Long-Term Adaptive Changes in Primate Vestibuloocular Reflex. I. Behavioral Observations

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SUMMARY AND CONCLUSIONS

1. Experiments were concerned with the long-term adaptive changes that occur in the primate vestibuloocular reflex (VOR) when the visual input associated with head movements is disturbed by various optical devices, including telescopic spectacles (magnification 2.0 and OS), fixed-field spectacles (field of view fixed with respect to the head; hence, equivalent here to "zero power" lenses), and dove prism spectacles (providing left-right reversal of vision).

2. Assessed with sinusoidal oscillations (0.1-1.0 Hz), the VOR of the normal rhesus monkey measured in the dark was close to "ideal" for maintaining ocular stability during head turns: 180° out of phase with the head and gain (slow-phase eye velocity/head velocity) close to one.

3. Telescopic and fixed-field spectacles induced adaptive changes in the gain of the reflex, which proceeded roughly exponentially, eventually achieving up to 75% compensation. No phase changes were observed. Caloric responses in the high-gain state were elevated above normal by an amount corresponding to the increase in VOR gain indicated by passive oscillation. The compensatory eye movements coupled to voluntary head turns in the dark were only slightly greater than would have been predicted solely from the passively assessed VOR gain in both normal and high-gain animals; nonvestibular factors continued to play, at best, a minor role in the stabilization of retinal images during head turns in the adapted animals. Recovery after removal of the spectacles also followed a roughly exponential time course, though it was often more rapid than the original acquisition, especially from the high-gain state.

4. Additional features of this adaptive VOR gain mechanism were: a) rate of acquisition and percentage compensation achieved were very similar from one animal to another and for repeated exposures in the same animal; thus, adaptive gain changes had a machinelike quality and showed no progressive learning effect; b) spectacles were ineffective with 8-Hz stroboscopic illumination, suggesting the necessity for retinal slip; c) the normal and low-gain states were very enduring, surviving a week of head immobilization with almost no change, whereas the high-gain state showed some very slow recovery back toward normal (though the extent of this recovery was dependent on the duration of the prior spectacle experience).

5. Left-right reversing prisms resulted in a large decrease in the gain and a slight phase lag in the horizontal VOR. Both changes proceeded roughly exponentially (time constants approximately 2 and 7 days, respectively). Gain and, to a lesser extent, phase lag, were frequency dependent in the range 0.1-1.0 Hz, both decreasing with increases in frequency. Caloric responses and the compensatory eye movements coupled to voluntary head turns in the dark were both considerably attenuated with respect to normal.

6. After 3 wk of prism adaptation, gain and phase of the reflex were close to asymptote, but daily sessions of forced oscillation begun at this point resulted in a further stage
of adaptation, mostly involving increasing phase lag. A new asymptote was achieved in 3–5 wk and again the phase and gain were frequency dependent, the gain decreasing but the phase lag now increasing with frequency in the range 0.1–1.0 Hz. Reversed responses were most evident with velocity steps but only as an initial transient, rapidly giving way to normally directed responses (time constant averaging 2.1 s). A similar time sequence—transient reversal followed by a return to normal—was also evident during voluntary head turns in the dark and caloric nystagmus (though the initial reversal here was, at best, very weak).

7. It is concluded that in the monkey the VOR is a plastic system, which is subject to visually mediated, long-term adaptive regulation; these processes function to adjust the performance of the system so that a stable retinal image is preserved during head turns.

INTRODUCTION

The function of the vestibuloocular reflex (VOR) is to maintain a stable retinal image during head rotations by generating appropriate compensatory eye movements. In the rhesus monkey, this reflex has a gain (measured as slow-phase eye velocity/head velocity, in the dark) close to one, and contributions from other sources, for example, neck proprioception or preprogramming, are very minor (3). An important aspect of this system is its open-loop mode of operation (11), and in order to function appropriately it must be properly calibrated. A number of studies have demonstrated that the VOR undergoes adaptive changes when the visual input associated with head movements is modified by various optical devices such as dove prism or telescopic spectacles or conditions simulating the same (7–10, 12–16, 20, 22, 23). Such adaptation must depend on vision since in the final analysis, only vision can document the adequacy of the VOR. Persistent slip of the retinal image during head turns not only signals the need for recalibration of the VOR, but also specifies the exact nature of the change needed to achieve it, e.g., an increase or decrease in gain.

Our primary interest is in the neural modifications underlying these adaptive processes in the VOR and we have undertaken a series of electrophysiological studies in the awake rhesus monkey in an attempt to determine their anatomical location. The present report is the first of a series of four papers and describes the various optical devices that we have used to induce adaptation and the general nature of the VOR changes that result. The second paper (18) documents recordings from semicircular canal primary afferents—which provide the input signals for the VOR—and shows that their responses to natural vestibular stimulation are unaffected by adaptation; the neural changes must, therefore, occur within the central nervous system. The last two papers (19, 21) document recordings from the flocculus, a structure that others have suggested is the site of the neural changes underlying adaptation (11–13, 22). The first of these two papers describes the discharge patterns in the flocculus of the normal monkey and defines the information processing in that structure; this report also provides a quantitative data base for subsequent comparison with data from the adapted monkey, which forms the substance of the last paper. The latter reports changes in the vestibular responses of the most common type of Purkinje output cell in association with adaptation, but it is argued that these neural changes are more likely to be a secondary consequence—rather than the primary cause—of the VOR gain changes.

METHODS

Data were collected from eight adolescent rhesus monkeys (Macaca mulatta) weighing between 4 and 5 kg. Under Nembutal anesthesia, each monkey was fitted with a pedestal secured to the skull in the vertical stereotaxic plane through implanted bolts to allow fixation of his head and the attachment of various spectacles. Silver/silver chloride electrodes (after Bond and Ho (4)) were implanted to permit measurement of horizontal and vertical eye movements by DC electrooculography (–3 dB at 25 Hz).

The horizontal vestibuloocular responses were assessed from the compensatory eye movements generated by the monkeys when they were passively oscillated about the vertical axis in the dark in a primate chair powered by a torque motor under servo control. The monkeys' heads were secured to the chair in the normal stereo-
FIG. 1. A sample segment of data used to determine the gain and phase of the VOR. The monkey was oscillated in total darkness. H. and H, chair (head) position and velocity; E and E, horizontal eye position and velocity. Positions are measured in degrees, and velocities in deg·s⁻¹. Irregularities in the chair velocity trace originated in the waveform generator and not the servo system.

taxic position with the axis of rotation passing midway through the interaural line. Monkeys were water deprived and trained on a visual-fixation task (after the paradigm of Wurtz (24)) to allow calibration of the oculogram.

Eye velocity and chair velocity were derived by differentiation of the oculogram and chair position signals, respectively (bandwidth: DC to 25 Hz), and all signals were displayed on a rectilinear six-channel Gould Accuchart recorder (DC to 100 Hz, −3dB). Gain and phase of the VOR were measured using sinusoidal chair oscillations in the frequency range 0.1−1.0 Hz, with amplitudes ranging from ±5° to ±35° (gain − peak-to-peak eye velocity/peak-to-peak chair velocity). Phase of the vestibulocular response was calculated from the eye velocity and chair velocity peaks (see Fig. 1). Following the practice of other investigators (8, 22), we arbitrarily assigned zero phase shift to the pure antiphase behavior that would be seen if ocular compensation were perfect, hence any lead or lag is an index of the extent to which the system deviates from the ideal normal performance. Because the oculogram is very sensitive to changes in luminance, monkeys were placed in the dark for at least 20 min before calibration of the oculogram, which was achieved with dim LED fixation lights (each subtending approximately 10° of arc) placed 20° to each side of the primary gaze position. Oscillation tests were interrupted at approximately 1-min intervals to check the gain of the oculogram (resolution equivalent to about 1° of eye movement). An assortment of background noises were created in an effort to maintain alertness of the animal.

Each VOR gain data point was based on the mean of at least 20 measures. Peak-to-peak measures eliminate problems related to dark drift, which can reach several degrees per second in the rhesus monkey. Phase measure accuracy was somewhat dependent on the test frequency; individual phase measures at 0.1 Hz were each accurate to within 7°, those at 1.0 Hz to within 14°. Phase data points were each based on the mean of 10 measures.

As a further assessment of the horizontal VOR we employed caloric irrigation tests. Like all vestibular tests these were carried out in total darkness and any spectacles that the animals were wearing were removed. To facilitate stimulation of the horizontal canals, the monkeys' heads were tilted back 25° and one ear infused with cold water (28°C), though occasional tests were done with warm water (46°C). Water was delivered with an infusion pump through 1.5-mm-diameter polyethylene tubing introduced 20 mm into the external auditory meatus. The infusion rate was 0.3 ml/s applied for 20 s. All tests were carried out after 20 min of dark adaptation to allow the gain of the oculogram signal (which was determined at that time using the standard fixation task) to stabilize. Using the slow-phase eye velocity profile as a quantitative measure of the caloric response, we were surprised to find that cold-water irrigation gave reliably reproducible data for a given animal from session to session (standard deviation less than 10°/s, with peak velocities of about 100°/s in the normal animal), and the interanimal variation was also less than we had feared (mean peak velocities for three monkeys ranged from 90 to 110°/s).

By coupling the head to a low-friction rotary potentiometer (cf. Bizzi et al. (3)), which limited head movements to the horizontal plane, it was possible to assess the magnitude of the compensatory eye movements coupled to voluntary head turns made in complete darkness. The head could be immobilized by an electrical brake to facilitate calibration of the oculogram. Monkeys were encouraged to make head turns by hand claps and extraneous noises; no visual stimuli were employed. Analog recordings of eye and head rotation were stored on an FM tape recorder for subsequent playback and quantitative analysis. Monkeys were fitted with one of four types of spectacles, with the surrounding visual field being masked off with black tape. 1) Binocular
telescopic spectacles, of two kinds, were used: a) concave eye pieces and convex field lenses in a Galilean configuration provided ×2 magnification with a viewing aperture subtending 46° to each eye, b) a reversal of the above lens arrangement provided ×0.5 magnification with a viewing aperture subtending 50° to each eye. 2) Binocular fixed-field spectacles, in which two identical photographic slide transparencies were each viewed through a convex lens (as in the common slide viewer). The transparencies were placed one focal length away from the lenses, providing upright, enlarged, virtual images at infinity subtending approximately 45° to each eye. The transparencies were backed with a white acrylic plastic diffusing material and the animal surrounded by several light sources to provide a reasonably uniform background illumination; we are satisfied that no sharp external light gradients were apparent to the animal. Two different photographic pairs were used: the first was of a seated monkey, and the second a reproduction of a Jackson Pollack abstract painting entitled, “Number 3, 1949” (presently in the Hirshhorn Gallery, Washington, DC). This optical arrangement provides a visual world that is fixed with respect to the head and, hence, if its retinal image is to remain stable during head turns, then the normal compensatory eye movements must be eliminated. 3) Binocular dove prism spectacles provided upright, left-right reversed images. The prisms were specially machined from clear acrylic and arranged base out for maximal field of view. Prism separation and alignment were adjusted to provide a few degrees of binocular overlap to facilitate fusion of images. Most of the field, however, was viewed monocularly. Viewing apertures subtended approximately 50° vertically and 40° horizontally to each eye.

Animals were seated in a primate chair throughout the spectacle experience to prevent them from interfering with the lenses; this necessitated hand feeding. In some experiments this chair was oscillated about the vertical axis with the monkey’s head secured to it (passive exposure condition). A few experiments were carried out in a stroboscopically illuminated room (10-μs flashes at a frequency of 8 Hz).

RESULTS

Table 1 shows the VOR gain and phase measures over the frequency range 0.1–1.0 Hz for several monkeys before exposure to any spectacles. Gains were very close to unity and phase showed a negligible lag from zero. There were no significant differences between gain and phase measures at different frequencies. The vestibuloocular responses to alternating velocity steps (triangle-waveform stimulus) at 0.15 Hz were also assessed (as described by Miles and Fuller, Ref. 20) and showed a mean gain of 0.99 (SE, 0.015; n = 6).

### I. Adaptation to Telescopic Spectacles

Figure 2 shows the time courses of: a) acquisition of a new VOR gain level when monkeys wore ×2 or ×0.5 telescopic spectacles, and b) recovery after the spectacles had been removed and the animals returned to the home cage. In each case, the data from three animals are shown. Given the numerous variables involved, e.g., alertness, mobility while wearing the spectacles, and time spent sleeping, the data from the three animals are surprisingly consistent. Exponential curves were fitted to these data, forcing through the mean start points and mean asymptotes and, with the exception of the initial changes in the first few hours—when the actual changes usually exceeded the best-fit curve—provide a reasonable index of the time course of the changes. RMS errors of the least-squares best fit for the two acquisition curves in Fig. 2 are 0.07 (×2 spectacles) and 0.03 (×0.5 spectacles). Phase was not significantly different from normal in any of the adapted animals over the range 0.1–1.0 Hz.

It took the animals longer to acquire the high-gain state than the low, and this is reflected in the mean time constants of acquisition taken from the best-fit curves: 39 h for the adaptation to ×2 spectacles and 8 h for the ×0.5 spectacles. However, there are several differences between the visual experience provided by the two kinds of spect-

### Table 1. Gain and phase of VOR in normal rhesus monkey

<table>
<thead>
<tr>
<th>Frequency, Hz</th>
<th>Gain</th>
<th>Phase, deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1 (7)</td>
<td>1.03 ± 0.02</td>
<td>−1.5 ± 0.5</td>
</tr>
<tr>
<td>0.2 (8)</td>
<td>0.99 ± 0.01</td>
<td>−1.9 ± 0.7</td>
</tr>
<tr>
<td>0.4 (4)</td>
<td>0.98 ± 0.02</td>
<td>1.1 ± 2.2</td>
</tr>
<tr>
<td>1.0 (4)</td>
<td>1.00 ± 0.03</td>
<td>−2.2 ± 1.0</td>
</tr>
</tbody>
</table>

Values are means ± SE. Phase is relative to “perfect” compensation; negative values indicate lag. Values in parentheses are n.
Spectacles, which may influence the rate of acquisition, and these will be considered later in the DISCUSSION section. No systematic investigation of these various factors was undertaken.

The adaptive process never fully compensated for the spectacles, VOR gains reaching a mean asymptote of 1.70 (SE, 0.013) with the $\times 2$ spectacles and 0.73 (SE, 0.017) with the $\times 0.5$ lenses ($n = 6$). (Although the data shown were all obtained with 0.2 Hz, $\pm 20^\circ$ oscillations, gains were independent of frequency and amplitude in the ranges 0.1–1.0 Hz and $\pm 5$–$\pm 35^\circ$.) This was not due to any physical limitations of the system; higher values (1.9 or more) were obtained when the animals in $\times 2$ lenses were subjected to daily sessions of forced oscillation (0.2 Hz, $\pm 30^\circ$ for 5 h), and much lower values (0.35 or less) were obtained with fixed-field spectacles (see Fig. 7).

After removal of the spectacles, recovery also proceeded with a roughly exponential time course; RMS errors of the least-squares best-fit exponential for the recoveries from both the high- and the low-gain states in Fig. 2 are 0.05. Recovery rates, as indicated by the time constants of the best-fit curves, were similar in the two cases: 9 and 15 h for the high- and low-gain states, respectively.

Compensatory eye movements coupled to active head turns

The apparent failure of the VOR adaptive processes to achieve full compensation for the spectacle lenses is puzzling and led us to consider other possible mechanisms, such as preprogramming and neck proprioception, which might operate in the normal free-head situation but not in our passive oscillation tests. For this reason, we examined the compensatory eye movements coupled to the animals' normal, self-generated head turns in total darkness. Rather than attempt laborious measurements directly from the raw data, we recorded both eye and head position signals on analog tape and then, on
playback, synthesized gaze by summing the two signals with an operational amplifier. By adjusting the weighting of the eye position input to the summing amplifier so that the adjusted eye movement signals exactly counterbalanced the original head movement signals, it was possible to simulate a flat "gaze" signal (see Fig. 3). Knowing the weighting factor, it was then a simple matter to deduce the "gain" of the original compensatory eye movements, e.g., if it was necessary to halve the eye signal to obtain a flat gaze trace, then the animal must have been generating compensatory eye movements that were exactly twice as great as the head movements (gain = eye movement/head movement = 2.0). Assessed in this way, the compensatory eye movements coupled to normal head turns in darkness showed some variation from movement to movement, necessitating that the data be played back with several different weightings to establish gain values for every head movement. For the naïve animals, these gains typically varied from 0.85 to 1.05 with different head movements, but there was no apparent consistency about this variation—it did not seem to vary systematically with either the magnitude or the velocity of the head movement—and the mean was not significantly different from the passively assessed mean VOR gain (mean ± SE for three animals: 0.96 ± 0.13 for "active" versus 0.93 ± 0.08 for "passive").

After adaptation to ×2 spectacles, compensatory eye movements coupled to active head turns again showed considerable variability from one head movement to another (gains ranged from 1.6 to 2.0) and still there was no consistent relationship between this gain and the magnitude or velocity of the head movement. On occasions, the active gain showed complete compensation for the spectacles, but the mean was still short of this. Nonetheless, the gains of the compensatory eye movements coupled to active head turns were, on average, a little greater than those coupled to passive oscillation (means ± SE for three animals, 1.84 ± 0.019 for active versus 1.73 ± 0.013 for passive), and this difference was significant ($P < 0.001$, two-way analysis of variance). This may represent some small contribution from neck proprioception or preprogramming, though it is probably more likely due to small differences in the level of arousal in the two situations. Whatever the explanation, the active situation does
FIG. 4. Caloric responses following cold-water irrigation of the right ear with the head tilted 25° back from the normal stereotaxic position to activate the horizontal semicircular canal (one animal). The irrigation period is indicated by the black bars. A: sample data from the monkey when adapted to ×2 spectacles. (E, horizontal eye position; \( \dot{E} \), horizontal slow-phase eye velocity, in deg·s^-1). Rightward (ipsilateral) movements are indicated by upward deflections. B: similar data from the animal when normal. C: mean slow-phase eye velocity profiles for three caloric tests in the high (a) and normal (b) gain states. D: ratio of the mean slow-phase eye velocities during caloric responses in the high-gain and normal states. Throughout a major portion of the response, the ratio (high gain/normal) was 2.15 (SEs of ratios ranged from 0.05 to 0.03), compared with a horizontal VOR gain ratio based on passive oscillation tests of 2.03.

Caloric tests of vestibular function

In order to test whether adaptation was specific to the test situation, we also performed caloric tests as a measure of vestibu-
VESTIBULOOCULAR REFLEX ADAPTATION I

x2.0
Spectacles
on

x 2.0
Spectacles
off

Gain = 1.02 + 0.61 \times e^{-0.023 t}

FIG. 5. VOR gain changes associated with repeated exposures to \(x2\) spectacles (one animal). Spectacles were worn for periods of 8 days interspersed with 8 days of recovery. Note the time constant \(t\) in the gain equations is in hours. RMS error for the least-squares best-fit exponential was 0.06 for both the acquisition and recovery data.

ular function. Slow-phase eye velocities following caloric irrigation were consistently greater than normal when the animal was in the high-gain state following exposure to \(x2\) lenses, and by an amount approximating the difference in the VOR gains. Figure 4 compares the caloric responses of a monkey when normal (mean VOR gain, 0.94; SD, 0.04) with those when it was adapted to \(x2\) spectacles after daily sessions of forced oscillation while still wearing the spectacles (VOR gain, 1.91; SD, 0.07). Over the major portion of the response, the mean ratio of the eye velocities (high gain/normal) based on three separate irrigations in each of the two conditions was 2.15, a figure that compares very favorably with the ratio of the VOR gains assessed by passive oscillation, 2.03. In one other monkey the two ratios were 1.88 and 1.80, respectively. Thus, caloric irrigation provides an estimate of vestibular function following spectacle adaptation, which is fairly consistent with the results of the passive oscillation tests.

Repeated exposure to telescopic spectacles

The rate of acquisition of the high-gain state during exposure to \(x2\) spectacles and also the degree of adaptation finally achieved were relatively independent of any previous experience the monkey may have had with telescopic spectacles. Figure 5 shows the time course of the VOR gain changes when a monkey was exposed to \(x2\) spectacles on three consecutive occasions with interspersed recovery periods. Exponential curves were fitted to the data for each exposure and each recovery, and their time constants derived. It is evident from the individual data points in Fig. 5 and the derived time constants listed in Table 2, that there is no progressive increase in \(a\) the rate of acquisition, \(b\) the final gain achieved, and \(c\) the rate of recovery. For recovery, however, the time constant is clearly significantly larger for the second than for either the first or the third; this is due to one data point. The fact remains that the time constant of the third recovery is not significantly different from the first, and the rate of recovery does not increase progressively with two repetitions.

Plasticity of VOR

To assess the enduring nature of the VOR and, in particular, its ability to retain the modified state in the absence of reinforcement, we examined the effect of immobilizing the monkeys' heads, a procedure that precludes the simultaneous visual and vestibular experience needed to actively maintain VOR calibration.

No spectacles were worn during the period of immobilization and animals were blindfolded during transportation to the VOR test room. When the animal was in the naive or low-gain state, the VOR gain changed very little during head immobilization over the period of a week (Fig. 6). How-
ever, in the high-gain state, the gain tended to fall roughly exponentially during immobilization, though much more slowly than during normal free-head recovery (compare Figs. 6 and 2) and achieved asymptote short of the normal preadapted level: hysteresis. The magnitude of this hysteresis depended in part on the duration of the prior spectacle experience. Thus, when the animal had worn the spectacles for only 24 h, the hysteresis was negligible, whereas after wearing them for 14 days, the gain reached asymptote at 1.21. However, increasing the prior spectacle exposure to 5 wk (not shown) did not result in any further significant increase in the hysteresis. The longest time constant observed following 14 days of spectacle experience was 141 h and the highest asymptote was 1.27 (n = 4). The decay was not due to inadequate head immobilization since when monkeys continued to wear the ×2 spectacles throughout the period of head immobilization, the effect on the decay was negligible.

Unsuccessful attempts to change VOR gain with ×2 spectacles in stroboscopically illuminated surroundings

Two animals fitted with ×2 spectacles were subjected to a stroboscopically illuminated environment (10 µs flash at 8 Hz) for 5 days. Neither animal showed a significant change in gain although under normal luminance conditions both showed a normal adaptation to ×2 spectacles.

Fixed-field spectacles

The fixed-field spectacles provide a visual input that is fixed with respect to the head (see METHODS). If the animal is to stabilize the retinal image provided by these spectacles during head turns, then his VOR must

![Graph](image-url)

**FIG. 6.** Effect of immobilizing the head on the gain of the VOR. All data were from the same animal. See text for discussion.
be attenuated to zero. Figure 7 shows that such spectacles do produce a considerable attenuation in the VOR gain. The changes proceeded roughly exponentially (RMS error for the least-squares best-fit exponential, 0.05), with a time constant of 23 h (SE, 3.9) and an asymptote at 0.32. Again, the exponential curve is forced through the mean initial gain and the resultant fit is least good at the earliest times, when the actual gain attenuates much more rapidly than the fitted curve. With subsequent daily sessions of forced oscillation (0.2 Hz, ±30° for 5 h), the gain continued to fall very slowly at a roughly linear rate of 0.0034 per day for the remaining 10 days for which measures were taken. If this rate of attenuation were to have continued, it would have taken a further 70 days before the gain reached zero.

The magnitude of the gain attenuation with fixed-field spectacles was independent of the test frequency used in the range 0.1–1.0 Hz, and phase was never significantly different from normal. The mean asymptotic gain values for four animals were 0.32, 0.35, 0.38, and 0.41, measured at 0.2 Hz. There was no significant recovery over a 7-day period if the head was immobilized when the spectacles were removed, again confirming the enduring nature of the low-gain state.

II. Adaptation to Reversing Prisms

The telescopic and fixed-field spectacles employed above called for changes only in the gain of the VOR, and phase changes were, as expected, negligible. Left-right reversing prisms, by contrast, demand a 180° phase change in the horizontal VOR if the animal is to maintain stable retinal images during head turns. However, in agreement with previous findings in man (8, 9) and cat (22), the major initial response in the rhesus monkey on exposure to these prism spectacles was a massive attenuation of the horizontal VOR with rather minor changes (a lag) in the phase (see Fig. 8). Again, these changes proceeded roughly exponentially; for three animals, the mean time constant of the gain change was 49 h (SE, 5.4) and of the phase change, 166 h (SE, 43.0). After 3 wk, gain and phase reached asymptotes far short of the ideal: for the three animals, using 0.2-Hz test frequencies, mean gain was 0.27 (SE, 0.08) and mean phase lag was −32° (SE, 4.8°). However, the gain was very dependent on the test frequency and in the range 0.1–1.0 Hz showed greater attenuation at the higher frequencies (see Fig. 9B and D).

We examined the eye movements coupled to active head turns in darkness in one of these monkeys and observed attenuated compensatory eye movements; “reversed” compensatory eye movements were never seen. The gain of these compensatory eye movements fluctuated considerably, even during a single head movement, ranging from 0.3 to 0.6 (mean, 0.47). Caloric responses were also attenuated to approximately 55% of the normal and not reversed.

Since the data suggested that both gain and phase had reached asymptote, it was de-
Fig. 8. Three-dimensional graph detailing the time course of the horizontal VOR gain and phase changes during adaptation to left-right reversing prisms (one animal). Each data point is the mean of 20 measures. Commencing after the measurement on the 22nd day, the monkey was subjected to daily sessions of forced oscillation. See text for discussion.

sessed at this point to impose daily sessions of forced oscillation at 0.2 Hz, ±30°, each lasting 5–6 h. After just 1 day of the forced oscillation routine, the horizontal VOR gain (assessed with 0.2 Hz, ±20° test oscillations) showed further considerable attenuation and phase lag. In the case shown in Fig. 8, the gain dropped below 0.2 and a phase lag of 90° was evident. Over the next 2 wk the gain continued to fall and the phase, which became extremely difficult to measure, fluctuated considerably from day to day and even in the course of one test session (SDs as high as 40°), ranging from moderate lag (approximately −90°) to almost complete reversal (−170°). Gradually, over the succeeding 5 wk, these responses become more consistent, the gain increasing to 0.3–0.4 with a phase lag of about −150° at 0.2 Hz (see Fig. 8). However, the gain and phase were both very sensitive to the test frequency in the range 0.1–1.0 Hz; while the phase lag increased with frequency, the gain decreased (see Fig. 9E). Thus, the VOR gain and phase changes associated with prism adaptation in the monkey appear to follow the same general pattern as those previously reported for man (9) and cat (15). In our case, however, we did not observe very significant phase changes until we used the forced oscillation routine. (Note that the frequency dependence was evident even before this—see Fig. 9B and D.) Reversed compensatory eye movements were most evident using triangle-waveform oscillations of the chair, which also served to emphasize the unusual dynamic characteristics of the response. Thus, it is evident in Figs. 9C and 10 that reversal is only transient, with slow-phase eye velocity commencing in the same direction as the chair movement immediately following the turnaround but decaying roughly exponentially thereafter with a time constant of approximately 2 s. By the end of each half-cycle, the eye velocity has frequently passed through zero and is either "normally directed" or about to become so. The time constant of the decay ranged from 1.5 to 5.1 s and averaged 2.1 s (three animals).

Caloric responses
Caloric nystagmus in these reversed animals was considerably attenuated (to approximately 40% normal; see Fig. 11) and normally directed, except perhaps during the initial few seconds when there is some slight suggestion of a brief reversal. Figure 12 shows the initial phase of caloric nystagmus in six tests on two different animals that had both shown the initial transient reversed eye movements during triangle-
FIG. 9. Effect of left-right reversing prisms on the horizontal VOR (one animal). A–C: responses to velocity steps. Note by day 21, when attenuation has reached an asymptote (cf. Fig. 8), the slow-phase eye velocity profile shows a roughly exponential rise with a time constant of about 2 s. By day 55 (after 5 wk of daily forced oscillations) the initial response is now reversed but decays roughly exponentially with a similar time constant so that eye movements are normally directed by the end of each half-cycle. Unfortunately, the eye velocity trace is contaminated with an artifact at each turnaround. D, E: responses to sinusoidal stimulation (Bode plots); vertical bars indicate SD and discontinuous lines represent the simulation data. Inset: an analog version of the Davies-Melvill Jones model (5). Circuit parameters were derived from the velocity step responses, the only differences between the 21-day and 55-day simulations being in $R_1$ (60 and 45 k$\Omega$, respectively) and $R_3$ (78 and 138 k$\Omega$, respectively). Other parameters were: $R_0 = 10$ k$\Omega$, $R_2 = 100$ k$\Omega$, $R_4 = 200$ k$\Omega$, $C = 10 \mu F$. See DISCUSSION section for a detailed explanation.

waveform oscillation tests. All responses were the result of cold-water irrigations of the right ear and the resulting nystagmus showed the usual ipsilateral slow-phase eye movements (upward deflection in Fig. 12), though much less vigorously than normal. However, commencing some 7–10 s after the onset of irrigation and immediately prior to the onset of the ipsilaterally directed, slow-phase eye movements, the eyes have a tendency to drift in the contralateral direction (see arrows in Fig. 12). Such contralaterally directed eye movements were seen in all 16 of the caloric tests conducted, though in four cases they were too weak to be distinguished from the prevailing ocular drift (e.g., B and C in Fig. 12). Except for these transient and not very compelling initial responses, caloric irrigation elicited slow-phase eye movements in the usual direction. Thus, at best, reversed caloric responses were transient and rapidly gave way to normally directed, though attenuated, responses.

**Eye movements coupled to self-generated head movements**

The data shown in Figs. 8–12 indicate that the rhesus monkey's ability to reverse its vestibuloocular responses in the 3-mo time
FIG. 10. Reversed vestibuloocular responses after 70 days of prism adaptation, including daily sessions of forced oscillation. These were among the most dramatic reversed responses observed in the four monkeys studied. Notation as for Fig. 1.

span of our experiments was extremely limited. However, it seemed possible that the monkeys might be able to achieve better performance during active head turns than during the passive rotations, which served as the basis for our VOR gain measurements. Data such as those presented in Fig. 13 suggest to us that they are not. Thus, while the "compensatory" eye movements coupled to self-generated head turns in total darkness showed reversal (eyes moving in the same direction as the head), it was both weak and transient. During the larger, longer-lasting but still reasonably rapid head movements (e.g., C in Fig. 13), reversed compensatory eye movements were only evident during the initial period of the head movement and were followed by small, normally directed compensatory movements. These ocular responses are at least similar in form to those seen in the passive oscillation tests using the triangle-waveform stimulus: an initial reversed response that decays rapidly and gives way to normally directed responses.

It should be noted that when the monkey first wears the prism spectacles, visual input is only really effective in reversing the eye movements associated with self-generated head turns when the latter are rather slow; most voluntary head movements in light were associated with attenuated, normally directed, compensatory eye movements, hence the animals must suffer considerable retinal image slip during this time. Following adaptation, however, good reversal was ob-
FIG. 11. Effect of prolonged prism adaptation (including daily forced oscillation) on caloric responses: cold-water irrigation of the left ear with the head tilted 25° back from the normal stereotaxic position to activate the horizontal semicircular canal (one animal). The notation is the same as for Fig. 5, with leftward (ipsilateral) movements producing downward deflections. A: sample data from the monkey when normal. B: similar data from the same monkey when adapted to left-right reversing prisms for 55 days. C: mean slow-phase eye velocity profiles for three caloric tests in the normal (a) and prism-adapted (b) states. D: ratio of the mean slow-phase eye velocities during caloric responses in the prism-adapted and normal states. Throughout a major portion of the response, the ratio (prism adapted/normal) was 0.45 (SEs of ratios ranged from 0.02 to 0.09).

served in light during most head movements, though we did not actually obtain a gain measure.

DISCUSSION

The present experiments have attempted to document the general nature of some adaptive processes in the primate vestibuloocular system. When sinusoidal test stimuli are used it is clear that adaptive changes can occur in both the gain and the phase of the vestibuloocular responses. The need for adaptive gain control in an open-loop control system such as the VOR has been well argued by others (11, 22), but the necessity for phase control is less apparent and has received little attention. Telescopic and fixed-field spectacles call for, and elicit, changes only in the gain of the VOR, and
in discussing adaptive gain control we shall restrict our considerations to the data obtained with these optical devices. Although dove prism spectacles also elicit VOR gain changes, we feel that their major diagnostic value concerns what, for want of a better term, for the present we shall refer to as adaptive phase control. We feel that this sharp distinction between gain and phase control is not merely a didactic convenience since the neural mechanisms underlying adaptive control of these two parameters are most probably quite different.

Adaptive gain control
There are a number of factors concerning the visual experiences provided by the various optical devices, which may have had subtle, unintended repercussions, especially on the rate and extent of the adaptive gain changes.

1) Area of retina appropriately stimulated.
Since the viewing apertures were only 45–50° in the various spectacles, the amount of retina appropriately stimulated was very limited. Probably more important, however, is that the frame of the spectacles, being fixed with respect to the head, may have hindered adaptation with the ×2 spectacles (by providing competing images), while aiding the process in the other two devices.

2) Optical quality of the images. While chromatic and spherical aberrations were very minor in the ×0.5 and fixed-field spectacles, they were quite evident in the ×2 spectacles despite the use of an achromatic doublet field lens. Furthermore, the ×2 spectacles had a limited depth of focus, which resulted in blurring of objects closer than about 2 m. Accordingly, we arranged for most objects within the field of view to lie beyond this point. This was not a problem with either the ×0.5 lenses (which have a large depth of focus) or the fixed-field arrangement (which was adjusted for normal viewing). We do not know if the animals could fuse the binocular images.

3) Image velocities. The differences in the magnification factors (considering the fixed-field spectacles as equivalent to zero power telescopic) would mean that, initially at least, the monkey was dealing with greater retinal image velocities (for a given head movement) in the ×2 and fixed-field spectacles than in the ×0.5 spectacles. In the former, if there were no visual following (clearly unlikely), then retinal image velocities would approximate head velocity, while in the ×0.5 spectacles they would be only half as great. Since we do not know exactly how successful the animals were in reducing retinal-slip levels with visual feedback and, furthermore, nothing about the velocity characteristics of the visual neurons carrying the error information for VOR recalibration, it is not possible to deduce the significance of these differences between the various spectacles. (It will be recalled that adaptation did not take place when the surroundings were stroboscopically illuminated, a finding that is consistent with the view that retinal-image slip is an essential element in the process (cf. Ref. 17).)

4) Field of view. Only a 23° cone of the outside world was visible to the animal wearing the ×2 spectacles, while some 100° were visible with the ×0.5 lenses. There was, therefore, less need to make head movements to explore the surroundings when wearing the reducing spectacles. Animals in fixed-field spectacles of course viewed an unchanging scene subtending approximately 45° to each eye, and many of their head movements seemed to be directed...
toward extraneous sounds in the room (which housed a colony of caged monkeys).

The last two factors may have induced the monkeys to produce different patterns of head movements when wearing the different spectacles, and the head movements that best satisfied their whimsical exploratory needs may not have been optimal for the VOR recalibration process. As a result of all of these variables, it is not possible to infer the extent to which the adaptive processes per se are responsible for the differing acquisition rates and percentage compensations achieved with the various optical devices. Indeed, this leads one to suspect that the acquisition rates reported here are all rate limited by extraneous factors related to the spectacle experience and, hence, do not represent the system’s true capabilities.

Although the rate-limiting factors are not clear, it is nevertheless evident that the gain changes associated with the various optical devices were always adaptive, operating always to improve retinal image stability during head turns. Furthermore, for a given optical arrangement, both the rate and the magnitude of these changes were very similar from one animal to another and also for repeated exposures in a given animal; adaptation proceeded in a rather machine-like fashion.

Plasticity

Once an appropriate VOR gain has been achieved it would clearly be an advantage for the system to be able to retain it without the need for continuous visual reinforcement. This is necessary if performance is to endure periods of sleep, darkness, and so forth. Thus, once the system has been molded into the correct state it should retain the state until the need arises to remold it. A system that is modifiable and has the ability to retain the modified state without reinforcement is said to be plastic. Head immobilization is one way of precluding the visual-vestibular interactions necessary for the active maintenance of the VOR (another would be blindfolding), and the reflex’s ability to survive such “deprivation” provides a measure of its enduring capability. When the VOR was in the normal or low-gain state it was clearly stable, showing little if any significant change when the head was immobilized (at least for a period of up to 1 wk). However, the high-gain state was quite labile, especially during the initial acquisition phase, and the VOR tended to gravitate to a lower (more normal) level during head immobilization. That this decline tended to become less severe following longer exposures to the spectacles suggests that some kind of consolidation process is involved, but some decline was always evident in the present experiments, even with the longest exposures to ×2 spectacles (5 wk). Robinson (22) also noted some slight recovery toward normal when cats were placed in darkness overnight during the acquisition phase of prism adaptation, and this disappeared once adaptation was complete.

A single-state system?

The above discussion implies that, in the monkey, the compensatory eye movements coupled to head rotations are generated almost entirely by the VOR (cf Ref. 3), which can be viewed as a single-state system with an invariant gain at any given time. It is known that man can adopt strategies that can have a considerable immediate influence on the eye movements coupled to head movements even in the dark (2). This makes it very difficult to establish the gain of the “basic” VOR in man. Similar experiments have yet to be tried in the monkey, but it is clearly important to establish that in the present experiments we were measuring and modifying the fundamental VOR and not witnessing on-line parametric adjustments resulting merely from some learned strategy on the part of the monkey. There are several characteristics that encourage us to believe that such factors did not contribute significantly to our present findings:

1) Neither the rate of adaptation to telescopic spectacles nor the rate of recovery following their removal increased with repeated exposures, as one might have expected if the animals had merely been learning some strategy that could be used at any time to adjust the magnitude of their compensatory eye movements.

2) Caloric tests revealed changes in the vestibuloocular system of the adapted animals, which (with the possible exception of the prism adapted) closely paralleled those
seen with the more usual passive oscillation tests. Given the vastly different contextual information available to the animal in these two test situations, one might have expected very different results if strategy-specific parametric adjustments had been involved.

3) When the monkey’s VOR adapts to fixed-field spectacles, the benefits accrued are minimal. The adaptation does not, for instance, enable the monkey to better visualize the events that he can hear going on around him and one might reasonably expect that after a few hours viewing the unchanging scene, the monkey would become disinterested. Nonetheless, the vestibuloocular responses continued to show adaptive changes for the several days that it took to reach an asymptote. It is not even necessary for the monkey to produce the head movements; passive oscillations work equally well. Thus, an actively involved and highly motivated subject does not seem to be a prerequisite for adaptation to proceed. Under normal circumstances, it would seem that little is required of the animal beyond moving its head and keeping its eyes open.

4) When assessed by the usual passive techniques, VOR adaptation to the various spectacles was never complete, raising the possibility that additional mechanisms were available to the actively moving animal to achieve “full” adaptation. But this was not the case; the compensatory eye movements accompanying self-generated head turns were similarly lacking. Thus, the adapted animals continued to be as dependent on the VOR for the maintenance of stable retinal images as the normal animal and did not make use of neck proprioception or pre-programming strategies. Given the time frame of the present experiments, this was probably not surprising since even vestibullectomized monkeys, which have no alternatives, take several weeks to deploy such options (6).

In conclusion, we feel that the mechanisms coupling compensatory eye movements to head movements operate most of the time in an extremely machinelike fashion in our experiments. Strategy-specific parametric adjustments do not seem to obtrude and under our conditions, compensatory eye movements appear to result entirely from the operation of a single-state system, the vestibuloocular reflex.

**VOR adaptation to left-right reversing prisms**

Left-right reversing prisms induce considerable attenuation and phase lag in the horizontal VOR. That the horizontal VOR gain would fall with prism adaptation is not surprising since the retinal image slip associated with head turns would be similar to, though more vigorous than, that experienced by the animal wearing fixed-field spectacles. Thus, in both cases, when the head turns, say to the right, then the images seen by the animal will also move to the right, and in both cases the system interprets this as signaling the need for a gain reduction. However, what is so special about the visual experience provided by reversing prisms that, over time, gradually induces a progressively increasing phase lag? No phase changes result from the fixed-field spectacle experience and it seems unlikely that they would develop with prisms simply because of a difference in the magnitude of the slip velocities. We suggest that the crucial factor may be the direction of the eye movements associated with the retinal slip. The implication here is that the system normally responsible for gain adjustments deciphers errors solely from the direction of the retinal slip associated with head movements, while the phase-shifting mechanism must also take into account the direction of the associated eye movements. We know that when the monkeys first wear fixed-field or reversing prism spectacles, they must rely heavily on visual feedback to reduce retinal slip during head turns. The prisms are particularly stressful and during most head turns the best that can be achieved at first is an attenuation of the normal compensatory eye movements, reversal only being achieved during rather slow head turns. Thus, initially, the eyes are moving in a direction that is contrary to the direction of the associated retinal slip with both the fixed-field and the prism spectacles. The result in both cases is an attenuation of the gain of the VOR, with only very minor phase changes in the prism-adapting animals. As the reflex gain attenuates with time, how-
ever, visual feedback is gradually more effective in achieving reversal of the eye movements coupled to head turns in the prism-adapting animals so that now the situation is different in the two cases: with the fixed-field spectacles, head turns continue to be associated with ipsilaterally directed slip and contralaterally directed eye movements, while with the prisms, both the slip and the eye movements are ipsilaterally directed. We suggest that it is this conjunction of slip and eye velocity that provides the impetus for the observed phase changes.

It has been suggested that the progressive phase lag that develops during prism adaptation is achieved by an inhibitory side loop of the reflex pathway that operates as a phase-lead element (5). This is one way of explaining how normally directed vestibulo-ocular responses still predominate at low frequencies, whereas good reversal is only seen at high. It is also implicit in this model that the neural mechanisms and substrate subserving the phase changes are different from those ordinarily regulating the gain. We have applied this model to our data and used simple analog techniques to derive the system parameters. Our object was to see if this model would simulate the VOR gain-phase relations seen in the prism-adapted monkey at a) the initial asymptote stage (21 days), and b) the subsequent asymptote achieved after further prism exposure combined with forced oscillation (55 days); see Figs. 8 and 9. After constructing the circuit shown, inset in Fig. 9, component values were selected on the basis of the vestibulo-ocular responses to velocity steps. 1) The gain of the linear element \( \frac{R_1}{R_2} \) was determined from the asymptotic eye velocity/chair velocity. This yielded values of 0.6 and 0.45, which compared favorably with the caloric responses in this animal (mean caloric response when animal prism-adapted/mean caloric response when normal, was 0.55 and 0.42, respectively). 2) The coupling time constant of the lead element \( R_C \) was determined from the time constant of decay of the eye velocity during velocity steps: 2 s. 3) The gain of the lead element was determined empirically, using the chair velocity signal during alternating velocity steps as the input to the circuits, and adjusting \( R_3 \) to obtain an output exactly matching the normal eye velocity profile obtained with this same stimulus. (This procedure was used because of the uncertainties surrounding the rise time of the velocity steps produced by our servo-driven chair.)

Once these parameters were determined, Bode plots were derived and these are indicated by the discontinuous lines in the gain-phase plots of Fig. 9D and E. It is apparent that this simple model, using parameters derived from the velocity step data, was only partially successful in predicting the system's sinusoidal behavior. Thus, the model nicely explains the frequency dependence of the phase lag, but fails to account for the observed rapid decrement in gain as the frequency increases from 0.2 to 1.0 Hz. Of course, to derive a complete transfer function for the system would require far more data than we have—preferably three decades rather than our one—and then probably some variant of the Davies-Melvill Jones (5) model could be found to provide an accurate simulation. If, however, the prism-adapted system is also amplitude dependent (as Melvill Jones and Davies subsequently found in the cat (16)), then such simple models are clearly going to be of little use.

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REFERENCES
