driving the VOR, but the computation yielding relative eye–otolith translation has not yet been performed. The figure tracks the slope of the line (relating VOR modification to axis location) as a function of time. The units of the ordinate are d/s per 1/cm viewing distance per cm axis location, while the abscissa represents time. The upper line represents the observed data, while the lower line represents the prediction of the ideal model. Initially ($\leq$ 30 ms), the observed slope is zero, as in Fig. 5B. At 35 ms, the slope begins to change rapidly, reaching a plateau that is maintained over the interval 40–65 ms after rotation onset. Seventy-five ms after rotation onset, the slope again changes, this time dropping to a final value equal to that of the ideal model. In general, the slope does not change gradually and continuously, but discontinuously and abruptly, reflecting successive refinements of the VOR response. The evolution in time of the x intercept also shows plateau periods interrupted by short periods of rapid change, again consistent with multiple sequential refinements of the VOR response not shown. Changes in intercept and slope occur in tandem, and the plateau times are congruent: from 40–65 ms, both slope and intercept match the otolith-based VOR model (Fig. 5B), while at the time of peak eye velocity (100 ms), both slope and intercept match the ideal VOR model (Fig. 2).

GVP Cell Modulation

Having characterized the eye movement response to steps of abrupt head rotation about different axes of location during near and far viewing, we next asked whether GVP cells in the cerebellar flocculus were modulated only in association with the VOR response to rotation, or if they also were involved in the response to translation. We recorded from 27 identified horizontal type I GVP cells in up to 24 different combinations of axis location, viewing distance, and target eccentricity. Here we show that both axis location and viewing distance effect the GVP response to transient head rotation. The timing of these effects suggests that axis location may directly affect GVP firing, while viewing distance exerts its effect only via eye velocity feedback.

We examined the effect of translation on GVP cells by rotating the head about different axes during far viewing (Fig. 6A). Data collected with anterior axis rotation is shown by dashed lines; posterior axis rotation data is shown by solid lines. The lowest set of traces confirms that the rotational components of the two head movements (downward-going superimposed traces) were identical by design. The evoked eye movement responses (upward-going superimposed traces) were virtually identical because, with far viewing, axis location has no effect on eye movement (Fig. 2). Despite identical head rotation and eye velocity trajectories, GVP firing depended on axis location (upper set of traces). Contralateral head rotation about a posterior axis translates the head contralaterally in space and resulted in increased GVP firing (solid line; mean $\pm$ 1 SEM for 23 cells). Identical rotation about an anterior axis translates the head ipsilaterally and results in decreased GVP firing (dashed line; eight cells). Both effects occur 25 ms after the onset of head rotation (vertical dashed line). In the interval 60–80 ms after rotation onset, posterior axis rotation results in a 8 sp/s increase in firing while anterior axis rotation results in a 4 sp/s decrease. The reverse effect obtains with ipsilateral rotation: posterior axis rotation decreases firing by 3 sp/s while anterior axis rotation increases firing by 10 sp/s (not shown). These effects are also observed in data from individual cells, with latencies as early as 20 ms (not shown). Because eye and angular head velocities were identical, the dependence of GVP firing on axis location could be due only to differences in head translation. We conclude that contralateral head translation caused GVP cells to increase their firing with a latency of no more than 25 ms.

Figure 6B shows the effect of viewing distance on GVP firing. The head was rotated contralaterally about a posterior axis during near (dashed lines) or far (solid lines) viewing. With either viewing distance, firing increased by 10 sp/s, beginning ~27 ms after the onset of head rotation (uppermost traces, mean $\pm$ 1 SEM). Thus, the early effect of head translation was independent of viewing distance. Forty milliseconds after the onset of head rotation, firing increased with near compared to far viewing. Because both angular and linear head velocities were identical, this difference in firing was most likely caused by the increase in evoked ipsilateral eye velocity, which began 20 ms after rotation onset (middle traces). This is consistent with the effect of eye velocity on type I GVP cells during smooth pursuit: firing rate was proportional to ipsilateral eye velocity. The difference in firing was not related to a change in vergence eye position (lowermost traces), which remained constant at 0 (far viewing) or 15° (near viewing) for the initial 100 ms following rotation onset.

DISCUSSION

Three Successive Approximations to a Nearly Ideal VOR

Rotation of the head about a vertical midline axis not only rotates but also translates the eyes relative to visual targets. The change in gaze angle required to stabilize a given object depends on viewing distance. The VOR compensates for ~90% of the change in visual angle due to rotation-induced translation. This is similar to the performance of the VOR in compensating for rotation. The compensation was not achieved all at once, but instead was generated by a series of successive approximations (Fig. 7). This figure shows the time at which various signals drive compensatory eye movements (Panel A), a schematic signal flow diagram illustrating these signals (Panel B), and a block diagram showing how these signals correspond to different components of the VOR response (Panel C).

Initially, compensatory eye velocity was driven only by head rotation (Panel A, 10–20 ms). This response corresponds to the short latency three neuron arc of Lorente de No [11], and is represented in Panels B and C by the lowermost pathway. Little computation is performed by this pathway; the change in sign indicated by the "−1" box is due to the connectivity of canals with eye muscles. The response is rapid, but does not take into account the effect of eye translation. During far viewing, this pathway is all that is required to generate an ideal VOR.

After 20 ms, viewing distance began to affect eye velocity (Panel A, 20–30 ms). The effect, increased velocity with nearer viewing, is independent of axis location and as a result may be either compensatory (if the axis of rotation lies behind the eyes) or anticompensatory (if the axis of rotation lies in front of the eyes). This signal is computationally similar to, and may use the same neuronal substrate as, the signal that later will compensate for eye–otolith translation. However, the additional eye velocity that is generated is insufficient to produce this compensation at this time. It is possible that the eye–otolith translation pathway has very slow dynamics, first becoming active 20 ms after rotation onset but requiring 80 ms to reach full response (see below).

After 30 ms, an otolith-derived signal was added, compensating for head translation (Panel A, 30–45 ms). This is represented by the upper pathway in the model (Panels B and C),

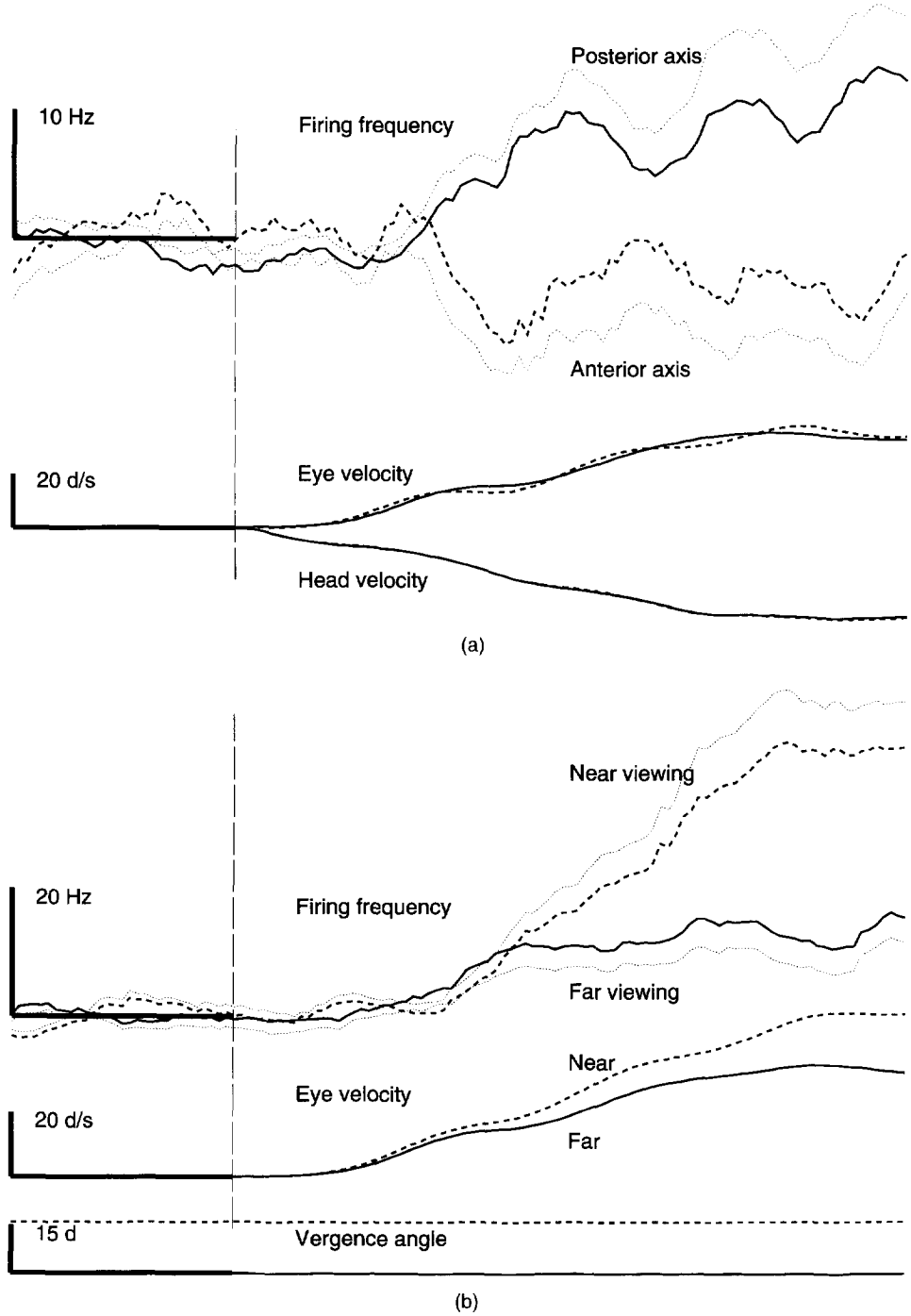

FIG. 6. GVP cell firing in response to sudden head rotation depended on viewing distance and axis location. (A) Averaged GVP cell responses (± 1 SEM) to sudden head rotation about a posterior (solid line, 23 cells) or anterior (dashed line, 8 cells) axis show an abrupt divergence 25 ms after the onset of head rotation. Simultaneously recorded conjugate eye velocities (downward-going) and head velocities (upward-going) are overlaid for the two cases. Contralateral head rotation begins at the vertical dashed line. Heavy horizontal calibration lines on left are 30 ms long. (B) Averaged GVP cell responses (± 1 SEM) to sudden head rotation about a posterior axis during near or far viewing (23 cells). The two traces were offset to align firing in the interval 0–100 ms prior to head rotation (see [12] for a description of the effect of viewing distance on resting GVP discharge). Simultaneously recorded eye velocity and vergence eye angle are shown below.

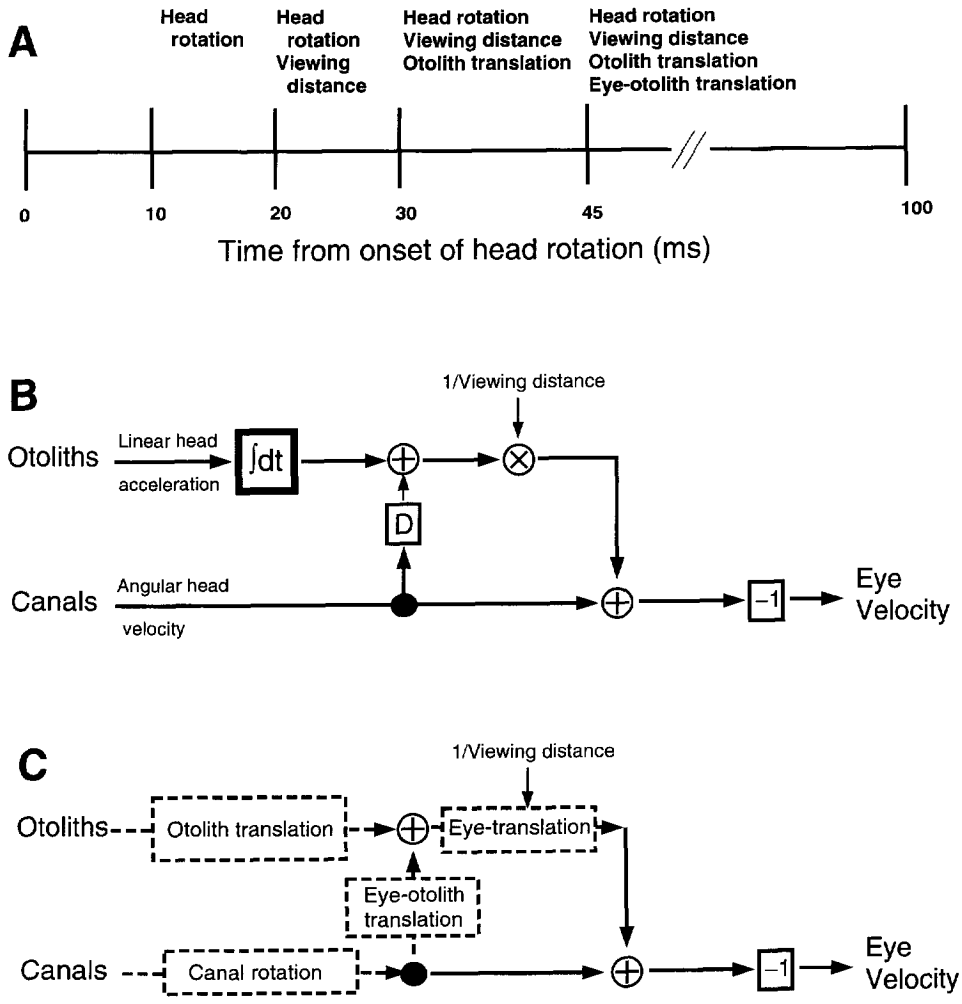

FIG. 7. Time course and model of VOR response to off-axis head rotation. (A) Signals used to drive eye velocity in response to head rotation in four different epochs after the onset of head rotation. See text for discussion. (B,C) Signal flow graph of VOR response to head rotation. Integration box transforms otolith signal from translational acceleration to translational velocity. Scaling of canal signal by "D," the distance between the eyes and the otoliths, corrects for relative eye-otolith translation and when added to otolith translation produces a signal encoding eye translation in space. This signal is scaled inversely with viewing distance and added to a canal rotation signal to obtain a compensatory eye velocity signal. See text for additional details.

which combines with the lower (rotational) pathway to produce the final VOR response. Translation signals, unlike rotation signals, are scaled by inverse viewing distance (multiplicative interaction in upper pathway). The integration stage transforms the otolith signal (linear acceleration) into the required linear velocity. Either of these two additional stages (multiplication by inverse viewing distance or integration) may explain the longer latency of the otoliths compared to the canal pathways. During pure head translation, this pathway is all that is required to generate a compensatory VOR. With distant viewing, the scaling with inverse viewing distance effectively removes this pathway.

Finally, between 45 and 100 ms after rotation onset, the translation of the eyes relative to the otolith organs was computed and compensated, resulting in a fully compensatory VOR (Panel A, 45–100 ms). This stage is represented by the pathway joining the canal and otolith inputs (Panel B). "D" is the anatomical constant describing the distance between the otoliths and the eyes, by which the rotational signal is scaled to compute the rotation-induced translation of the eyes relative to the otoliths (Panel C). This signal is then treated just like an otolith signal, that is, it is scaled by inverse viewing distance. Weak, early activity in this cross pathway may produce the early and comparatively small modulation of the canal-driven response by viewing distance seen 20 ms after rotation onset.

The particular timing observed for the different components of the VOR response may depend on the dynamics of the vestibular stimulus. For example, had we used an axis of rotation far from the animal, the increase in translation relative to rotation might have resulted in the otolith signal becoming discernable somewhat earlier. The significant portion of our results is the unmasking of multiple discrete temporal components in the VOR, and not the specific timing at which those components appear.

There are two previous reports describing the dissection of the VOR response into discrete temporal components. When the VOR is adapted to a higher or lower gain, there appears, both in the monkey and the cat, to be a discrete channel that conveys the adapted portion of the response [7,18]. When the up and down VORs in the unadapted cat are compared, there appears to be an early common component and a later divergent component [18]. Such temporal dissociations suggest distinct neuronal substrates, which may be further revealed by appropriate selective lesion techniques (e.g., [13]), or by single-unit recording techniques. The second half of this report represents the beginning of such an attempt.

GVP Response to Sudden Off-Axis Head Rotation

Type I horizontal GVP cells in the cerebellar flocculus and ventral paraflocculus, which anatomically represent a side loop in the VOR pathways, discharged 25 ms after the onset of head movement in response to translation. After an additional 15 ms, these cells changed their firing, depending on viewing distance. These data suggest that the flocculus is, indeed, involved in the response to rotation-induced translation. The data in Fig. 6A, showing an effect of translation on early GVP firing, was obtained during far viewing, when there was no effect of translation on eye velocity. This signal must, therefore, be canceled, perhaps at a later point in the VOR pathway. This is reminiscent of the proposal of Miles et al. [12] for addition of canal signals to GVP cells, and the subsequent cancellation of those signals at the level of the vestibular nucleus by the addition of an equal but opposite signal. Perhaps a similar mechanism obtains for translational signals. An intriguing possibility is that the translational signal is only completely canceled during far viewing, when the VOR does not compensate for translation; during near viewing, incomplete cancellation would cause this signal to drive compensatory eye movements. Furthermore, if GVP cells are part of a positive feedback loop (as proposed by Miles et al. [12]), then the translational signal might reverberate within the loop, continuing to compensate for eye translation after the acceleration, and, therefore, the otolith stimulation, had ceased.

The effect of viewing distance on GVP firing might represent a feedback of eye velocity on GVP cells [12]. Both polarity and timing were consistent with this interpretation. Type I GVP cells increased their firing rate 10 ms after rotation-induced translation caused an increase in ipsilateral eye velocity. Our current goal is to incorporate our findings into the Miles–Lisberger model of the VOR [10,12]. To do this, further analysis of GVP responses to sudden head rotations are required. Because the Miles–Lisberger model was derived primarily based on data recorded during sinusoidal steady-state stimulation, GVP responses must also be obtained during sinusoidal steady-state performance of smooth pursuit, VOR cancellation, and VOR in the dark, using different viewing distances and rotational axes.

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COMMENTARY

Stimulus

The use of sudden velocity steps, as opposed to sinusoidal stimuli, allows the study of the VOR dynamics in challenging situations of every day life, for instance, during fast unpredictable head motions, when the visual following system is too slow to provide early eye movement compensations. The stimulus and the combination of angular and linear head motions might explain the recordings of very good compensatory eye movements, which corresponded to 90% of the ideal compensation. This result is similar to values obtained for pure rotation, which is considered as a strong reflex, and higher than those obtained in experiments using pure linear accelerations and imaginary targets. Transient stimuli also allow to analyze the effect of a parameter (here target distance and rotational axis location) from eye movement onsets to steady-state responses. This possible decomposition in time of a parameter influence facilitates a better understanding of the central processing taking place between head motion and compensatory eye movements, and might help to postulate which central nervous system pathways are activated to produce these compensatory responses.

Anticompensatory Eye Movements (EM)

At early stages of rotation, anticompensatory EM were produced for an anterior rotational axis and close targets, as viewing distance increased the VOR responses before head translation produced any effect on eye movements. The authors suggested that these anticompensatory responses originated from a guess of a posterior axis of rotation, as it is usually the case in everyday life, for instance, during yaw rotation of the head on the top of the spine. These early effects of viewing distance would, therefore, anticipate the future influence of linear acceleration. Combining Fig. 5a, which shows that the early effect of near viewing was independent of rotational axis location and the ideal and observed responses plotted on Fig. 2, we were able to determine the location of the axis, which would correspond to an appropriate early modulation of eye velocity with viewing distance. This axis was located 2.2 cm or 3.3 cm behind the eyes, depending if the ideal or observed curve was considered. This means that the default rotational axis was situated half-way between eyes and otoliths, and not at the top of the spine. It could be interesting to compare this default rotational axis with the most common axis of horizontal head rotation in the monkeys during whole-body displacements, in case it is different from the top of the spine.

Model

The model shows very nicely how each parameter influences the eye movements to reach adequate compensation. As mention by the authors, the long latency of the otolith-ocular reflex compared to angular VOR can be explained by integration process or scaling with viewing distance. However, it is difficult to understand why the correction for eye translation with respect to otolith translation does not happen at the same time as the otolith translation effect, or even earlier, at the same time as viewing distance. The distance between otoliths and eyes is an idiosyncratic constant; therefore, the rotation-induced eye-otolith translation can be calculated as soon as the rotation commences. To conclude, we will just add that the VOR responses to eccentric head rotation is a useful reflex, as it produces a proper compensation for viewing distances and rotational axes before 100 ms from onset. It is, therefore, the main contributor to visual stabilisation at early stages of natural head movements. It was shown that this reflex can in some cases be anticompensatory, but this was only observed on a short period of time, between 20 and 30 ms from stimulus onset, which might not produce an ocular fixation error big enough to be disturbing during every day life activities.

CLAIRE GIANNA
MRC HMBU National Hospital for Neurology & Neurosurgery, Queen Square, London, WC1N 3BG, UK