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Responses of the Translational Vestibulo-ocular Reflex in Normal Human Subjects during Attempted Cancellation

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Running Title: Cancellation of the translational VOR

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Abstract:

The inter-aural translational vestibulo-ocular reflex (IA-tVOR) was measured in eight normal subjects in response to sinusoidal acceleration head translations. Eye movements were recorded binocularly using an infrared video tracker (El-Mar). Results indicated that the tVOR is very robust and has a latency of less than 20ms. Subjects were asked to view targets located 20 and 100cm from the nasion during sinusoidal accelerations at frequencies of 0.5, 1, 2, 3, and 4Hz. The 20cm target could be either earth-fixed or could be moved with the head. In the latter case, the subjects attempted to cancel their IA-tVOR. The results were quite surprising. While the reflex sensitivity was seen to increase markedly with the 20cm target, as expected, cancellation results were better than expected. In other labs, the cancellation of the angular VOR had been found to only be possible at frequencies of 1Hz or less. However, we found that all of our subjects were able to cancel their IA-tVOR's quite effectively even at 2Hz with a reduction in sensitivity of greater than 50%.

INTRODUCTION:

The vestibulo-ocular reflex (VOR) functions to stabilize images on the retina during head movements. This reflex is commonly broken down into two different systems, the angular VOR (aVOR) that uses information from the semicircular canals and compensates for rotations of the head, and the translational VOR (tVOR) that compensates for head translations using otolith information. Both of these reflexes need to be subject to moment-to-moment changes in gain and even direction (for the tVOR), based on the distance and direction of viewed targets (Viirre et al, 1986; Paige, 1989; Paige and Tomko, 1991a,b).

Early experiments on the tVOR indicated that the reflex latency was quite long, around 30-40ms (Bronstein and Gresty, 1988; Snyder and King, 1992; McConville et al, 1996). However, recent experiments have suggested that the reflex latency may be much less than this, of the order of 10ms (Angelaki, 1998). However, the evidence for this short latency was indirect as it was based on fitted transfer function parameters rather than direct measurements. Nonetheless, some experiments have demonstrated a direct connection between otolith afferents and abducens motoneurons, implying that the reflex latency should be very short (Sasaki et al., 1991; Uchino et al., 1996,1997). In addition, our own experiments have showed that the reflex latency should be less than 19ms (Tomlinson et al., 2000). Thus the reflex is known to be both robust and of very short latency.

Whenever a target is viewed which moves with the head, the VOR must be cancelled. Although many experiments have investigated the dynamics of aVOR cancellation, no one has looked at tVOR cancellation. These experiments were undertaken in order to shed more light on this question.

METHODS:

Experiments were performed on 8 subjects (7 male, 1 female, ages 22-54). Subjects had no previous history of vestibular or neurological disorders; none exhibited any spontaneous nystagmus. Eye movements were measured with a binocular infrared video tracker (El-Mar Ltd.) which operated at 180Hz. Head movements were measured with a pulsed magnetic field device (Flock of Birds) attached to a firmly fitted headband. Both eye and head movements were digitized at 400Hz and stored on disk for off-line analysis.

Subjects were accelerated along the inter-aural axis using sinusoidal stimuli (see Figure 1) while viewing targets located 20, 30 and 100cm from the eyes. The head was fixed as firmly as possible to the sled using a custom made dental bite. Each experimental series consisted of 5-10 cycles delivered frequency. Before each series, the eye movement recordings were calibrated by having subjects fixate a series of targets located at –10, -5, 0, 5, and 10 degrees eccentricity in both the horizontal and vertical directions.

For data analysis, only saccade free cycles were used. For each of the five frequencies and three target distances, eye and head movement profiles were averaged using a custom software package and stored for further analysis. These average files were then imported into SigmaPlot (Jandel Scientific) for further analysis and plotting. Velocity and acceleration were calculated using a four-point differentiator based on a least squares technique (Savitzky and Golay, 1964). This is similar to the familiar two-point central difference differentiator but is less sensitive to high frequency noise.

RESULTS:

A representative head displacement at 3Hz is illustrated in Figure 1.

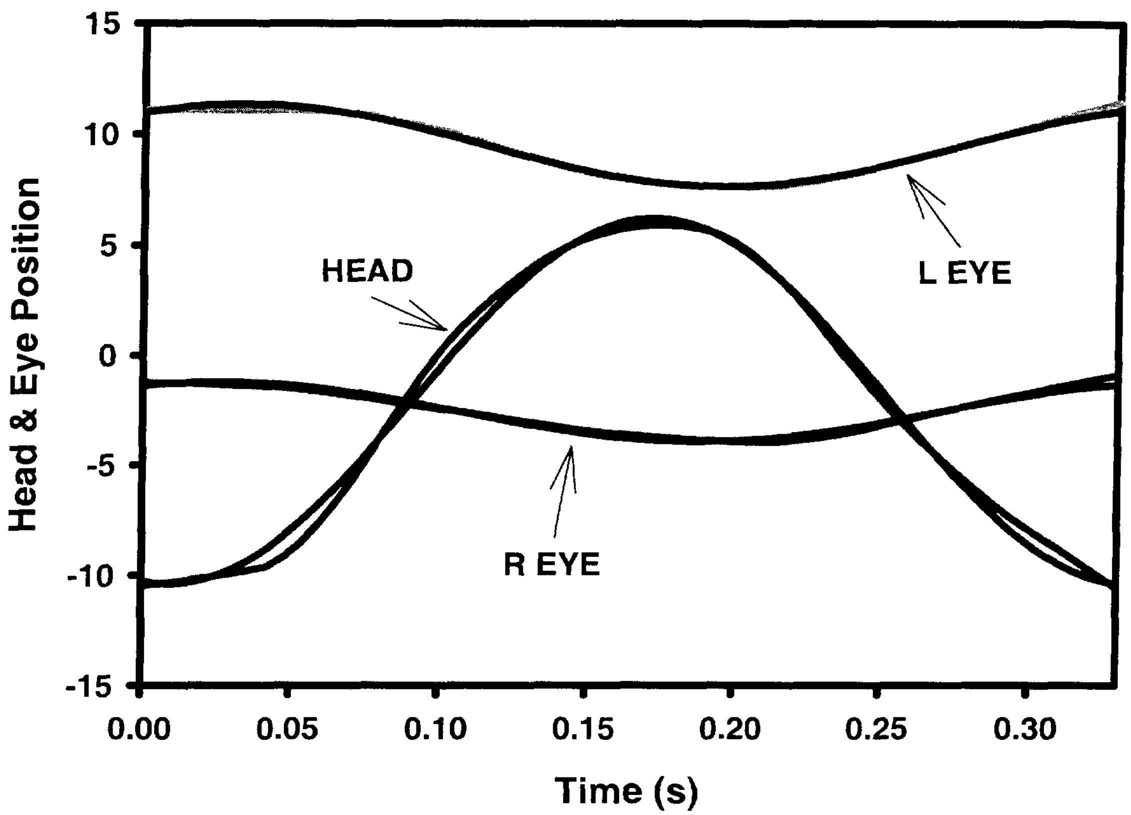

Figure 1: Binocular eye and head movements from a representative subject at 3Hz with a target located at 20cm. Note that the subject had no difficulty maintaining vergence. In each case the head and eye curves have been fitted with a sinusoid at the stimulus frequency. (R EYE = right eye; L EYE = left eye; Positive values are right) The blue lines are best fit sinusoids.

Note that the subject had no problem maintaining a vergence angle of more than 12 degrees in spite of the high frequency stimulus. The blue traces represent the non-linear least-squares fit to the head and eye movements using the equation

$$y = y_0 + A\sin(2\pi ft + \theta)$$

The fitted parameters were used to calculate the reflex sensitivity at each frequency. A cancellation trial is shown in Figure 2. Note that even at this high frequency the eye movement response is different in phase from that seen in Figure 1.

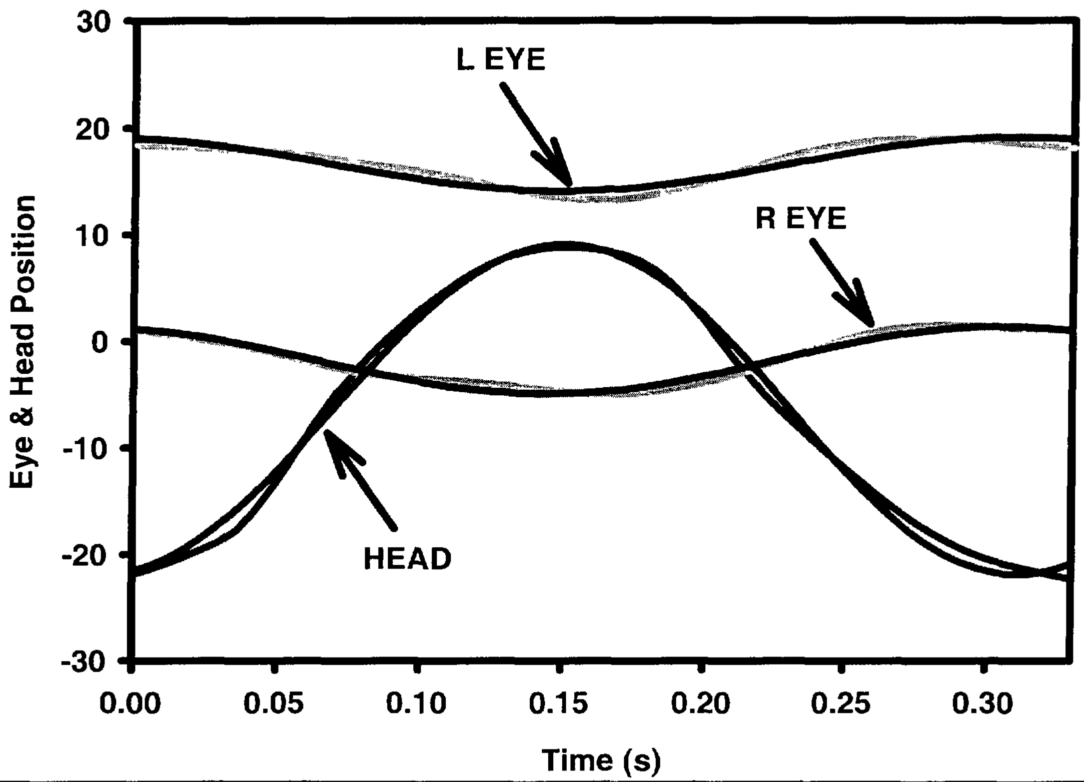

Figure 2: Typical eye and head movements during tVOR cancellation at 3Hz with a 20cm target. Note that the subject was able to maintain vergence. As in the previous Figure, the eye position is in degrees and the head position is in cm. The blue lines are the best-fit sinusoids.

Figure 3 illustrates both tVOR and tVOR cancellation responses for another subject at 2Hz. Of particular note is the maintenance of the vergence angle between the two trials. Although the vergence angle is the same in both cases, the evoked eye movement is clearly much less in the cancellation trial than it is in the trial with the earth-fixed target.

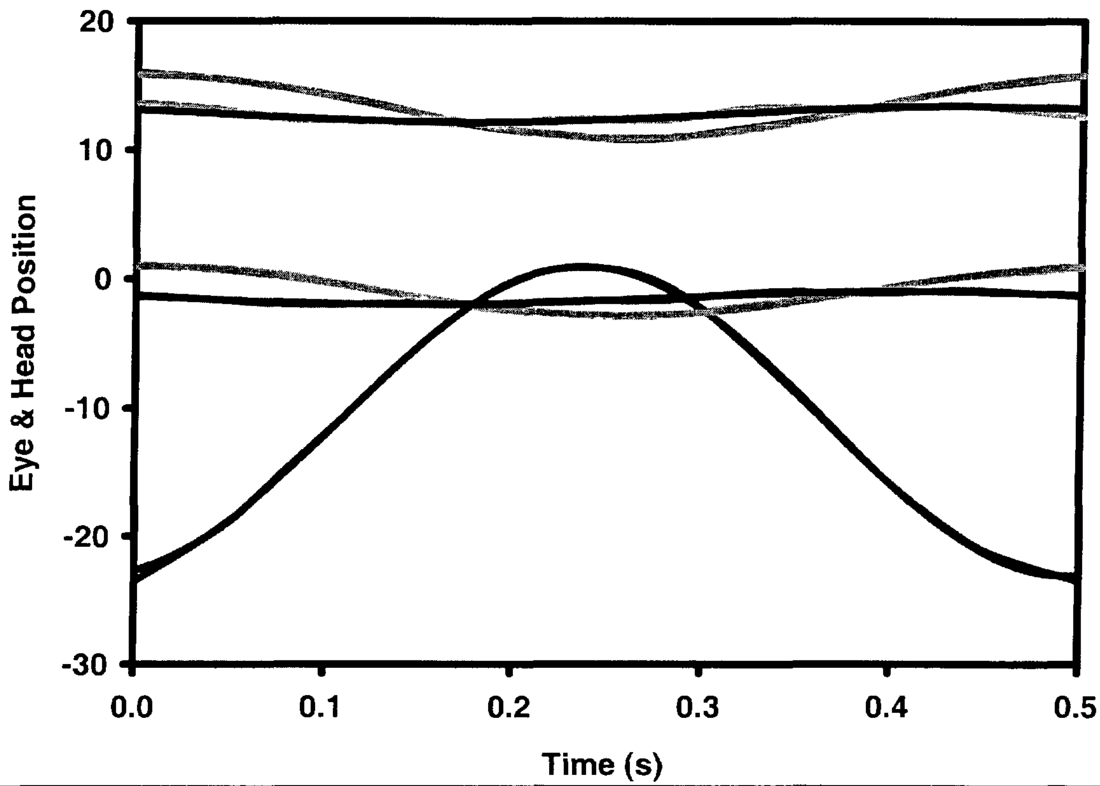

Figure 3: Superimposed eye movement traces for tVOR and tVOR cancellation at 2Hz along with their best-fit sinusoids. The cancellation traces are in blue which the tVOR traces are fitted with green lines. The head movement traces were identical so only the cancellation trial is illustrated. Note that although there is a robust response when subjects viewed an earth-fixed target (green traces) when subjects cancelled their tVOR by viewing a target moving with the head (blue traces) the response was greatly attenuated, even though the vergence angle was maintained.

The eye movement sensitivity is shown as a function of frequency for the earth-fixed target and cancellation trials with a 20cm target distance in Figure 4. Reflex sensitivities were reduced at all frequencies below 4Hz and were near zero for the frequencies below 3Hz. Similar results were obtained during the 30cm trials. The phase of the responses is illustrated in Figure 5. In this case, the phase for trials with an earth-fixed target is near 180 degrees as would be expected for a compensatory reflex. However during cancellation a large phase lag was observed. Thus both the sensitivity and the phase lag show clear differences between the cancellation and earth-fixed target trials for all frequencies below 4Hz.

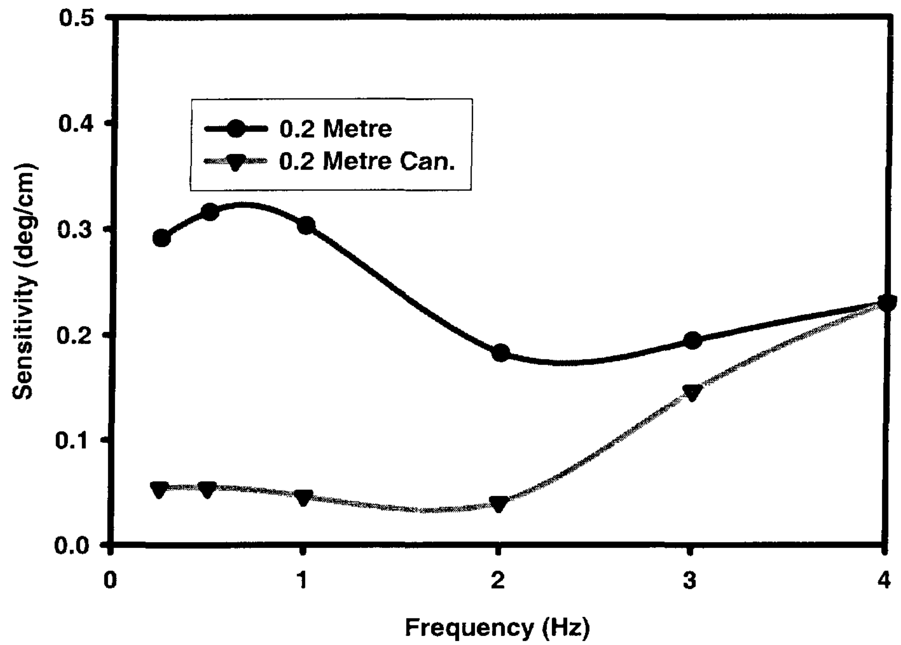

Figure 4: Sensitivity of the tVOR with and earth-fixed target (circles) and during tVOR cancellation (triangles). Note that the sensitivity during the cancellation trials is near zero for all frequencies below 3Hz. (Mean values based on all eight subjects)

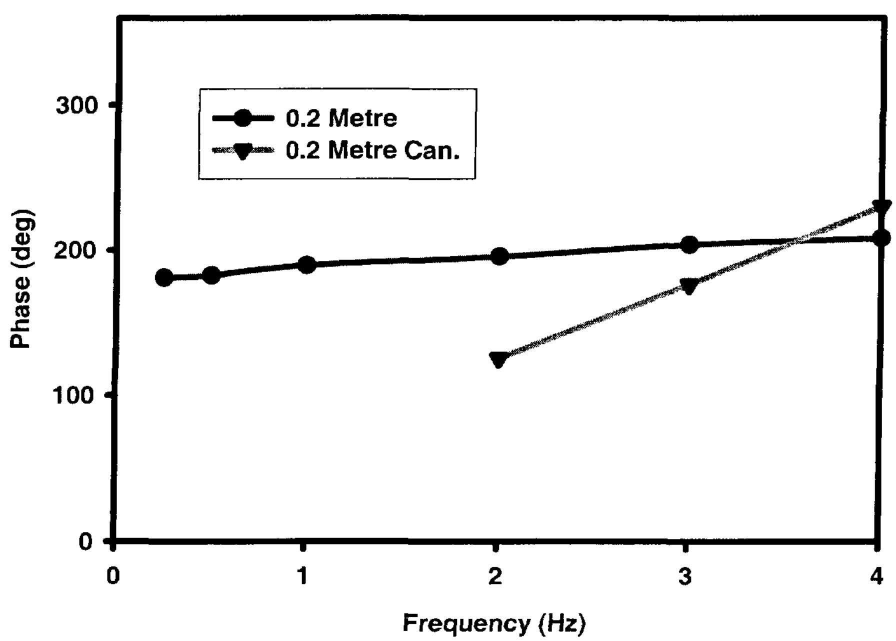

Figure 5: Response phase during viewing of an earth-fixed target (circles) and tVOR cancellation (triangles). Note the phase lag in the cancellation trials at the lower frequencies. No data points are given for cancellation trials below 2Hz as the eye movement amplitude was too small to yield valid estimates.

DISCUSSION:

Early papers have all suggested that the VOR is cancelled by using the smooth pursuit system. Thus, it was believed that when subjects cancelled their VOR by observing a target that moved with the head, vestibular eye movements would result in retinal slip of the image, which would, in turn, activate smooth pursuit. This was based on the observation that smooth pursuit and VOR cancellation had similar frequency responses and patients with smooth pursuit deficits generally exhibited cancellation deficits as well.

In spite of these observations, many authors have continued to question whether or not VOR cancellation was purely dependent on smooth pursuit. Tomlinson and Robinson (1984) found that the behaviour of some vestibular nuclear neurons was not compatible with this theory. Later Lisberger (1990) demonstrated that monkeys were able to slightly reduce their VOR gains during cancellation experiments with latencies far less that those associated with smooth pursuit tracking. In human subjects with labyrinthine disease, Leigh et al. (1987) demonstrated that the supposition that VOR cancellation was based on a linear summation of vestibular and pursuit signals could not explain the patient's behaviour during head-free tracking. Finally, Leigh et al. (1989) demonstrated that humans could visually cancel their torsional VOR even though there is no torsional pursuit system. Thus there is much evidence that VOR cancellation is not simply a function of smooth pursuit.

Unfortunately, we now know that there are other visual tracking mechanisms that might play a role, specifically short latency visual tracking. Specifically, Miles and his coworkers (Gellman et al., 1990) demonstrated that human subjects were able to initiate ocular following responses with latencies as short as 70ms or less. Thus visual following may, after all, be the mechanism responsible for VOR cancellation.

In spite of this, the results presented here would suggest otherwise. No one has ever suggested that ocular following mechanism might operate at frequencies as high as 3Hz. Indeed, it is generally felt that ocular following, or smooth pursuit, contributes little above 1Hz and nothing above 2Hz. However, we have demonstrated that subjects were able to cancel their tVOR very effectively at 2Hz and could reduce the reflex sensitivity by about 25% at 3Hz. Thus we would suggest that cancellation of the tVOR cannot simply be explained by the addition of a smooth pursuit or ocular following signal. Instead, some non-visual mechanism must also be involved as suggested by Lisberger (1990). How this mechanisms functions remains to be determined.

Finally, the robust and short-latency nature of the IA-tVOR should be considered in any environment involving high translational accelerations. When viewing targets located at optical infinity, the eye movements evoked by such accelerations are inappropriate. In the previous study, we demonstrated that the NO-tVOR was also very robust although the evoked eye movements are generally much smaller. Given this, and our new observations that the tVOR can be cancelled up to 3Hz, NO accelerations are unlikely to pose many instrument readability problems for pilots. In addition, the cancellation of this reflex is far better than might have been expected. Thus, when viewing near targets that move with the head, such as the HUD in a high performance helicopter like an Apache, so long as the accelerations remain below 3Hz, the displays should remain readable, especially if the symbols are kept large. However, if translational accelerations exceed 3Hz, particularly in the IA direction where the evoked eye movements are large, then instrument readability may be seriously compromised.

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