ADAPTATION OF THE VESTIBULO-OCULAR REFLEX WITH THE HEAD IN DIFFERENT ORIENTATIONS AND POSITIONS RELATIVE TO THE AXIS OF BODY ROTATION

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Abstract — We investigated the influence of static head orientation and position, relative to the axis of body rotation, upon vestibular adaptation. With the head centered, displaced anterior to the axis of body rotation, or tilted 40° to 45° in roll or pitch, the gain of the vestibulo-ocular reflex (VOR) was trained (to go either up or down) for one hour using artificial manipulation of the visual surround to produce a visual-vestibular mismatch. Before and after each training session, the VOR was measured in darkness with the head in the training as well as in several non-training positions. We found that transfer of VOR adaptation to non-training positions was almost complete when comparing head eccentric versus head-centered rotations. For tilts, however, transfer of VOR learning was far less complete suggesting that static otolith signals provide a strong contextual cue that gates the expression of an adaptive VOR response. Finally, following training to increase the VOR gain, greater for centripetally than centrifugally directed slow phases. Centripetally directed postrotational drift also developed. These findings imply that the gain increase paradigm also leads to abnormal function of the velocity-to-position neural integrator, which holds eccentric positions of gaze.

Keywords — VOR; adaptation; context specificity; transfer.

Introduction

During head perturbations, such as occur during locomotion, compensatory slow phase eye movements are produced to stabilize gaze and thereby keep images steady on the retina. Without such eye movements, the image of the visual world would "slip" on the retina during every head movement, degrading visual acuity. Two powerful ocular motor reflexes, the optokinetic and the vestibular, stabilize the eyes in space during such perturbations.

The rotational vestibulo-ocular reflex (rVOR), using afferent input primarily from the semicircular canals, allows clear vision during brief angular movements of the head. The rVOR produces a slow phase eye movement of the same amplitude but opposite phase with respect to head rotation; the gain (eye velocity/head velocity) is approximately 1.0 under normal circumstances. The translational vestibulo-ocular reflex (tVOR), using afferent input primarily from the otolith organs, creates a slow phase eye movement during linear movements of the head. The amplitude of eye rotation must vary inversely with the distance of the object of regard (1, 2). Any rotation of the head is always accompanied by both rotation and translation of the orbits (recall it is for motion of the orbits, which house the retinas, that the vestibular
system must compensate), and so compensatory eye movements normally reflect contributions from both the semicircular canals and the otolith organ (3,4). Furthermore, the amplitude and the direction of the compensatory slow phase must also depend upon the location of the line of sight, both in depth and relative to the axis of rotation of the body.

The VOR gain is maintained around unity (for distance viewing) by a neurological control system that presumably is sensitive to the retinal slip that occurs when eye movements during head perturbations are not compensatory. This adaptive control mechanism is essential for the VOR to maintain accurate stabilization of gaze despite the changes that occur with normal development and aging, with acquired disease and trauma, and in more artificial circumstances such as wearing corrective spectacles.

For VOR adaptation to take place, the stimulus that drives VOR adaptation—retinal slip—should occur in circumstances in which the adaptive control mechanism can recognize that the cause of the retinal slip is an incorrectly calibrated VOR, and hence that there is a need for VOR adaptation. Movement of the head is the most obvious clue, and the occurrence of head motion and retinal slip simultaneously is thought to be the sine qua non for VOR adaptation. But other contexts might also serve to signal a circumstance in need of a specific VOR response, and it has been shown that both non-vestibular and vestibular cues can gate the elaboration of a particular adaptive VOR response.

Shelhamer and colleagues (5), studying humans, showed that a non-vestibular cue (vertical eye position) could be used to gate two different adapted horizontal VOR gains (horizontal gain was trained to be increased with eyes up, and decreased with eyes down). Baker and colleagues (6), studying cats, produced two opposing adaptive changes in the direction of the slow phase of the VOR with respect to that of head rotation. Which adapted VOR was evoked depended upon the static orientation of the animal with respect to gravity during training. Cats were trained in two different body orientations in the same session (10 min lying on the left side, 10 min lying on the right side, alternates for 2 h). For each body position, the visual surround was oscillated around an axis 90° orthogonal to the axis of head rotation, but with opposite sense with respect to the rotation of the head. Each animal developed two different VORs: the direction of the slow phase with respect to rotation of the head depended on the orientation of the body during the training, even though the pattern of canal stimulation was the same in both training positions. In this experiment a static otolith input, and perhaps the pattern of somatosensory inputs, provided the cue(s) for the context-specificity of the adaptation.

In a separate study, Baker and colleagues (7) showed that after modifying the direction of the VOR in a cat with two hours of rotation in one specific body orientation with respect to gravity, there was some transfer of VOR adaptation when the animal was tested in other body orientations. They trained cats while level or lying on one side, rotating around either an earth-vertical or an earth-horizontal axis. For each of the four conditions the visual surround oscillated around an axis orthogonal to that of the body oscillation. Afterwards they tested the VOR in the orientation used for adaptation as well as in other body orientations, though in all cases the pattern of canal activation was the same. The amount of adaptation in the non-training positions was less than in the training position. More recently, Wall and colleagues (8) have shown that adaptation of the rVOR (with the head level) is partially transferred to the modulation component of off vertical axis rotation (OVAR), an otolith-induced compensatory response.

These experimental results bear on the general question of how the brain chooses between generalizing an adapted VOR response learned in a particular context or keeping the adapted response specific to the context in which it was acquired. Here we investigated in normal human subjects the transfer of VOR adaptation that had been acquired in differ-
ent contexts. We altered the position and the orientation of the head relative to the axis around which the body was oscillated, in order to create different patterns of canal and otolith stimulation. To drive the VOR gain down or up, an artificial surround (optokinetic drum) was rotated in or out of phase, respectively, with the subject, who was being sinusoidally oscillated in a rotating chair. Two general types of experiments were performed: comparing the adaptation between eccentric (head displaced forward) and centered rotations, in which case there is a superimposed dynamic otolith input, and comparing adaptation between head tilted and head level rotations, in which case there is a change in static otolith input. Preliminary results, with a smaller group of subjects, have been presented (9).

Methods

Subjects

Six normal subjects, ages 22 to 47, participated in this study. There were two women and four men without any history of ear, eye, or neurologic disorders. Four subjects performed all trials in the entire group of experiments (eccentric rotation, roll tilt, pitch tilt), while two other subjects split a sequence of trials (one subject performing the pitch tilt experiments and the other the roll and eccentric rotation experiments). We thus had five subjects for each condition. All procedures were in accord with the standards of the committee on human experimentation of the Johns Hopkins University School of Medicine.

General Procedures

Subjects sat in a rotating chair within a 154 cm diameter optokinetic nystagmus (OKN) drum. The drum interior was white and randomly covered with black rectangles subtending 2° to 6° of arc. The chair was rotated sinusoidally at 0.2 Hz, 30% peak velocity. To elicit an increase in the VOR gain, the drum was rotated in counter phase to the chair, but at 21% peak velocity, requiring an eye response ×1.7 that of the vestibular stimulus (head rotation). To elicit a decrease in the VOR gain, the chair and the drum were rotated in phase and with the same amplitude (×0 viewing condition). The subject was asked to pick and follow one point on the drum during the training period, with eyes steady near the straight-ahead position for the ×0 viewing experiments, and eyes moving over a horizontal range of approximately ±40° for the ×1.7 viewing experiments. Each training session lasted for one hour and the VOR gain was measured, in darkness, before and after the training session. Although a visual vestibular conflict was purposefully used to elicit VOR adaptation, the velocity and frequency of the stimuli were such that no subject experienced motion sickness.

Specific Paradigms

For the eccentric adaptation experiments four training conditions were used: ×1.7 and ×0 viewing, each in the centered and in the eccentric position. The head was kept level, with the interaural axis passing through the axis of rotation or displaced 17 cm in front of the axis of rotation. A chin rest was used to maintain the position of the head during the training period.

For the roll adaptation experiments four training conditions were also used: ×1.7 and ×0 viewing, each in the head level and in one roll orientation, with the head tilted 45° toward one shoulder. During training, some subjects tilted their heads toward the right shoulder, and others toward the left. Results were normalized as if all subjects were trained while tilted to the left. The body was positioned in the chair so that the axis of rotation passed through the interaural axis of the head. A chin rest and head cushions were used to maintain this position.

For the pitch adaptation experiments, six training conditions were used: ×1.7 and ×0 viewing, with the head level, pitched 40° up, and pitched 40° down. Subjects wore a helmet that was attached to the chair with horizontal bars so that the axis of body rotation passed...
through the interaural axis no matter what the pitch of the head. Subjects were asked to track a target on the drum 20° up (for the head pitched up 40°) or 20° down (for the head pitched down 40°) relative to the 0° position with the head in the level position.

Eye Movement and VOR Gain Measurements

The horizontal position of the eyes in the orbits was measured with bitemporal DC-coupled electro-oculography (EOG, bandwidth 40 Hz). Just before and after each adaptation period the VOR gain was measured in darkness with the head in the appropriate set of positions (centered and eccentric for the eccentric experiments; level, right tilt, and left tilt for the roll experiments; level, pitch down, and pitch up for the pitch experiments). We used the horizontal EOG signal, which reflects the horizontal position of the eye in the orbit, to infer the horizontal VOR gain relative to space (that is, in an earth-horizontal plane). We assumed that both before and after training there were no abnormal vertical components (relative to the earth-horizontal plane) during horizontal head rotation.

The VOR gain was quantified as follows. An LED, located 120 cm in front of the axis of body rotation, was illuminated for several seconds in an otherwise dark room. The LED was then extinguished and the chair was immediately rotated approximately 30° in one direction. Peak velocity was 100°/s and the duration of the rotation was about 700 ms, producing roughly a “position step” of chair motion. The subject was asked to keep his or her gaze on the remembered position of the LED, leading to a smooth compensatory slow phase eye movement without any quick phases or saccades. Then, the LED was reilluminated and, if necessary, the subject made a corrective saccade to bring the eyes to the target. Rotations began or ended with the eyes near primary position using a repeated sequence of rotations of right, left, left, right. Thus, some rotations led to centripetal eye movements, and others to centrifugal eye movements.

The gain of the VOR was measured as the ratio between the amplitude of the slow phase compensatory eye movement made in darkness and the amplitude of the eye movement required for perfect compensation. The latter was inferred from the total amplitude of the slow phase eye movement and any subsequent corrective saccade following illumination of the LED (Figure 1). The gradual rise and fall of the velocity trace indicates that the trajectory of the compensatory slow phase was smooth, without any emebedded saccades. This simple technique, “the step-displacement method”, allows an accurate measure of the VOR with an internal calibration which minimizes errors due to drift and fluctuations in gain of the EOG signal. One potential problem with this method is that the VOR gain may be underestimated if the eyes were to drift centripetally at the end of the compensatory eye rotation. Such may have been the case with the x1.7 viewing paradigm since a centripetal drift appeared after VOR adaptation. We calculated this effect on VOR gain to be not greater than 3%.

Position steps were repeated approximately 12 times for each subject in each condition. For the eccentric and roll experiments the target light was presented straight ahead at eye level. For the pitch experiments the light was at eye level with the head level, or displaced 20° up or down for, respectively, the 40° pitch up or down positions of the head.

The head was stabilized during the position steps using a chin rest for the eccentric experiments, a bite board for the roll experiments, and a helmet for the pitch experiments. Eye and chair movements were displayed on a pen recorder and also saved with an IBM-PC compatible computer for later off-line analysis.

Data Analysis and Statistical Comparisons

The experimental paradigms and the data analyses were directed toward answering the following questions.

1. For any given type of trial (in a specific head position or orientation), we used the
Figure 1. Example of a compensatory slow phase eye movement (E) after x1.7 training in one subject. Note the backwards directed corrective saccade when the target light is switched on, signifying a VOR gain greater than 1.0. The velocity trace (dE) shows no evidence for embedded saccades in the compensatory slow phase response.

paired t test to determine if the subject's VOR gains were significantly different before and after adaptation.

2. In any given set of experiments (eccentric, roll, or pitch) we also used the paired t test to determine if the change in amplitude of the VOR gain following training was different between the training and non-training head positions and between different training positions (with the same condition of viewing). For this analysis we corrected for 1) errors due to different distances of viewing, such as occurred when training in the drum (67 cm from eyes) and testing with the LED (110 cm from eyes), or when training and testing in the centered versus eccentric positions, and 2) errors due to the different stimulus strengths between the gain up (x1.7) and the gain down (x0.9) paradigms (respectively –19° and –27.6° of drum motion relative to stationary eyes in space). Accordingly, we used as a measure of adaptation the observed change in amplitude of the compensatory slow phase (ASP) divided by the actual change required for perfect compensation (reqSP). The ASP is the measured gain difference multiplied by the amplitude of eye response necessary for perfect compensation during training at the given distance of viewing. The reqSP is the amplitude of relative drum motion as viewed from each position of the head during the identical chair rotation (see Appendix). We used the ratio ASP/reqSP to calculate the percentage of the reqSP that was actually achieved, and this number (Δ%) was used for the paired t tests.

3. To compare the amount of transfer of adaptation from the training to the non-training positions we calculated a transfer ratio (Radapt) from the percentage of VOR gain change (Δ%) in the training position and the percentage change (Δ%) in the non-training position. We then compared transfer ratios obtained in two different training positions in the same set of experiments (for example, for the roll experiments training level versus training in tilt) or ratios obtained in the same training positions in different experiments (for example, training level for the roll and the pitch experiments). A t value was obtained using the statistical “delta method” (t is the difference between the natural logarithms of the ratios divided by the square root of the variance of this difference) (10). This procedure allowed us to determine if the amount
of transfer varied from situation to situation. (Note that the question of whether or not there was transfer of adaptation per se is assessed by testing for a significant change in VOR gain in the non-training position following training, as described above in part 1.)

4. In the roll experiments, we also asked if the changes in VOR gain (% Δ) for centripetal and centrifugal eye movements were different. Using the paired t test, we compared in each training and non-training position the % Δ for the centripetal and the centrifugal eye movements.

We considered the results of the statistical tests significant when \( P \leq 0.05 \), and non-significant if \( P > 0.05 \).

Results

Eccentric Experiment (Figure 2 and Table 1)

The mean values of the VOR gain for all five subjects before and after training were significantly different for all four types of trials (centered and eccentric, \( \times 1.7 \) and \( \times 0 \) viewing) (Table 1). There were no significant differences in the achieved percentage of the required change in VOR gain (% Δ) between the training and the non-training positions except for \( \times 0 \) training in the eccentric position (compare four adjacent pairs of bars in Figure 2).

Finally, there were no significant differences in the amount of transfer of adaptation (\( R_{\text{adapt}} \)) from the training to the non-training positions in the different conditions of training.

Roll Experiment (Figure 3 and Table 2)

There were significant differences between the pre and post adaptation VOR gains, in all four combinations of head level, head tilted, \( \times 1.7 \) and \( \times 0 \) viewing conditions, when measured in the head orientation that was used for training (“T” in Table 2). After training with the head level, for both \( \times 1.7 \) and \( \times 0 \) viewing, there were also significant changes in VOR gain when tested with left tilt and right tilt. After training with the head tilted (left), for both \( \times 0 \) and \( \times 1.7 \) viewing, there were also significant changes in VOR gain when tested with the head level, but not with right head tilt.

When comparing the % Δ in the training and the non-training orientations (compare adjacent bars in each set of three bars in Figure 3), for head level \( \times 1.7 \) viewing, the gain change was significantly larger when tested in the level (training) orientation compared to the left and right tilt orientations (Figure 3, first set of three bars). There were, however, no significant differences, after head level \( \times 0 \) adaptation, between the head level and the left or right tilt orientations though the gain change was still larger when tested in the head level position (Figure 3, second set of three bars). For head (left) tilt training, and both \( \times 1.7 \)

<table>
<thead>
<tr>
<th>Training condition</th>
<th>( \times 1.7 ) centered</th>
<th>( \times 0 ) centered</th>
<th>( \times 1.7 ) eccentric</th>
<th>( \times 0 ) eccentric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change in gain</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test centered</td>
<td>+(( P \leq 0.05 ))</td>
<td>+(( P &lt; 0.005 ))</td>
<td>+(( P &lt; 0.005 ))</td>
<td>+(( P &lt; 0.005 ))</td>
</tr>
<tr>
<td>Test eccentric</td>
<td>+(( P \leq 0.05 ))</td>
<td>+(( P &lt; 0.005 ))</td>
<td>+(( P &lt; 0.005 ))</td>
<td>+(( P &lt; 0.005 ))</td>
</tr>
<tr>
<td>%Δ in training vs. non-training position</td>
<td>-(( P &gt; 0.05 ))</td>
<td>-(( P &gt; 0.05 ))</td>
<td>-(( P &gt; 0.05 ))</td>
<td>-(( P &gt; 0.05 ))</td>
</tr>
</tbody>
</table>

Note: %Δ represents the percentage of the required change of amplitude of the compensatory slow phase. + and - represent respectively a significant or a non-significant statistical result. \( P \) represents the \( P \) value of the paired t test. The sample size was 5 for each experiment.
centered and eccentric adaptation

Figure 2. Comparison of the percentage of required VOR gain change (\(\%\Delta\)) after head centered and head eccentric \(\times 1.7\) and \(\times 0\) training. Note the almost complete transfer of VOR learning between eccentric and centered positions.

Table 2. Roll Tilt Experiments. Results of the Statistical Tests after Head Level, Head Left Tilted, \(\times 1.7\) and \(\times 0\) Training

<table>
<thead>
<tr>
<th>Training condition</th>
<th>Test condition</th>
<th>(\times 1.7) Level</th>
<th>(\times 0) Level</th>
<th>(\times 1.7) Left Tilt</th>
<th>(\times 0) Left Tilt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change in gain</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test: level</td>
<td>(-)(^{(T)})</td>
<td>(-)(^{(T)})</td>
<td>(+)(^{(45)_{\circ}})</td>
<td>(-)(^{(45)_{\circ}})</td>
<td></td>
</tr>
<tr>
<td>((F &lt; 0.01))</td>
<td>((P &lt; 0.01))</td>
<td>((P \leq 0.05))</td>
<td>((P &gt; 0.05))</td>
<td>((P &lt; 0.05))</td>
<td></td>
</tr>
<tr>
<td>Test: left tilt</td>
<td>(-)(^{(5)_{\circ}})</td>
<td>(+)(^{(5)_{\circ}})</td>
<td>(-)(^{(T)})</td>
<td>(+)(^{(T)})</td>
<td></td>
</tr>
<tr>
<td>((P &lt; 0.005))</td>
<td>((P &lt; 0.001))</td>
<td>((P &gt; 0.05))</td>
<td>((P &lt; 0.05))</td>
<td>((P &lt; 0.001))</td>
<td></td>
</tr>
<tr>
<td>Test: right tilt</td>
<td>(-)(^{(45)_{\circ}})</td>
<td>(+)(^{(45)_{\circ}})</td>
<td>(-)(^{(90)_{\circ}})</td>
<td>(-)(^{(90)_{\circ}})</td>
<td></td>
</tr>
<tr>
<td>((P \leq 0.05))</td>
<td>((P &lt; 0.001))</td>
<td>((P &lt; 0.001))</td>
<td>((P &gt; 0.05))</td>
<td>((P &gt; 0.05))</td>
<td></td>
</tr>
</tbody>
</table>

\(\%\Delta\) in training vs. non-training orientations

| Level vs. Right    | \(+\)\(^{(P < 0.01)}\) | \(-\)\(^{(P > 0.05)}\) | \(+\)\(^{(P \leq 0.05)}\) | \(+\)\(^{(P < 0.01)}\) |
| Level vs. Left     | \(+\)\(^{(P \leq 0.05)}\) | \(-\)\(^{(P > 0.05)}\) | \(+\)\(^{(P < 0.005)}\) | \(+\)\(^{(P < 0.005)}\) |
| Right vs. Left     | \(-\)\(^{(P > 0.05)}\) | \(+\)\(^{(P \leq 0.05)}\) | \(+\)\(^{(P < 0.001)}\) | \(+\)\(^{(P < 0.001)}\) |

Note: \(\%\Delta\) represents the percentage of the required change of amplitude of the compensatory slow phase. + and − represent respectively a significant or a non-significant statistical result. \((T)\) means in the training orientation; \(45^\circ\) means in a head lateral tilt or level orientation \(45^\circ\) away from the training orientation; \(90^\circ\) means in a head lateral tilt orientation \(90^\circ\) away from the training orientation. \(P\) represents the \(P\) value of the paired \(t\) test. The sample size was 5 for each experiment.
and xO viewing, the %Δ in the training (left tilt) orientation was significantly larger than that measured in the non-training orientations (Figure 3, third and fourth set of bars). Similarly, the %Δ was significantly larger in the head level compared to the right tilt orientation, with both x1.7 and xO training.

There was no significant difference between the %Δ when tested in the orientation used for training, comparing the x1.7 head level and the x1.7 tilt adaptation conditions. On the other hand, the %Δ tested in the training orientation was significantly larger for xO head tilted adaptation than for xO head level adaptation (compare the two larger differently patterned bars on the top or on the bottom half of Figure 3).

Finally, we compared the amount of transfer of adaptation (R_adapt) from the training to the non-training positions in the different conditions of training and found no significant differences except for the comparisons of head level/right tilt ratio in the xO head level adaptation compared to left tilt/head level ratio in the xO tilt adaptation, and head level/left tilt ratio in the xO head level adaptation compared to left tilt/head level ratio in the xO tilt adaptation. In both cases there was more transfer after head level than after tilt adaptation.

We also noted a difference in the %Δ depending upon whether eye motion was toward (centripetal) or away from (centrifugal) the primary position of gaze (compare two adjacent bars of Figure 4). The difference in %Δ between centrifugal and centripetal movements was significant in the training orientation for x1.7 head level and x1.7 tilt adaptation, and in the left tilt orientation after xO head level adaptation. In each case, the %Δ was always larger for centripetally-directed eye movements, but the effect was much more pronounced after the x1.7 training. Likewise, after x1.7 training, a centripetal drift appeared after the centrifugal slow phases (Figure 5).
centripetal/centrifugal differences in roll experiments

Figure 4. Differences in percentage of required VOR gain change (%Δ) after ×1.7 and ×0 training, head level and head tilted laterally, for centripetal and centrifugal slow phase eye movements. In each set of six bars, the first pair of bars reflects tested with left tilt, the second pair of bars with head level, and the third pair of bars with head tilted right. Note that in the training position the change in VOR gain is greater with centripetally-directed slow phases, in both ×1.7 viewing experiments.

Pitch Experiment (Figure 6 and Table 3)

There were significant differences between pre and post adaptation VOR gains in all six combinations of head level, head pitched up, and head pitched down orientations when measured in the position used for training ("TT" in Table 3). After training in the head level orientation, both in ×1.7 and ×0 viewing there were also significant changes in VOR gain when tested in both pitch orientations.

After training with the head pitched down, for ×1.7 and ×0 viewing, there were significant changes in VOR gain when tested in the head level orientation, after ×1.7 training but not ×0 training. For both ×1.7 and ×0 training there was no significant change in VOR gain when tested in the pitch up orientation.

After training with the head pitched up, for both ×1.7 and ×0 viewing, there were also significant changes in VOR gain in the head level orientation, but not in the pitch down orientation.

When comparing the %Δ in the training and the non-training orientations, for head level training with ×1.7 viewing, the %Δ was significantly larger in the training orientation than in the non-training orientations (with the exception of ×0 head level versus pitch up) (Figure 6, second set of bars).

After pitch down training, with either ×1.7 or ×0 viewing, the %Δ was significantly larger in the training orientation than in the non-training orientations. For the non-training orientations, the change was larger in the head level orientation compared to the pitch up orientation, after ×1.7 viewing, but not after ×0 viewing (compare the adjacent bars in the two middle sets of three bars in Figure 6).

After pitch up training, the %Δ in the training orientation was also significantly dif-
CENTRIPETAL AND CENTRIFUGAL EYE MOVEMENTS AFTER X1.7 TRAINING

Figure 5. Example of smooth vestibular compensatory eye movements for centrifugal and for centripetal eye motion in the orbit, after x1.7 training in the head level position, in one subject. Note the drift of the eye back toward the primary position after the centrifugal eye motion (heavy lines).

Different from that in the non-training orientations. For the non-training orientations, the change was larger in the head level orientation compared to the pitch down orientation, after both x0 and x1.7 training (compare the adjacent bars in the two right-hand sets of three bars in Figure 6).

For x1.7 viewing, the %Δ was significantly larger in the training orientation with pitch up than with head level training. For x0 adaptation, %Δ was significantly larger in the training orientation with pitch up than with head level or pitch down training (compare the two larger differently patterned bars on the top or bottom half of Figure 6).

There were no significant differences in the amount of transfer of adaptation (R_adapt) from the training to the non-training positions.
in any of the training paradigms (compare each pair of adjacent bars in two different sets of three bars in Figure 6).

Finally, we compared the amount of transfer of adaptation from training to non-training orientations in the lateral tilt experiments with the amount in the pitch tilt experiments; there were no significant differences.

**Discussion**

**General Findings**

Two general conclusions emerged from our experiments. First, there was, by and large, complete transfer of adaptation in the eccentric vs. centered adaptation experiments. In other words, the presence or absence of a superimposed dynamic otolith signal related to translation of the head did not provide enough of a contextual cue to gate the expression of an adapted VOR response. Secondly, in both sets of tilt experiments (roll and pitch), the amount of transfer of adaptation was related to how close the angle of tilt during post adaptation testing was to the angle of tilt during training. In other words, static otolith signals appeared to serve as a compelling contextual cue for the expression of VOR adaptation. We will discuss these two results in turn.

**Eccentric Rotations**

For the eccentric vs. centered rotation experiments the absence of an otolith effect may have been due to the fact that dynamic otolith summation may not be a compelling enough contextual cue for adaptation specificity. On the other hand, the actual linear force applied to the otoliths during eccentric rotation were exceedingly small (the peak tangential acceleration was only 0.01 g and the peak centrifugal acceleration was only 0.005 g). It may be that if the head had been translated with a higher linear acceleration, there might have been less transfer (more context specificity) of VOR adaptation between eccentric and centered rotations. It should also be emphasized
that the dynamic otolith signal was not the only possible contextual cue; proprioceptive and other somatosensory signals were also available to provide a context for the learned response. They did not, however, significantly influence the expression of the adapted VOR.

### Tilt Experiments

In contrast to the eccentric position experiments, for the tilt experiments we found a considerable influence of the static orientation of the head upon the expression of VOR adaptation. This finding can be interpreted as adaptation in either a space or a canal coordinate system. If adaptive changes in VOR gain are in a space-coordinate system (that is, dependent upon the vector of head rotation relative to gravity and independent of which particular canals are stimulated) then one would predict complete transfer of adaptation in our experiments since we always assessed changes in VOR gain relative to the response required in an earth-horizontal plane.\(^2\) Of course, the otolith signals and the pattern of canal stimulation must still be used by the brain to compute the vector of head rotation relative to gravity and so ensure that the adapted response is correctly invoked. Since

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\(^2\)If transfer is complete the change in gain will be identical in every test orientation of the head. Assuming the eyes are directed straight ahead in the orbit, for lateral head tilt the size of the horizontal eye movement in the orbit will be smaller than with head level (a vertical component in the orbit must also appear), but the percentage change will be equal to that for the overall VOR in space. Similar considerations apply to up and down pitch of the head (a torsional component must also appear). Since the amount of horizontal eye movement in the orbit is different when tested in the tilt versus the head level orientation, it is possible that a nonlinear adaptive change in gain might lead to an apparent difference in the amount of transfer of adaptation. Paige (11), however, has shown that VOR adaptation is nearly linear for head velocities in the same range used in our experiments.
we did not find complete transfer of VOR adaptation in the tilt experiments one must hypothesize either that there is contextual gating of the adaptive response, for example by static otolith signals, or that the VOR learning is specific to the pattern of canal stimulation during training. This latter alternative seems less likely in view of the results of Baker and colleagues (7) who showed that different VOR gains could be gated by changes in static head position even when the pattern of canal stimulation was identical.

In our experiments we assume that the differences in the expression of VOR adaptation as a function of head position are determined primarily by changes in static otolith signals (in contrast to the eccentric rotation experiments, the change in g forces applied to the otoliths with head tilt is quite large). Our experiments, however, do not allow us to exclude the use of cues from the change in the pattern of stimulation of the semicircular canals (in our experiments both the relative amount of, and the phase relationships between, the stimulation of the horizontal and vertical canals varied with head tilt), or from somatosensory cues—such as the position of the head on the body or the altered relation of the trunk to the chair. The latter seem unlikely to be the important contextual cue since different somatosensory cues did not prevent complete transfer of adaptation in the head eccentric rotations.

One consistent finding among the tilt experiments was that the absolute amount of adaptation, though not the amount of transfer to non-trained positions, was usually greater for training in a head-tilted position than for training in the more natural head level position. The reason for this finding is not clear, though the relatively unusual contextual cues (otolith, somatosensory) provided by training in tilt may have potentiated the adaptive change in the rVOR. In the head level condition, there were no unusual contextual cues, only the visual-vestibular conflict that could be interpreted as an abnormality in the rVOR.

Our results may also have been influenced by the difference between the training stimulus (a sine wave) and the testing stimulus (a "position step"). It has been shown previously that there is incomplete transfer to other frequencies when the VOR is trained at only one frequency (12). If we had trained with a broadband stimulus closer to the "position step" used for testing, we might have elicited more adaptation. As a final caveat, the VOR was tested with the point of regard at a different distance (farther away) than during training. It is possible that viewing distance might also be a contextual cue for gating adapted VOR responses.

**General Considerations about Context Specificity of VOR Adaptation**

Retinal slip during head motion can arise from abnormalities in the afferent limb of the VOR (in the canals or otoliths), in more central structures including the vestibular nuclei, or in the efferent limb of the VOR such as the ocular motor pathways themselves (13). The brain has no easy way to distinguish among these possibilities unless it has additional experience in other contexts, in which, for example, the otolith and canal contributions during rotation can be evaluated separately. For example, if there is retinal slip during eccentric rotation, the brain might have difficulty in distinguishing between an abnormal contribution from the otoliths (tVOR) and an abnormal contribution from the semicircular canals (rVOR) unless it is also known whether or not there is retinal slip during rotation with the head centered. If there is no retinal slip during centered rotation, the abnormal VOR gain can be attributed to an abnormality in the sensing or processing of information about translation.

On the other hand, if retinal slip occurs not only during head rotation but also when there is no vestibular stimulation, as during attempted smooth pursuit or gaze-holding, a more central disorder, perhaps in premotor or motor structures, can be inferred. Or, if retinal slip occurs with the eyes in one orbital position, but not in another, a peripheral ocular motor problem might be deduced. Finally, defects in the mechanisms that adjust the VOR response for the point of regard (in depth or when gaze is directed away from the primary
Effect of Eye Position on VOR Adaptation

Surprising was the observation in the ×1.7 viewing paradigms, which called for an increase in the VOR gain, that the change in VOR gain was considerably larger for centripetally-directed slow phases than for centrifugally-directed slow phases. This asymmetry was greatest when the VOR was tested in the training position. One explanation for this finding is a change in the function of the velocity-to-position neural integrator (9, 14). This neural network provides the sustained tonic eye position signal needed to hold eccentric positions of gaze following saccades, vestibular and other types of conjugate eye movements (15). If this neural integrator were to become impaired or "leaky", a centripetal bias would be superimposed on vestibular slow phases, leading to an asymmetry such as appeared in our VOR data. We also found a centripetally-directed drift following saccades in darkness after ×1.7 training. Both these findings suggest that some aspect of the ×1.7 adaptation paradigm led to a change in the function of the neural gaze-holding integrator. Both the pattern of eye motion (across the ocular motor range in ×1.7 viewing versus steady fixation in ×0 viewing) as well as the direction of VOR gain change (increase versus decrease) differed in the ×0 and ×1.7 experiments. We do not yet know which factor was mainly responsible for the apparent change in neural integrator function after ×1.7 viewing. There is, however, other evidence for a close relationship between the function of the neural integrator and the vestibular system. Anatomically, the neural integrator is thought to reside within the medial vestibular nucleus and adjacent nucleus prepositus hypoglossi (16), and peripheral vestibular lesions may themselves lead to a change in function of the neural integrator (17).

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REFERENCES


APPENDIX

Calculation of the desired compensatory slow phases during testing and during adaptation

Assume (18) that $E_0$ can be approximated by $-H \times (1 + R/D)$ where:

$E_0 = $ desired eye response in degrees
$H = $ chair amplitude in degrees
$R = $ distance from the eyes to axis of rotation (cm)
$D = $ distance from the eyes to the target (cm).

The eye movements in space needed to maintain fixation upon a stationary drum for $24^\circ$ of chair rotation (amplitude of chair rotation during the training) are:

- head centered, level, and roll tilt:
  $E = -24 \times \left(1 + 10/67\right) = -27.6^\circ$
- head eccentric (forward):
  $E = -24 \times 1/ = 27/50 = -37^\circ$
- head pitched down or up:
  $E = -24 \times \left(1 + 10/68\right) = -27.5^\circ$

The additional eye motion stimulus due to drum motion during adaptation is:

1) For gain up ($\times 1.7$) adaptation:
   a) $16.7^\circ$ from rotational motion;
   b) To keep the eyes stationary in space:
      i) Head centered, level and roll tilt:
         $D = 16.7 \times \left(1 + 10/67\right) = 19^\circ$
      ii) Head eccentric (forward):
         $D = 16.7 \times \left(1 + 27/50\right) = 25.7^\circ$
      iii) Head pitched down or up:
         $D = 16.7 \times \left(1 + 10/68\right) = 19.2^\circ$.

2) For gain down ($\times 0$) adaptation:
   a) $24^\circ$ from rotational motion;
   b) To keep the eyes stationary in space:
      i) Head centered, level and lateral tilt:
         $D = 27.6^\circ$
      ii) Head eccentric (forward):
         $D = 37^\circ$
      iii) Head pitched down or up:
         $D = 27.5^\circ$.

Thus the percentage of required gain change is:

(change in gain) / (required eye movement) / (drum stimulus)