USAARL Report No. 96-33

Visual Vestibular Interaction in the Dynamic Visual Acuity Test During Voluntary Head Rotation

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August 1996

19961029 103

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Unclassified
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704-0188

1a REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION / AVAILABILITY OF REPORT Approved for public release, distribution unlimited
2b DECLASSIFICATION / DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) USAARL Report No. 96-33	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a NAME OF PERFORMING ORGANIZATION U.S. Army Aeromedical Research Laboratory 6b. OFFICE SYMBOL (If applicable) MCMR-UAD	7a. NAME OF MONITORING ORGANIZATION U.S. Army Medical Research and Materiel Command
6c. ADDRESS (City, State, and ZIP Code) P.O. Box 620577 Fort Rucker, AL 36362-0577	7b ADDRESS (City, State, and ZIP Code) Fort Detrick Frederick, MD 21702-5012
8a NAME OF FUNDING / SPONSORING ORGANIZATION 8b. OFFICE SYMBOL (If applicable)	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO	WORK UNIT ACCESSION NO.
0601101A	3A161101A91C	LA	292

11. TITLE (Include Security Classification)
(U) Visual Vestibular Interaction in the Dynamic Visual Acuity Test During Voluntary Head Rotation

12 PERSONAL AUTHOR(S)
Moo Hoon Lee, Simon J. Durnford, John Crowley, Angus Rupert

13a TYPE OF REPORT	13b TIME COVERED	14 DATE OF REPORT (Year, Month, Day)	15 PAGE COUNT
Final	FROM TO	1996 August	29

16 SUPPLEMENTAL NOTATION

17. COSATI CODES			18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Spatial disorientation, vestibular, vestibulo-ocular relfex head rotation, visual acuity

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

Although intact vestibular function is essential in maintaining spatial orientation, no good screening tests of vestibular function are available to the aviation community. High frequency voluntary head rotation was selected as a vestibular stimulus to isolate the vestibulo-ocular reflex (VOR) from visual influence. A dynamic visual acuity test that incorporates voluntary head rotation was evaluated as a potential vestibular function screening tool. Twenty-seven normal subjects performed voluntary sinusoidal head rotation at frequencies from 0.7-4.0 Hz under three different visual conditions: visually-enhanced VOR, normal VOR, and visually supressed VOR. Standardized Baily-Lovie chart letters were presented on a computer monitor in front of the subject, who then was asked to read the letters while rotating his head horizontally. The electro-oculogram and dynamic visual acuity score were recorded and analyzed. There were no significant differences in gain or phase shift among three visual conditions in the frequency range of 2.8 to 4.0 Hz. The dynamic visual acuity score shifted less than 0.3 logMAR at frequencies under 2.0 Hz. The dynamic visual acuity test at frequencies around 2.0 Hz can be recommended for evaluating vestibular function.

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21 ABSTRACT SECURITY CLASSIFICATION Unclassified
22a NAME OF RESPONSIBLE INDIVIDUAL Chief, Science Support Center	22b. TELEPHONE (Include Area Code) (334) 255-6907 22c OFFICE SYMBOL MCMR-UAX-SI

DD Form 1473, JUN 86 Previous editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

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Introduction

The maintenance of gaze, as well as balance and orientation, is accomplished by the interaction of inputs from several sensory systems, chiefly the vestibular, visual, and somatosensory. Intact vestibular function is indispensable to maintaining orientation in space, yet candidate aircrew receive minimal vestibular screening at best (Clark and Rupert, 1992). Vestibular deficits typically are exhibited later, in trained aircrew, as difficulty in maintaining controlled flight in actual or simulated instrument meteorologic conditions. Since vestibular function is so important to aviation safety, why is it that only vision and auditory function are screened adequately? Quite simply, there are no vestibular function screening tests available for the flight surgeon to administer. A useful screening test for vestibular function would have to be quick and simple to administer and score, quantitatively standardized, and the results easily interpretable.

The vestibulo-ocular reflex (VOR) normally serves to stabilize the gaze in space during head movements by generating compensatory eye movements. Patients with absent vestibular function typically suffer from imbalance and oscillopsia. The latter results from loss of the VOR, and manifests itself as disturbing illusory object movement. Partial lesions of the vestibular system produce changes in vision and eye movement. For example, movements of the body or head in patients with vestibular and/or brain stem disease can provoke an illusory motion of a visually fixated target (Bender and Feldman, 1967). The VOR is the basis of currently available vestibular function tests, including the bithermal caloric test and the rotation chair test. Sinusoidal passive rotation has been used for the diagnosis of vestibular disorders (Baloh et al., 1982; Wall et al., 1984; Wolfe et al., 1982), but this test requires bulky, complicated, and expensive equipment.

Active head rotation, a simple maneuver to perform in the doctor's office, has been used recently to generate the vestibulo-ocular reflex in a fashion that lends itself to quantitative analysis. This may, in turn, prove useful in assessing individuals with vestibular disorders (Jell et al., 1982; O'Leary and Davis, 1990; Tomlinson et al., 1980). It is reasonable to assume that mechanisms producing compensatory eye movements during head motion should match the dynamic range of natural head motion, suggesting active head motion as a suitable means for testing vestibular function. The oculomotor stabilizing reflex predominantly depends on vestibular afferent input and is minimally influenced by eye tracking reflexes (Barnes et al., 1978; Hyden et al., 1982; Tomlinson et al., 1980), the cervico-ocular reflex (Bronstein and Hood, 1987), or voluntary mental tasking (Jell et al., 1988).

In the active head rotation test, precise sinusoidal stimulation is not feasible. Further, VOR gain and phase have not been standardized to enable rational decisions concerning fitness for flying. For these reasons, the results of vestibular testing could be used only to identify normal responses or suggest possible vestibular abnormalities.

In this study, we examined the dynamic visual performance of normal subjects during active high frequency head rotation to investigate the feasibility of using this procedure as a screening test for vestibular function. In the frequency range of the dynamic visual acuity test, the gains of the VOR were compared under three different visual conditions -- visually enhanced VOR, visually suppressed VOR, and normal VOR -- to assess the extent to which vision is influenced by the retinal input reflex. These results will be important in determining the appropriate stimulus condition of the dynamic visual acuity test as a stimulus for a test of vestibular function.

Materials and methods

Subjects were 27 U.S. Army flight students or rated aviators ranging from 19-43 years old. All had passed the standard U.S. Army flight physical, had binocular visual acuity better than 20/20 uncorrected, and had no known vestibular or oculomotor disorders. All subjects completed a medical questionnaire and submitted their medical records for review so as to exclude those with a history of vertigo, motion sickness, or neck injury.

Electrodes, suitable for electro-oculography (EOG), were taped on the outer canthus of each eye. The EOG signal was DC amplified and the minute electrical potential used to calculate eye velocity. The head position signals were calculated from a headband-mounted rate sensor fitted snugly to the head. Figure 1 shows the instrumented head band (Micromedical Technology, Inc.*) worn by the subjects.

Figure 1. Instrumented head band worn by the subjects.

As shown in Figure 1, the cylinder on the forehead is a sensor that records head rotation velocity about the cylinder's axis. The active axis can be turned 90 degrees for recording vertical head movements. The cable connects to circuits inside a portable computer, which are software controlled. The computer generates an auditory test cue, collects the data, and computes gains and phases. A calibration bar, with a red light emitting diode (LED) at center and 10 degrees to the left and right, was placed 3 m in front of the nasion with the subject seated comfortably in the fixed chair. EOG calibration was performed before each test and after the last test.

*See manufacturers' list.

Due to the mechanical design of the head sensor, it was not possible to directly measure the exact velocity at which the subject turned his head. The head rate sensor was calibrated in every subject through a controlled head shaking test at a frequency of 1.0 Hz. The computer assumed that the normal subject had perfect gain during the test and adjusted the data from the velocity sensor to match the velocity recorded from the subject's eyes.

A small laser pointer, also mounted on the head band, served to project a small spot onto a screen located 3 m in front of the subject. This provided a visual target that rotated with the head movement (head-fixed) for the test of visual suppression of reflexive eye movements. Sound cues for head oscillation were generated from a computer controlled electronic metronome. A series of clicks presented at increasing frequencies of 0.7, 1.0, 1.4, 2.0, 2.8, and 4.0 Hz were provided as cues for voluntary head oscillation.

The host computer for these experiments was a 386SX PC equipped with VORTEQ desktop system and ENG Ultra software (version 3.0; Micromedical Technology, Inc.*) which recorded head velocity and eye position signals. Data associated with saccadic eye movements were eliminated automatically using filtering analysis by predetermined velocity and direction. Both the composite eye and head velocity response cycles were approximated by adding the fundamental and the first harmonic components of each response after Fourier analysis (Figure 2). The head velocity response polarity was reversed during analysis. The VOR gain and phase were computed by comparing the eye velocity response to the head velocity response after alignment.

In generating head and eye velocity curves, the computer determined the frequency of all cycles of head rotation during the test and grouped them according to their frequency. All cycles close to 2.0 Hz (from 1.5 to 2.5 Hz) were grouped together. Each frequency group then was averaged individually to create a composite head and eye velocity curve. Then, calculations were made on these composite curves to derive gain and phase for each frequency group.

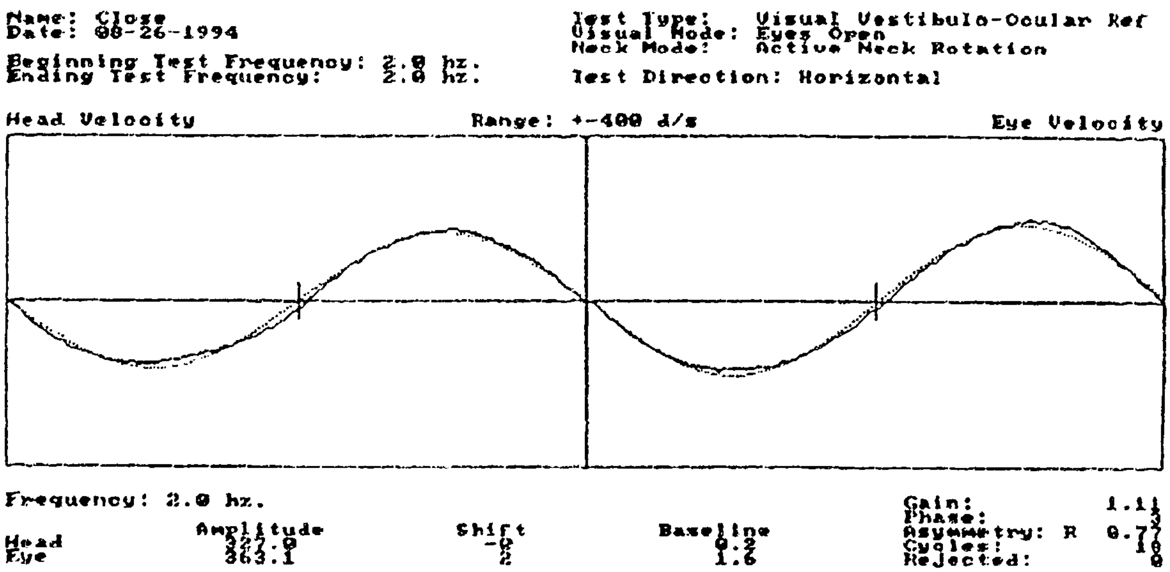

Figure 2. Composite head and eye velocity curve for the 2.0 Hz group along with the best fit composite curve.

A group of Bailey-Lovie (1976) chart letters of predetermined size was presented on a computer screen while the subject shook his/her head back and forth during the dynamic visual acuity test. A head velocity sensor measured head velocity while the subject shook his/her head horizontally ±20 degrees at the predetermined frequency. The letters were presented to the subject only when head motion exceeded a predetermined velocity to prevent "cheating" by the subject (Table 1). If the response was correct, smaller letters were presented to find the limit of recognition.

Table 1.

Critical head velocities that the subject should exceed before the optotypes will appear on the screen

Frequency (Hz)	Head velocity (degrees/sec)
0.7	56
1.0	80
1.4	112
2.0	160
2.8	224
4.0	320

Head velocity presented at each frequency originally was intended to represent mean angular velocity. Because the excursion of head movement became reduced in order to attain the higher required frequencies, the letter display portion of the rotation cycle became relatively shortened.

The Bailey-Lovie chart letters presented on the screen during the dynamic visual acuity test were of almost equal legibility at each level. Letter size progression was in uniform steps on a logarithmic scale (Bailey and Lovie, 1976). They were presented in a vertical column of five letters on each screen to prevent overlapping of the image (Figure 3). There were 12 columns of letters ranging from 1.0 to -0.1 logMAR available for display at a distance of 3 m. Illumination of the white background was approximately 5.26 cd/m^2, black letters 3.31 cd/m^2, and the white screen 132.3 cd/m^2.

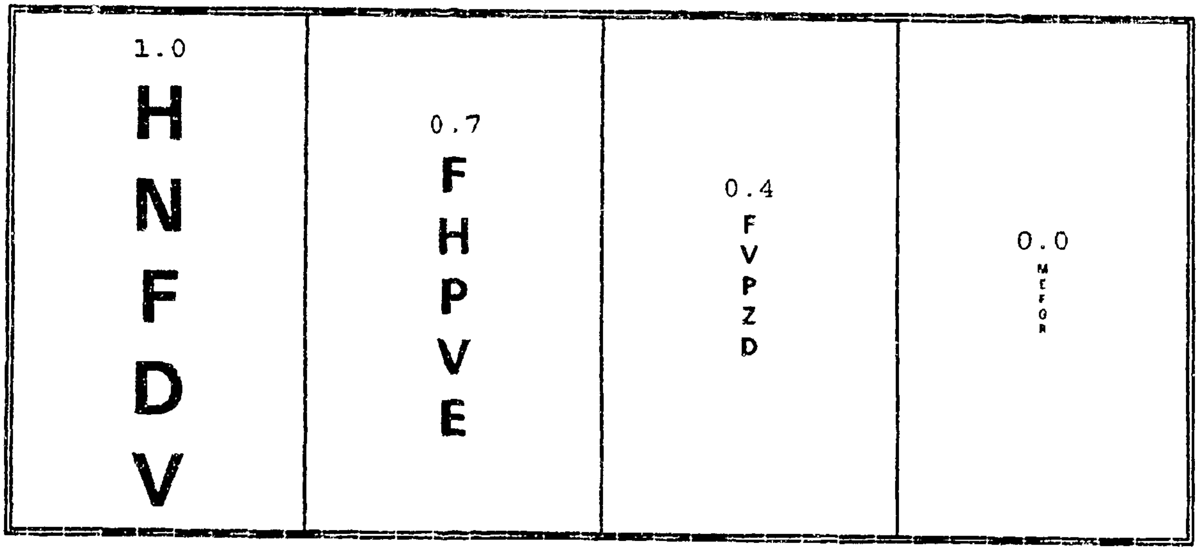

Figure 3. Examples of Bailey-Lovie letters

Test procedure

The active horizontal head rotation about the earth's vertical axis was conducted over the discrete frequencies of 0.7, 1.0, 1.4, 2.0, 2.8, and 4.0 Hz in synchrony with the sound of an electronic metronome. VOR gain and phase shift from all the subjects were measured under three different visual stimuli conditions:

1) Visually enhanced VOR (VVOR) -- obtained by making the subject fixate on the earth stationary target during head rotation,

2) VOR -- recorded from the subject attempting to fixate on the stationary target with eyes closed, and

3) Visually suppressed VOR (VSVOR) -- while the subject fixated on the light moving with the head movement.

Dynamic visual acuity scores were measured from the actively head-rotating subjects while they attempted to read the visual chart at the same discrete frequencies. The sequence of the three VOR conditions was balanced among subjects. The dynamic visual acuity test was conducted 1 month after the first three tests because of equipment limitations. Dynamic visual acuity was scored, by number of letters recognized, using the Bailey-Lovie scoring procedure (Bailey and Lovie 1976). Prior to testing dynamic visual acuity, static acuity was tested routinely (with both eyes open using the same apparatus).

Results

Gain in the different VOR conditions

Our subjects had no difficulty in performing the active head rotation at 0.7 Hz. However, obtained frequencies were progressively variable at higher frequencies. Typical recordings of head and eye position signals for all tested frequencies in the three VOR conditions are shown in Figures 4-9. For the relatively low frequencies (i.e., 0.7 and 1.0 Hz), eye position traces completely matched the head position traces (but in the opposite direction) in the visually enhanced condition. They were not as well matched in the eyes closed VOR condition, and in the VSVOR condition the visual suppression effect of the head-fixed target was evident. As the rotation frequency increased, the eye position signals were completely compensatory (equal magnitude and opposite direction) for the VVOR and VOR. Eye position traces of visually suppressed conditions displayed a competitive interaction between the vestibular and visual inputs in the intermediate range (from 1.0 Hz to 2.0 Hz).

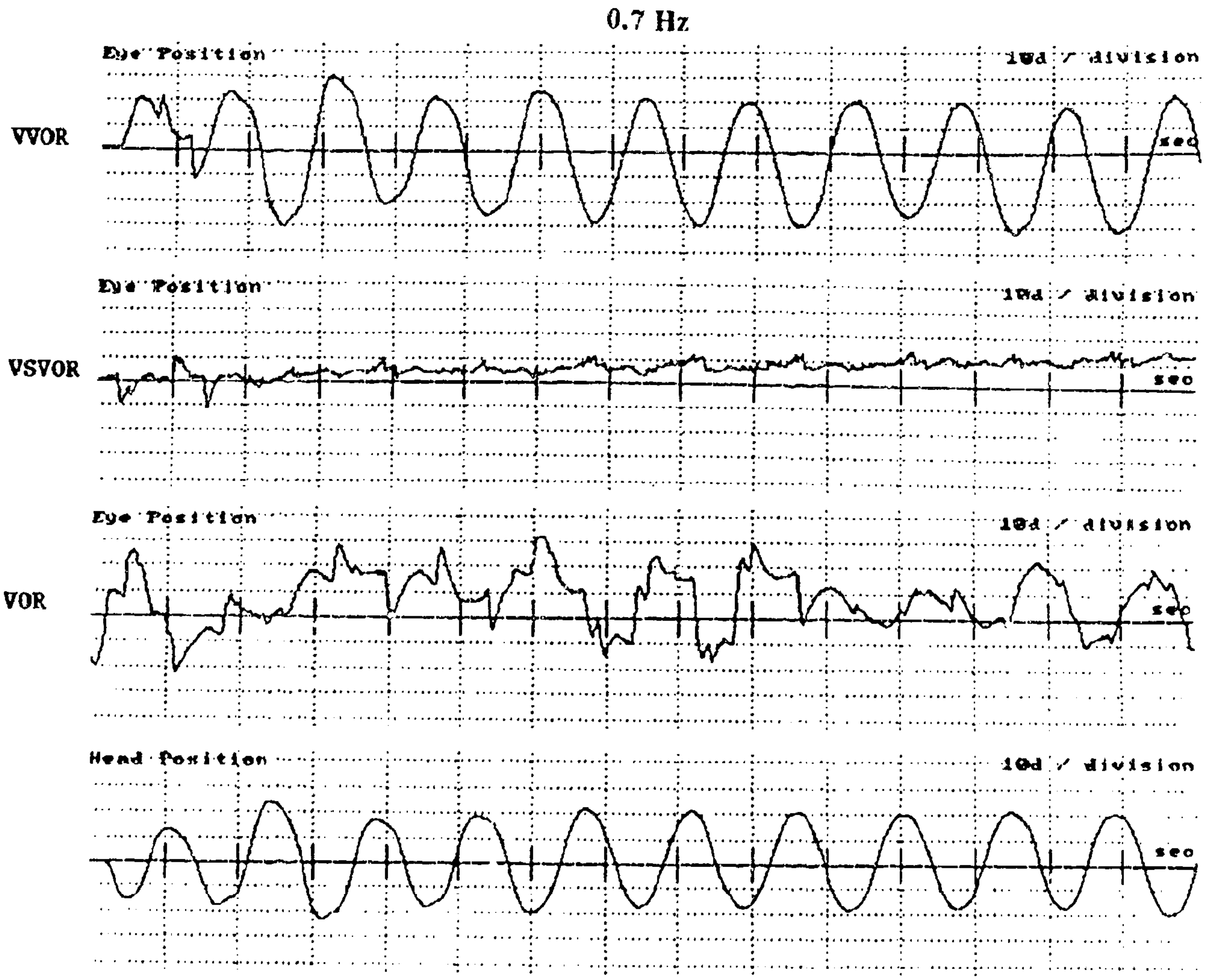

Figure 4. Eye and head position signals during head oscillation Of 0.7 Hz.

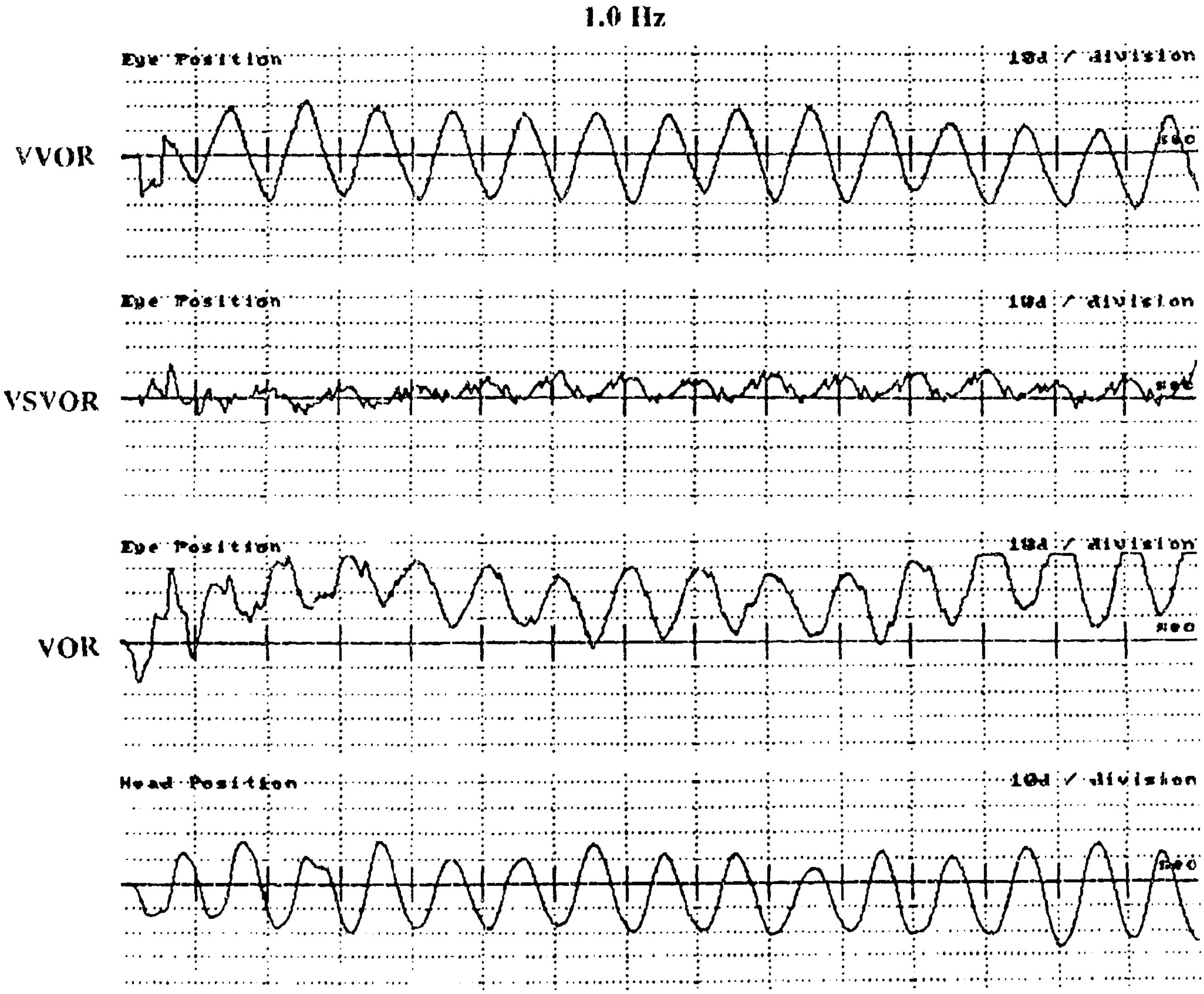

Figure 5. Eye and head position signals during head oscillation Of 1.0 Hz.

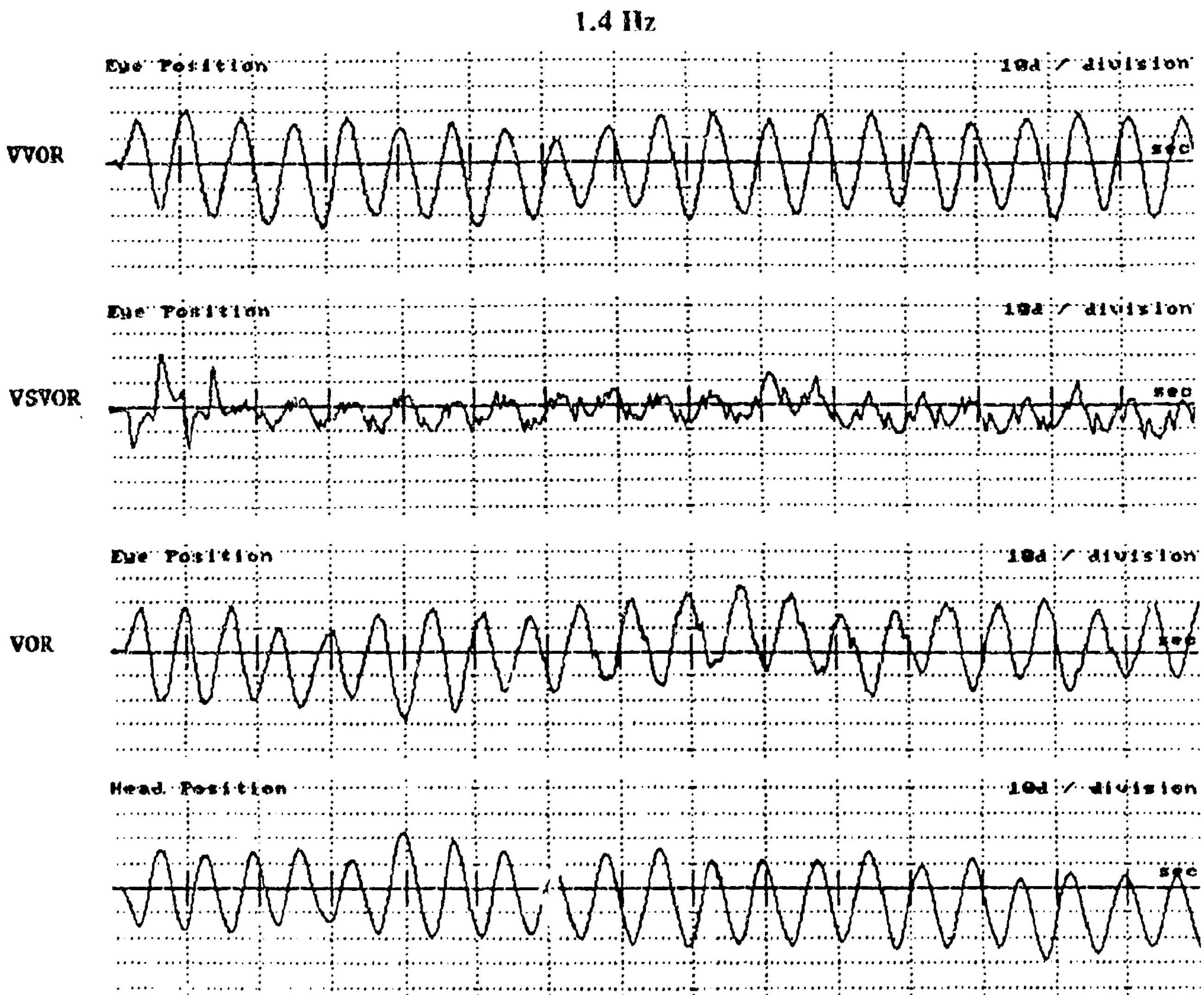

Figure 6. Eye and head position signals during head osillation Of 1.4 Hz.

2.0 Hz

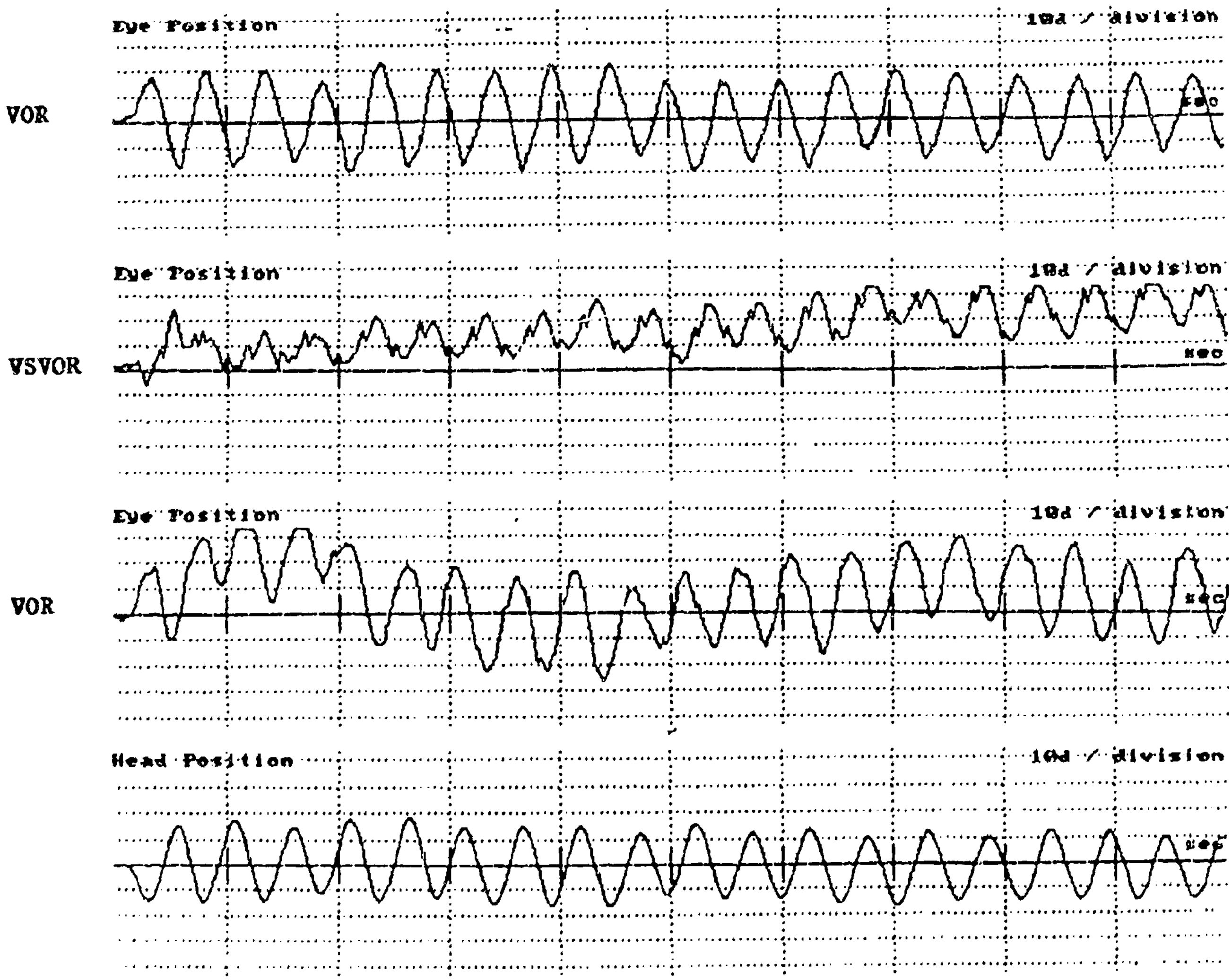

Figure 7. Eye and head position signals during head oscillation Of 2.0 Hz.

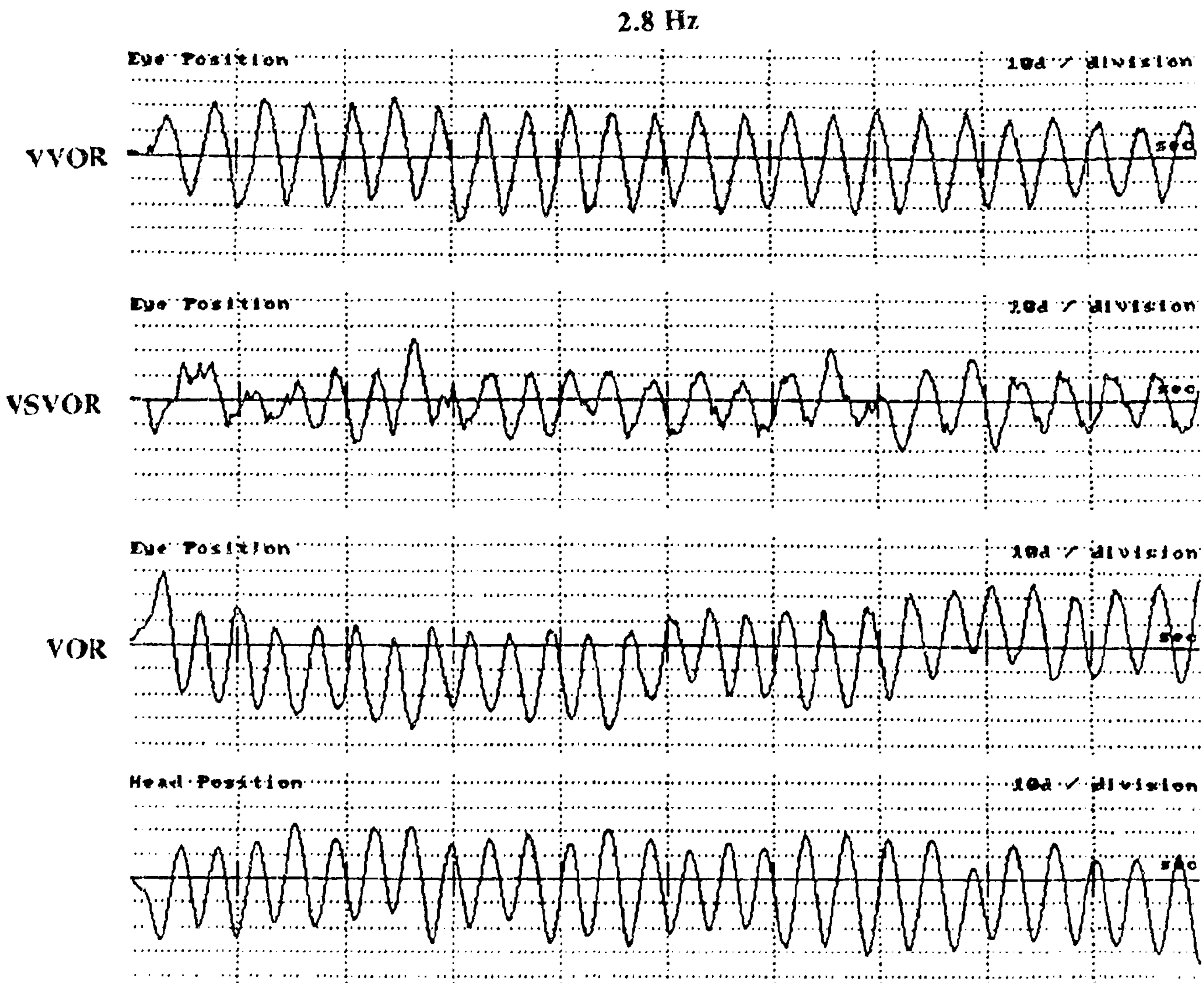

Figure 8. Eye and head position signals during head oscillation Of 2.8 Hz

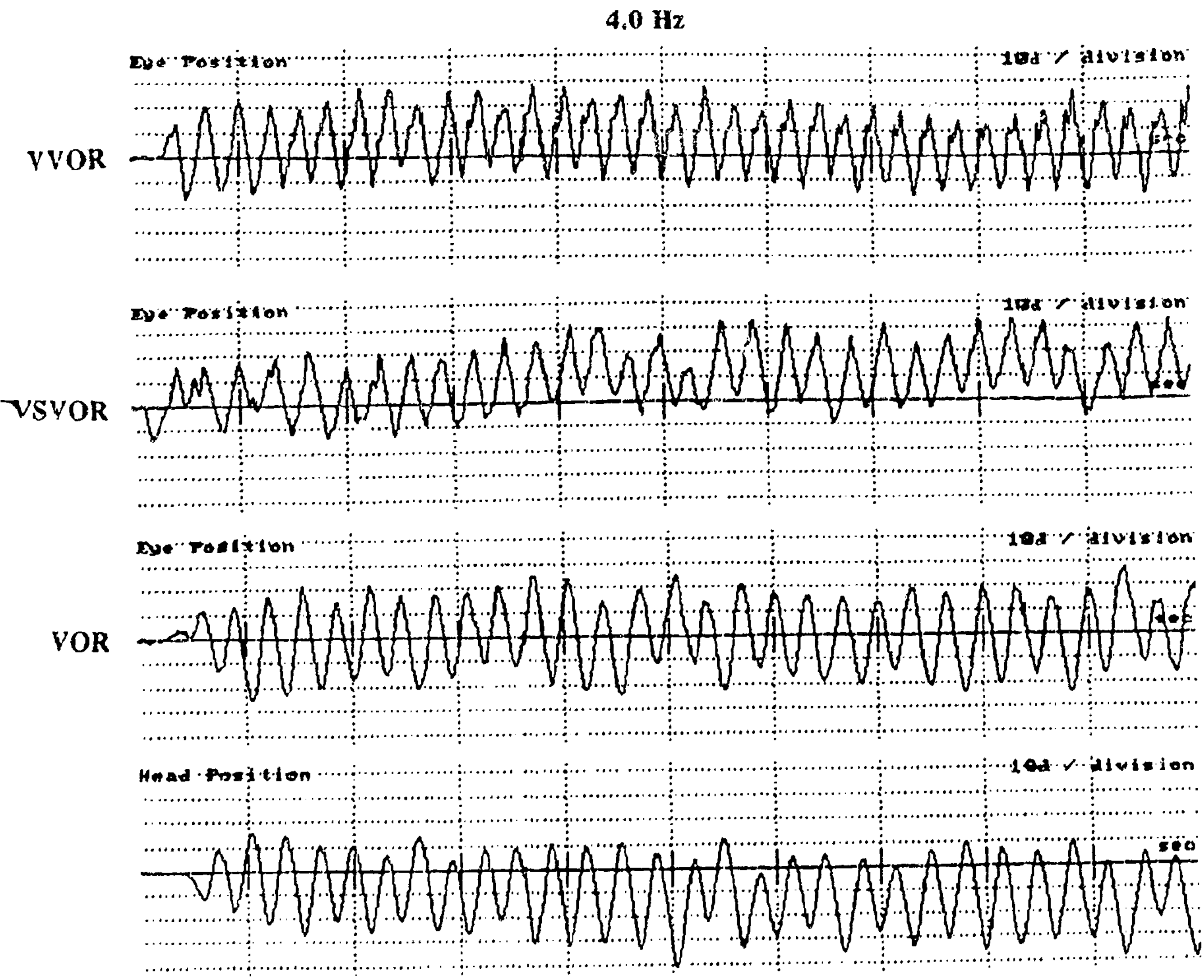

Figure 9. Eye and head position signals during head oscillation Of 4.0 Hz.

For the high frequencies (2.8 Hz and 4.0 Hz), the VSVOR curves were equal to those of the other conditions and compensatory to the head movement. That is, the vestibular oculomotor reflexes completely overrode visual fixation (mainly attributable to the smooth pursuit system) in this frequency range. The recorded data were, of course, matched by the subjective perception: the red spot seen at low frequencies in VSVOR condition was reported to appear as an increasingly longer line at increasingly higher velocities until the length of the line corresponded to the amount of head deflection during very rapid oscillations.

Frequency specific gains (eye velocity vs. head velocity) were averaged across subjects and the data analyzed with a two-factor (visual condition; head rotation frequency) repeated measures ANOVA. Significant main effects were found for both factors (visual condition: $F(2,50)=8.56, p<0.001$; frequency: $F(5,125)=7.76, p<0.00001$). Post hoc analysis of the visual condition using the Sheffe test indicated significant differences between VSVOR and VOR ($p<.01$) and between VOR and VVOR ($p<.05$). Post hoc analysis of the frequency data yielded significant mean differences between 0.7 Hz and 2.8 Hz ($p<.001$) and 4.0 Hz ($p<.05$), 1.0 Hz and 2.8 Hz ($p<.001$), and 1.4 Hz and 2.8 Hz (2.8 Hz ($p<.05$). More importantly from the perspective of the present study, the results indicated a statistically significant interaction between visual condition and head rotation frequency ($F(10,250)=3.67, p<0.001$). These data are summarized in Figure 10, which shows the relationship between the two variables as it pertains to gain.

As can be seen, the VVOR condition, which provided synergistic visual and vestibular inputs, yielded higher gains than the VOR or VSVOR conditions in the low frequency range (<2.0 Hz). Mean gains in the VSVOR condition, where visual inputs were suppressed by visual fixation, were lower than in the VOR condition in which visual stimulation were absent. The oculomotor reflexes were still influenced by the visual system input in these frequencies, but there was no significant difference in gain at the higher frequencies (>2.8 Hz).

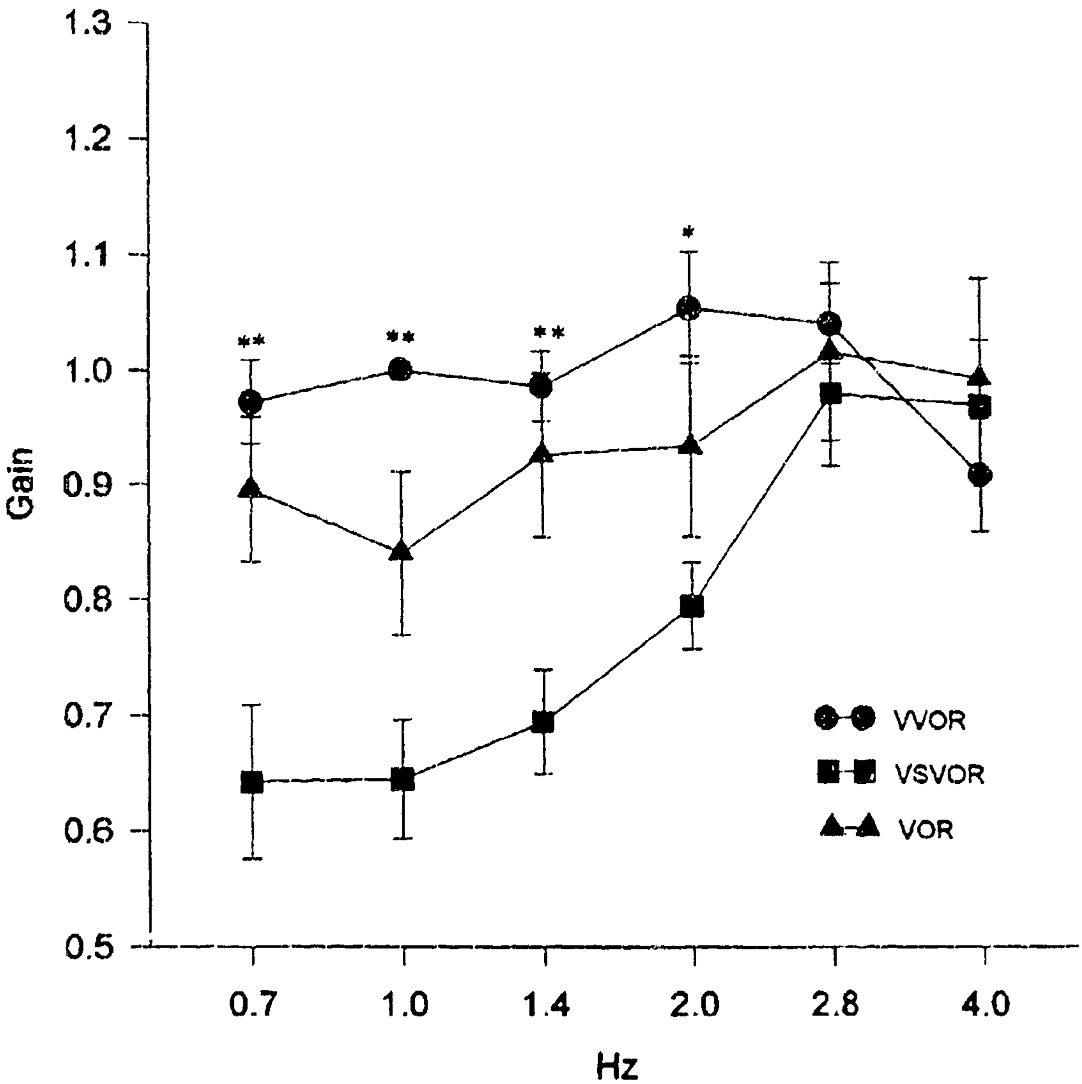

Figure 10. Mean velocity gains (eye/head) vs. head rotation frequencies for all subjects (in each visual condition).

Phase shifts

The mean phase shifts also are presented for each condition in Figure 11. There was a tendency of some phase lead in the VOR condition and some phase lag in VSVOR condition. Because of the large variability among subject performance, the mean difference in phase shifts for corresponding frequencies on the visual conditions failed to reach statistical significance.

Dynamic visual acuity score

Static visual acuities, using the Bailey-Lovie chart letters on the computer monitor, were obtained at a 3 m distance with the subjects sitting with both eyes open. The mean static visual acuity was -0.064 logMAR (20/17 Snellen). Visual acuity deteriorated minimally to 0.033 logMAR (20/22 Snellen) during head rotation of 0.7 Hz. Visual acuity decreased to 0.172 logMAR (20/30) at a head rotation of 2.0 Hz (Figure 12). In the higher frequencies of 2.8 and 4.0 Hz. the average visual acuities measured 0.298 logMAR (20/40) and 0.549 logMAR (20/71), respectively.

Discussion

The major role of the VOR is to stabilize the eyes for clear vision during movement in daily life. Walking and running result in periodic head movements at fundamental frequencies of 1.0 to 4.0 Hz with harmonics extending well above this (Grossman et al., 1988). Because other ocular control systems are relatively insensitive above about 2.0 Hz, the VOR functions as the primary control system for visual stabilization during locomotion (Guitton and Volle, 1987). Yet the VOR is seldom tested under controlled laboratory conditions in its natural, higher frequency range because of technical limitations of most rotational chair systems.

An alternative approach to VOR testing at higher frequencies is to employ active head rotation in which the neck muscles move the head and a rotational sensor attached to a head band is used to monitor head movement. This approach has been used at frequencies from 0.2 to about 6.0 Hz (Fineberg et al., 1987; Jell

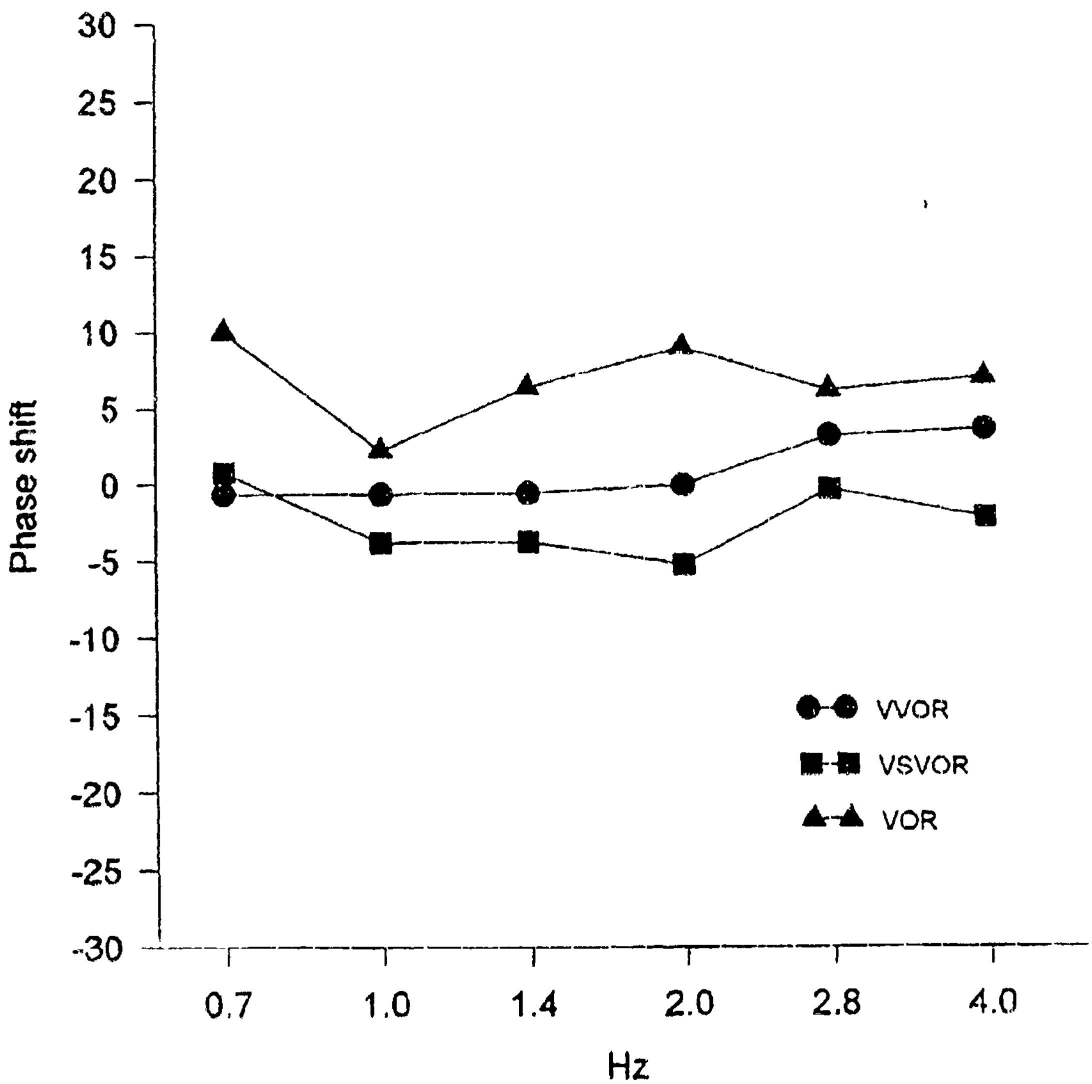

Figure 11. Mean phase shifts in each visual condition vs. head rotation frequencies for all subjects.

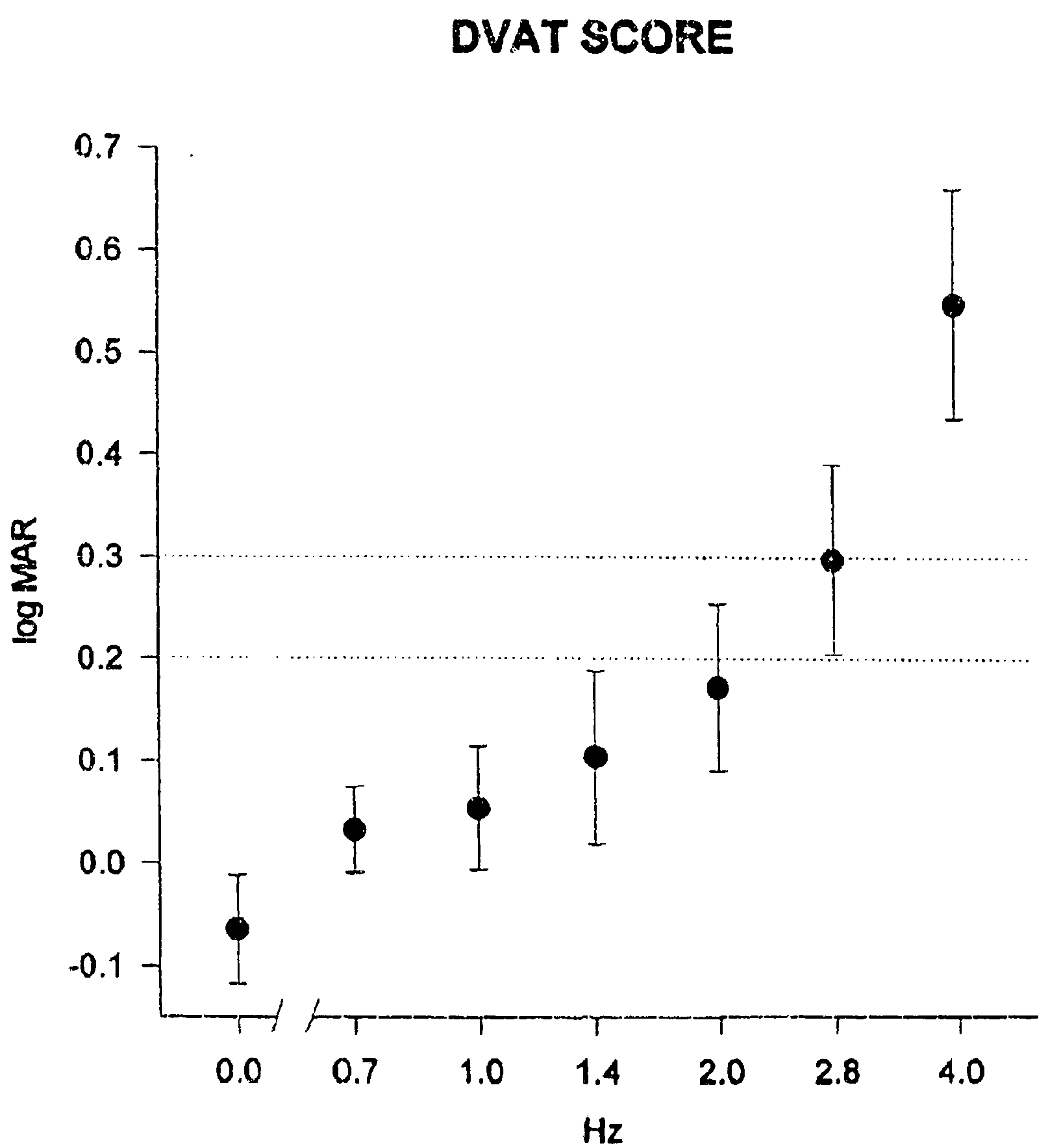

Figure 12. Mean dynamic visual acuity score in logMAR units vs. head rotation frequency.

et al., 1982; Jones and Gonshor, 1982; Nogami et al., 1989; O'Leary and Davis, 1990; Tomlinson et al., 1980). However, it is useful to consider 2.0 Hz as a functional boundary between lower and higher frequency responses because ocular smooth pursuit is relatively ineffective at stabilizing the eye at frequencies higher than 2.0 Hz (Barnes et al., 1978; Zackon and Sharpe, 1987). Below 2.0 Hz, the VOR's contribution to visual stabilization can be influenced strongly, or even suppressed, by other competing ocular motor systems and/or cognitive processes such as imagined targets (Baloh et al., 1984; Barr et al., 1976; Jell et al., 1988). In contrast, because of the insensitivity of other ocular systems above 2.0 Hz, the VOR is the system used for visual stabilization in this frequency range, and, furthermore, it is relatively unaffected by the presence or absence of real or imagined targets (Jell et al., 1988).

Recently, self-contained computerized methods of testing the VOR during active head rotation have become available commercially. This method has shown major practical advantages over other vestibular testing methods, including enhanced patient comfort, efficiency, portability, vertical VOR testing, and the use of natural frequencies (O'Leary and Davis, 1990). Useful clinical diagnostic information is obtained from this method using control theory descriptors (e.g., gain and phase) for comparisons with normal values.

A combination of this vestibular autorotation technique and a dynamic visual acuity test has been developed and promoted as a new method of screening for aminoglycoside vestibulotoxicity (Longridge and Mallinson, 1984; 1987). The Dynamic Illegible E test originally evaluated the ability of a subject to read different size characters while his/her head was passively turned back and forth once per second (1.0 Hz). Longridge and colleagues found that the normal population showed no deterioration of visual acuity beyond two Snellen rows (comparable to 0.2 logMAR).

Although the deterioration of the dynamic visual acuity score was less than 0.1 logMAR (mean DVAT score 0.054, SD 0.060) at 1.0 Hz in our experiment, the mean gain difference of VOR in three different visual conditions was prominent. That is, dynamic visual performance was remarkably preserved by the eye tracking reflex at 1.0 Hz. However, the dynamic visual acuity score was significantly reduced at 2.8 to 4.0 Hz, even in our normal subjects.

Atkin and Bender (1968) reported the maintenance of ocular stability during oscillatory head movement within a 0.1-5.0 Hz frequency range. They found that normal subjects can maintain ocular stability up to head velocities of 250-300 deg/sec. Pulaski et al. (1981) found that the VOR was compensatory for head velocities of up to at least 350 deg/sec, during both active and passive head rotation, provided there was an attempt to visualize a real (or imagined) stationary object in space. Performance of both the vestibular and the optokinetic ocular stabilization mechanism was velocity-limited (Atkin and Bender, 1968; Boff and Lincoln, 1988).

Although the mean gain above 2.8 Hz was maintained around one in our experiment, transient maximum velocity could exceed 300-350 deg/sec, beyond which ocular stabilization cannot be maintained. The limiting frequencies and velocities are considerably low in the retinal input oculomotor reflex (under 2.0 Hz and 100 deg/sec). Nevertheless, retinal inputs can play an essential role in ocular stabilization, even at the higher velocities and frequencies of head rotation, because the oculomotor effects of vestibular and optokinetic stimulation are additive. Additivity implies that if the difference between head velocity and the vestibular component of compensatory eye velocity (i.e., occurring in absence of vision) remains less than about 80-100 deg/sec, the optokinetic system can bring total eye speed to a value that fully matches head velocity (Atkin and Bender, 1968). In complete absence of vestibular function, this limiting head velocity obviously would be the same as the limiting velocity for pure optokinetic stimulation. We thus consider it reasonable to select the stimulus frequency above 2.0 Hz in which mean head velocity is 160 deg/sec as a screen for vestibular function.

Active head movement inevitably elicits the cervico-ocular reflex (COR) which also contributes to ocular stabilization. The compensatory role of the COR in normal subjects makes little, if any, contribution to retinal stability during head movement (Bronstein and Hood, 1986). This is evident from the very low gain and extreme variability in the direction of the slow components of the COR. Without labyrinthine function, the COR appears to take on the role of the vestibulo-ocular reflex in head-eye coordination to generate compensatory eye movements (shown experimentally at 0.3 Hz sinusoidal oscillation over ±25 degrees). Kasai and Zee (1978) reported the gain of the passively induced cervico-ocular reflex could be potentiated when the chronically labyrinthine-defective patients imagined a target on the wall. The gain also was higher during active rather than passive movements. But it played a relatively minor role in gaze stabilization -- especially for the rapid, higher frequency head movements that occur during active target seeking. The marked potentiation of the COR gain in the vestibular patients decayed consistently with increasing frequency of stimulation above 0.4 Hz (Bronstein and Hood, 1987). Our stimulus frequency (2.0 Hz) in the dynamic visual acuity test can minimize the effect of the COR even in subjects with vestibular abnormality.

In our experiment, the gain of the VOR in the visually enhanced condition (which was the same as that of the DVAT) was maintained around one. There appears to be no obvious relationship between gain or phase shift and visual acuity performance. The deterioration of dynamic visual acuity is presumed to have occurred due to oscillopsia and net retinal slip--the velocity of eye movement in relation to the fixed surroundings during head motion (Wist et al., 1983). Retinal slip occurs when head movement exceeds the critical velocity that cannot be compensated for by visual vestibular interaction. Retinal slip speed can be calculated as the vector sum of the velocities of eye movement in relation to the head and velocities of head movement and in relation to the fixed surroundings. Further research should evaluate the extent to which dynamic visual acuity performance is related to the retinal slip.

In conclusion, the frequencies between 2.0 Hz and below may be best for screening vestibular abnormality. This transitional range contains the frequencies in which the oculomotor reflex gradually diminished. The DVAT scores at 2.8 and 4.0 Hz were too deteriorated to differentiate normal from abnormal.

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Appendix

List of manufacturers

Micromedical Technology, Inc.
110 West Walnut
Chatham, Illinois 62629

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