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VISUO-MANUAL TRACKING PERFORMANCE OF MAN SUBMITTED TO VIBRATION

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ABSTRACT

Studies have described the decrease of sensorimotor system performance in man submitted to vibration. The observed alterations are due to both the mechanical effects of the vibration on the body segments involved in motor control, and to the physiological effects of the vibration on sensory receptors eliciting erroneous information inevitably reaching the central nervous system.

The effects of vibration on the tracking performance of visual targets were studied in man under laboratory-controlled conditions. The data show that the major site of action of the vibration is constituted by the muscular masses containing "kinaesthetic" receptors. The observed effects outlast the duration of the vibration.

Since the vestibular receptors of the inner ear are also activated by vibration at frequency and amplitude commonly encountered on helicopters, an experiment was designed to study the dynamical characteristics of the human vestibulo-ocular system in the 0.5 to 30 hertz frequency range by forced-rotating the head around the vertical axis. The rotation was transmitted to the head by a hard-cushioned helmet and a rigid bite bar. The vestibulo-ocular reflex (VOR) gain and phase were measured during fixation of a stationary visual target.

The results confirm earlier observations : the gain starts to decrease beyond 2 Hz and the phase rises towards 90°. They also show that beyond 8 Hz, the gain curve reverses in direction and increase continuously towards 2-3 at 25-30 Hz. Meanwhile, the phase curves do not vary much. In the same frequency range, the perceived visual instability is significantly altered.

It is concluded that the gain variation at high rotation frequency may explain the perceived visual target instability and may be suspected to be, in part, responsible for the decrease of human performance in visual tracking tasks executed in vibrating environments.

Modern vehicles, and particularly helicopters, generate vibration inevitably transmitted to pilots and passengers. Vibration of moderate amplitude in the range of frequencies encountered on helicopters has been shown to alter the control of posture (Martin et al., 1980) and movement (Roll et al., 1976 ; Lewis and Griffin, 1976, 1977, 1978 ; Gauthier et al., 1981) due to both mechanical effects of the vibration on the body parts mobilized in a given motion and to physiological effects induced as a result of the activation of particular sensory receptors addressing erroneous information to the central nervous system.

Numerous studies have demonstrated the mechanical aspects of vibration-induced alterations and bio-mechanical models have been developed to predict the effects of particular vibrations applied to man-machine interacting systems (Levison, 1978). In a series of studies sponsored by the Helicopter division of Aerospatiale, we showed that standing posture and postural adjustments (Martin et al., 1980) as well as spinal reflexes (Roll et al., 1981) and sensory motor controls were deeply altered by vibration applied to a seated subject.

The present report summarizes latter developments in the study of the effects of vibration on the visuo-manual tracking system and the involvement of the vestibular system (through head rotation) in the observed alterations.

Preliminary results on tracking performance under vibration condition were presented at the previous Forum held in Bristol and a detailed report on the effects of head vibration on ocular fixation will soon be released (Gauthier et al., 1982, in press).

OCULOMANUAL TRACKING PERFORMANCE

Subjects trained to perform on visual tracking tasks were vibrated at 18 Hertz and 0.1 g as measured at platform level. The experimental setup is shown in Fig. 1. The vibration was produced by a vertical hydraulic jack.

Fig. 1 - Experimental setup showing the vibrating platform supporting the seated subject. The spot target was presented on the screen of the oscilloscope. The tracking target was actuated by either the conventional stick or the mini-stick (placed on the right hand side of the subject), both equipped with potentiometric and strain gauge devices for position and force controls, respectively.

The visual targets were presented on a wide-angle oscilloscope screen positioned 57 cm away from the subject's eyes. Two basic tasks were proposed to 10 adult subjects ;

1 - tracking a target spot moving either sinusoidally in the horizontal direction over a 20 degree angle as seen by the subject, or around a circular path, 10 degrees in diameter. The tracking spot, slightly larger in size was controlled by the subject operating a short (mini-stick) or a longer (conventional stick) lever equipped with a set of potentiometers (position control) or a set of strain gauges (isometric, force-control condition).

2 - counteracting (recentering) the motion of a target moving around a circular path about 20 degrees in diameter by actuating the short or the long lever used in the previous task. Optimum control of the position of the target by the subject should result in keeping the spot in the target zone constituted by the center of the circular path described by the target in the absence of lever motion. The so-called long stick was constituted by a conventional helicopter stick equipped with a potentiometric strain gauge device. Used in the force-controlled configuration, the stick was immobilized by a rigid mechanical clamp. Likewise, the mini-stick was equipped with potentiometric and strain gauge devices located in the aluminium box seen under the handle (Fig. 2). The mini-stick was mounted on the right hand side of the subject, at arm rest level. A soft padded armrest permitted a comfortable manipulation of the lever.

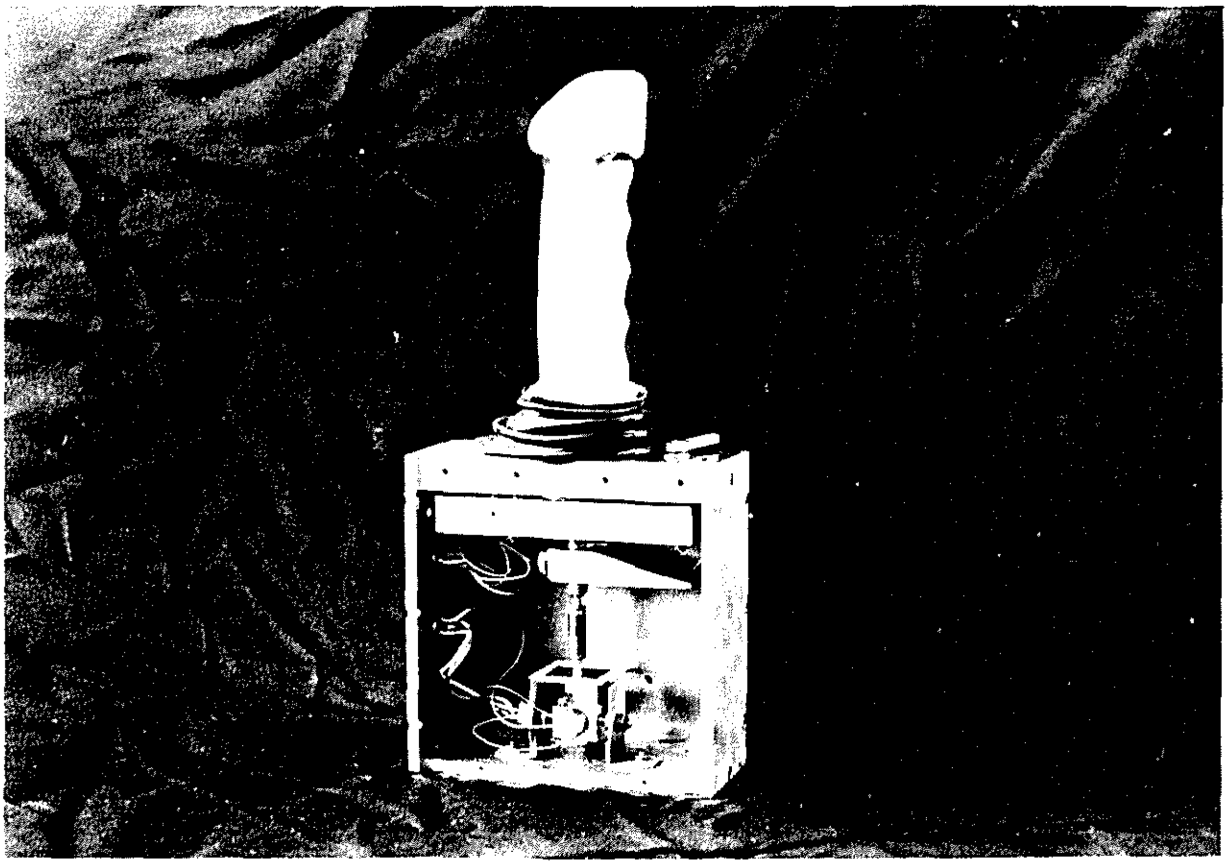

Fig. 2 - Mini-stick designed to control the tracking target position on the screen. Two degrees of freedom are allowed (lateral and anteroposterior). Two modes of use are permitted : 1 - position-control (isometric, low friction), 2 - force control (isometric).

A potentiometric and a strain gauge device are mounted inside the aluminum box supporting the handle.

The signals coming out of the two levers in the various configurations and two signals describing the target motion were simultaneously recorded on FM-tapes and on minicomputer disks for off-line analysis.

The performance of the subjects was evaluated in the various tracking situations, with and without vibration applied to the platform, through position and velocity error histograms and through direct comparison of target and tracking signals (pursuitograms).

A detail study of the effects of vibration on the performance of the visual manual system has been published previously (Gauthier et al., 1981). The two following figures are used to illustrate the main results. Fig. 3 shows time recordings of the forearm tracking of one subject before, during, and shortly after vibration of the platform supporting the subject and the manipulandum used as a position control device.

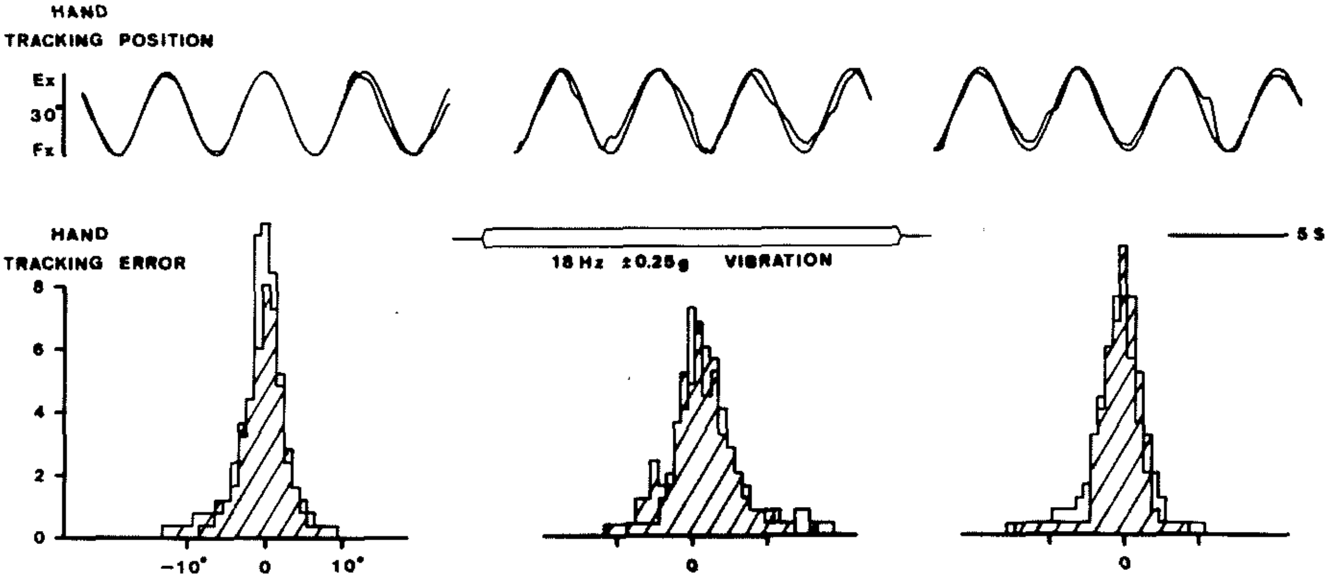

Fig. 3 - Effects of whole-body vibration on visual tracking performance. Vibration resulted in increase of hand tracking error. The alterations outlasted vibration duration. The position error histograms quantify the effects.

Visual examination of the signals reveals tracking alterations due to vibration which affect both position and velocity controls. The histograms of Fig. 3 quantify the performance for that specific subject (10 runs of 10 cycles per subject in each situation). The angular error occurring during flexion (hollow area) was of the same order of magnitude as that during extension (dash area). All histograms are practically centered around zero, which means that the subjects led as well as lagged the target. Vibration did not modify this particular mode of tracking commonly observed with low-frequency sinusoidal targets. On the contrary, vibration significantly increased position error as seen by an enlargement of the histogram main body and a larger maximum error amplitude.

After vibration, tracking with normal control resumed rapidly. The right side histograms, as well as the time recordings of Fig. 3 illustrate this finding. The corresponding histogram closely resembles the previbration. However, this should not mask the fact that the alteration outlasted the stimulus by the duration of a few cycles. In fact, the post-stimulus effect was partly averaged out since the analysis was conducted over a series of 10 cycles. Comparative analysis of the histograms derived from successive blocks of three cycles showed that at least three cycles were needed for the subjects to recover normal tracking performance. Likewise, three-cycle block analysis conducted on the signals recorded under vibration showed that the subjects tended to compensate for the stimulus-induced alterations since the third three-cycle block position histogram was more similar to that of a sinewave than the histogram corresponding to the first three cycles recorded after vibration onset.

It is also to be noted that when, on occasion, runs were extended to 20 cycles (100 s), compensation was more pronounced, but tracking performance evaluated through partial histograms derived from the first three post-stimulus cycles were much more altered. Time recordings showed that the alteration was often due to a 200-400 ms period of slowing or stopping of the movement immediately after stimulus cessation.

Fig. 4 shows, as an example, the pursuitogram of a subject resulting from the tracking of the target moving around a circular path (dotted line). The tracking was achieved with the mini-stick used as a position control device (isometric, low friction condition). Five full successive rotations are represented. On the same graph is also shown the performance of the same subject in

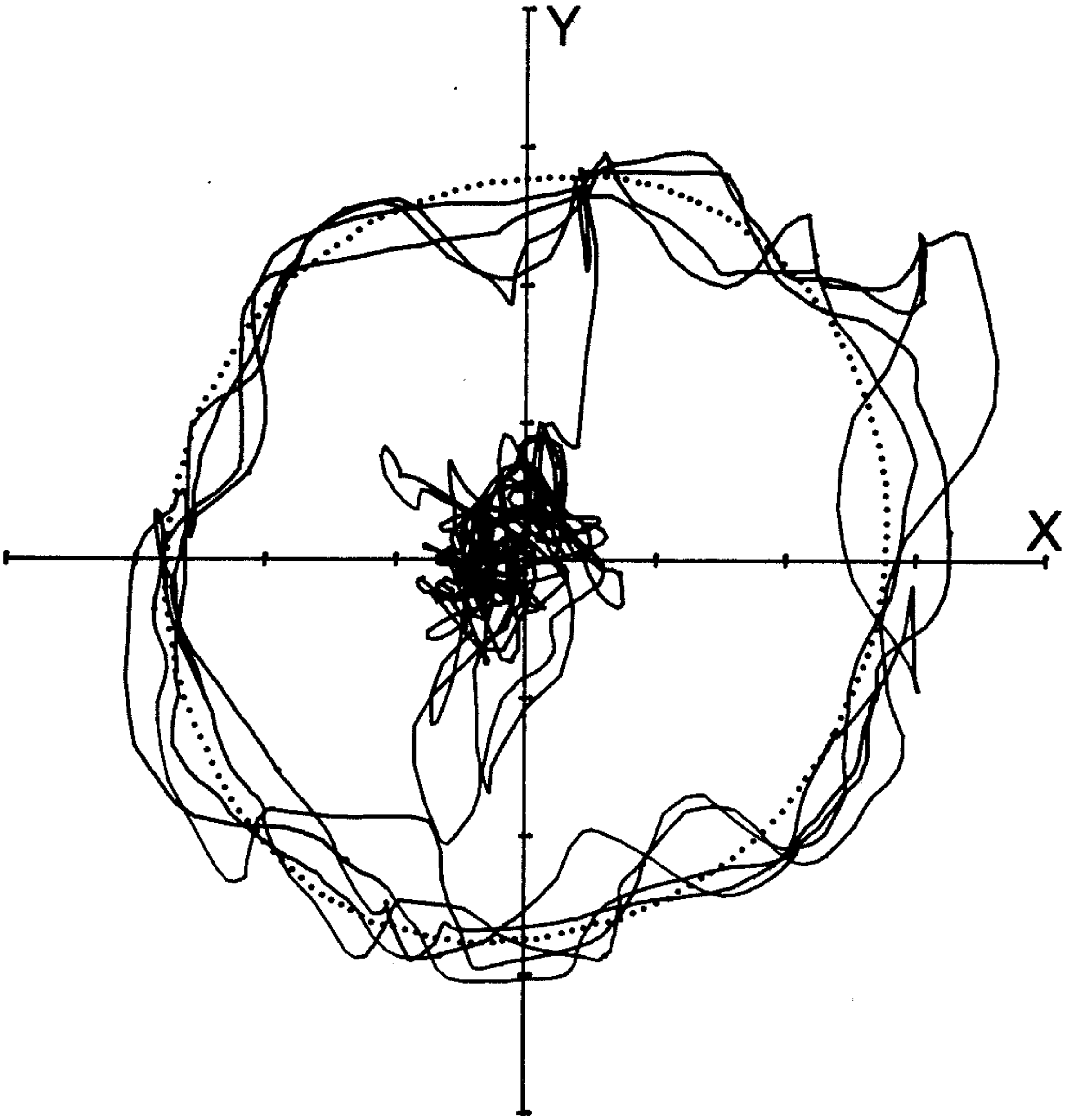

Fig. 4 - Pursuitograms of a subject in response to the tracking of a target moving around a circular path (dotted line) and superposed, at the center of the picture, is the trajectory of the tracking spot resulting from the attempt, by the subject, to keep it on the center of the screen.

the somewhat opposite task i.e. attempting to keep the target (centering) at the center of the screen. In this situation, the target will have also described a circle, had the mini-stick been left immobile.

The analysis of the effects of the vibration on the tracking performance was conducted on the vertical and horizontal components of the target position. Similar alterations of the tracking performance, as those described earlier, were observed when the vibration was applied to the platform supporting the subject.

The above observations demonstrate some aspects of the alterations of the visual manual tracking system resulting from vibration applied to the operating human subject. We showed in earlier studies (Roll et al., 1981 ; Gauthier et al., 1981) that the proprioceptive system, through which vibration-induced afferents enter the neurological network, is the main denominator for the observed alterations. However, we did not rule-out a possible decrease of the overall performance through an alteration of the oculomotor control system resulting from the activation of the vestibular system by the vibration of the head.

Indeed, the vestibulo-ocular reflex (VOR), necessary to stabilize vision when the head moves with respect to the visual world, undergoes modification under low-frequency vibration. The following study confirms this view, though not shared by other workers, who claim that the vestibulo-ocular reflex frequency response does not exceed 8 Hz (Young and Oman, 1969 ; Keller, 1978).

OCULAR STABILITY IN VIBRATING ENVIRONMENT.

To understand the role played by the VOR in the stabilization of vision in situations in which the whole body or the head alone is moved at higher frequency, we designed an experiment to study the VOR response in the 0.5 to 30 Hz frequency range.

When the head is vibrated, or if the vibration is transmitted from the vibrating body, eye movements, compensating for head rotation may be inappropria if the VOR gain is not exactly unity. The eyes will not remain on target and tracking error under visual guidance will be altered.

Because of technical difficulties to move the entire body of the subject, the head was rotated around a vertical axis. The results described below show that the VOR gain decreases continuously from 3 Hz to 12 Hz then increases to reach values up to 2.5 and 3 around 25 to 30 Hz. The perceived stability of the fixating target follows a somewhat opposite curve. The phase curve is not as much affected by the increasing frequency. The apparatus designed to rotate the head and thus activate the VOR is shown on the photograph of Fig. 5

A crash helmet was attached to a rigid frame made to rotate around a vertical axis by a electromagnetic vibrator. To transform the linear movement of the vibrator into rotation, a cam linked the vibrator shaft to the frame. The subject's head was tightly secured through high density foam rubber to the helmet by a dental mold attached to the mobile frame. The axis of rotation passed approximately through the center of the head. A linear motion detector, placed in parallel with the vibrator shaft provided a precise head movement measurement and a feedback signal controlling the vibrator excursion amplitude.

The right eye position was monitored by means of an infra-red photoelectric device derived from Gauthier and Volle (1975) original apparatus. The left eye was patched so that only monocular viewing was permitted. Emitter and receptor diodes were rigidly attached to the center of the helmet and to both sides of the mobile frame, as seen on the photograph.

A green diode (not shown on the photo) was positioned on a screen placed vertically, 38 cm from the subject's eye. It provided a fixed target used by the subject to enhance its VOR. On both sides of this target were 2 miniature red diodes, one degree apart providing calibration marks over a total 5° range. The red diodes were also used to determine the extent of the visual instability experiended by the subject. Eye and head position signals together with the corresponding velocity signals obtained by analog differentiation were recorded on paper and FM magnetic tape recorders.

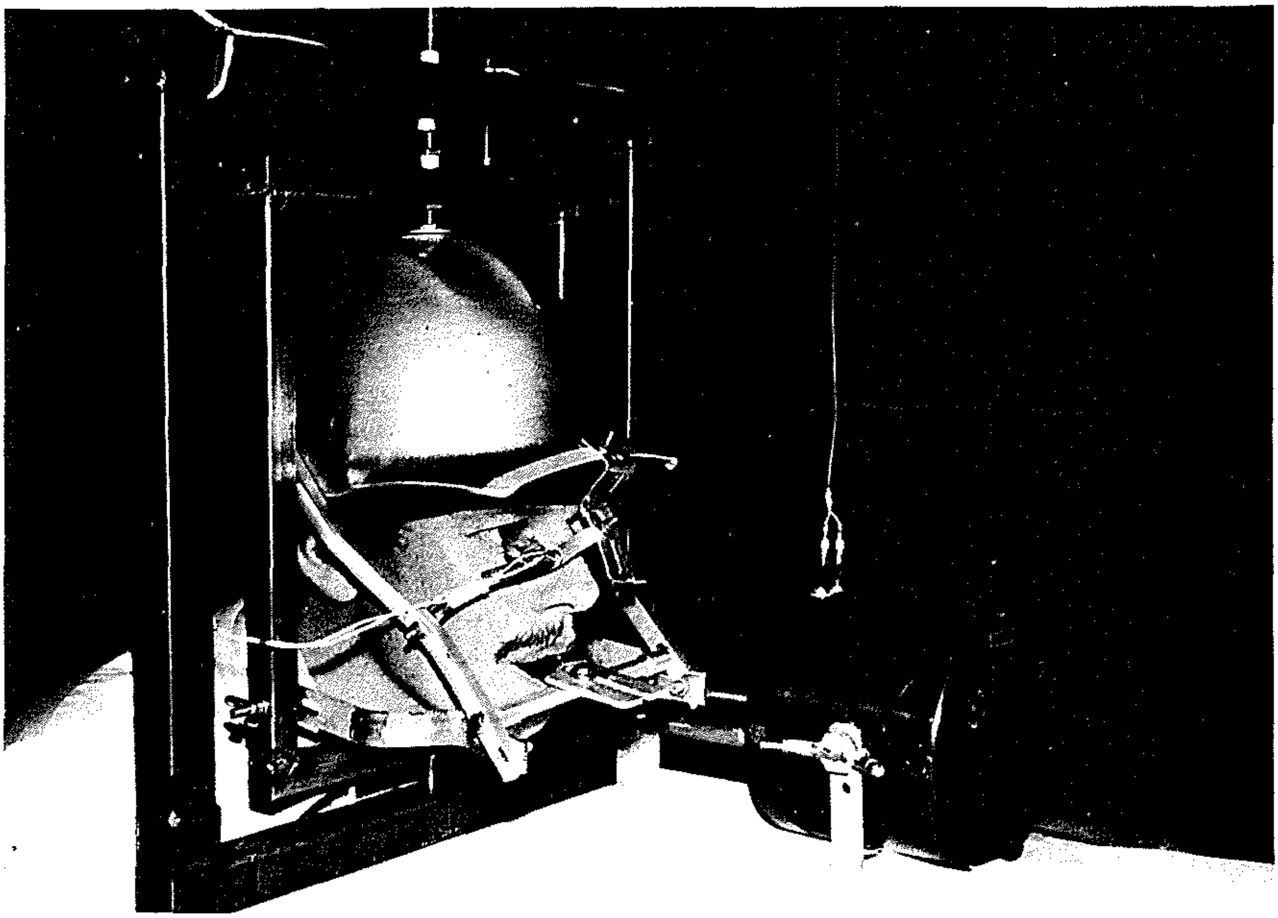

Fig. 5 - Experiment equipment. The S's head was firmly attached to the rotating frame by a hard-cushioned helmet and a bite bar. A linear position detector monitored head position. Eye position was measured by an infra-red photo diode system mounted in front of the right eye. The fixation target was stationary and positioned 38 cm away from the subject's eyes.

The experiments were run with 5 subjects, males and females ranging in age between 20 and 40 years. The VOR gain and phase measurements were conducted both by hand from high velocity and large amplitude paper tape recordings and by compute Gain and phase were calculated for each tested frequency as the average over 25 to 50 cycles for frequencies below 10 Hz and 50 to 100 cycles beyond 10 Hz.

A series of calibrations was run prior to each situation recording by asking the subject to scan several times across the 5 diodes presented on the stationary screen. All rotations had a peak to peak amplitude of 2 degrees.

Rotation of the head over a 2- degree amplitude at frequencies up to 30 Hz and the setup designed to adequately apply such rotations made the situation somewhat uncomfortable for the subject. Thus a limited number of data was gathered from each subject, but compensation was obtained by using a larger number of subjects. The results thus yielded a large inter-individual dispersion also compensated by the large number of subjects since the data are presented as an average over 8 runs from 5 different subjects.

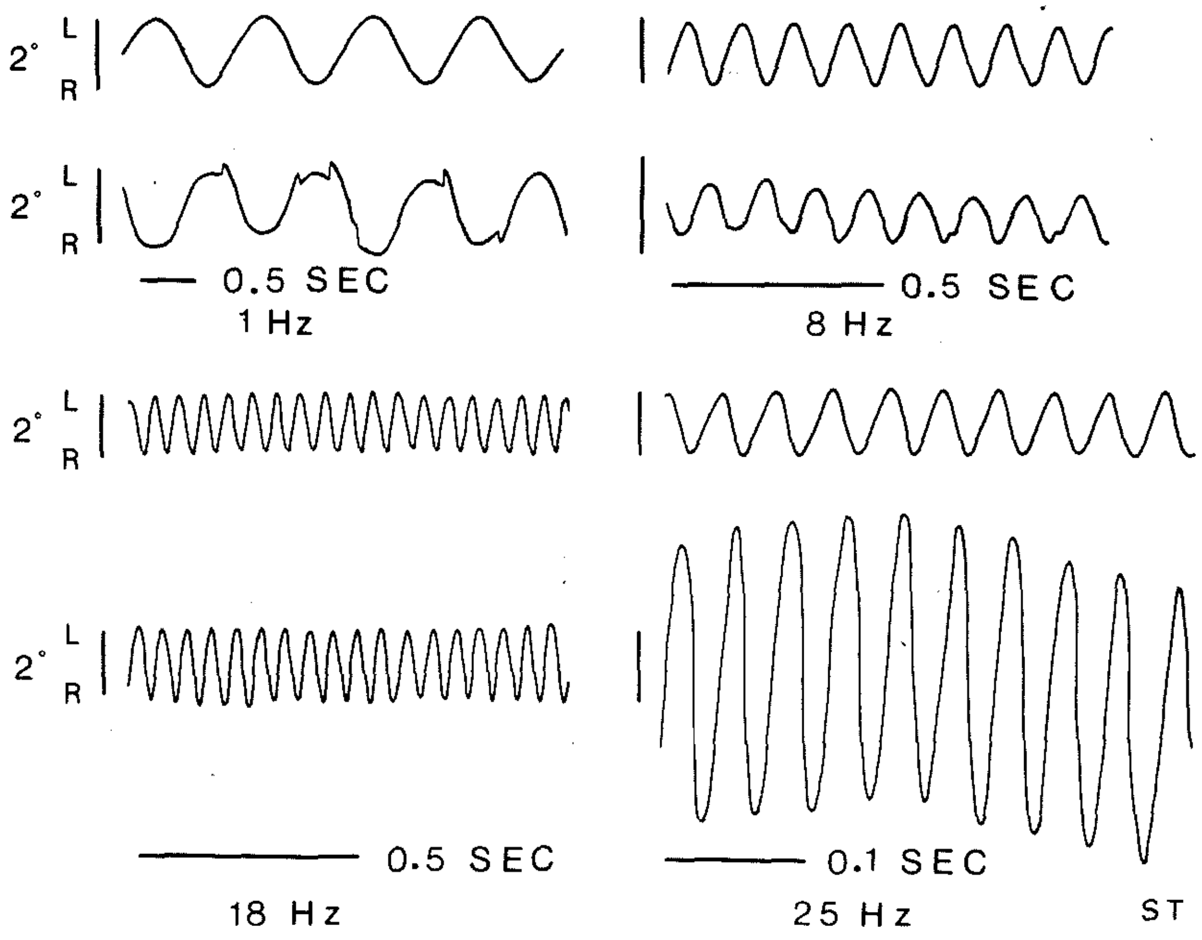

Fig. 6 - VOR with a stationary target. Typical eye movement recordings at various frequencies showing that beyond 1 Hz the eye and head movement amplitudes were no longer equal. The mean eye position remained fairly stable suggesting that the subject still used visual information to tentatively stabilize gaze.

Gain and phase curves were derived from eye and head velocity signals obtained from corresponding angular position signals by differentiation (Fig. 6). With a rotation at 1 Hz applied to the head, the eye was practically right on target except for small amplitude correcting saccades. At higher frequencies, the gain varied with the stimulus frequency.

Though the gain did not remain unity and the phase nil, the subject could still use the visual target to stabilize his gaze around the target. The gain curve shown in Fig. 7 decreases between 3 and 10 Hertz then reincreases to reach values up to 2 and 3 around 20 Hertz. This means that, on the average, the eyes rotated in their orbit over a 4 to 6 degrees angle while the head moved only 12 degrees in space.

This striking observation suggests some comments. Forced rotation of the head around a vertical axis resulted in compensatory eye movements induced by activation of the VOR and the smooth pursuit system and possibly the neck proprioception receptors. Computation of the VOR gain from eye and head velocity signals showed the suspected inadequacy of the VOR gain to maintain stable and clear vision throughout the frequency range between 6 and 30 Hz. The range below 6 Hz has been intensively studied by Keller (1978) and Buettner et al. (1981), in the monkey, and by Young and Oman (1969) and Gauthier and Robinson (1975) in man. These studies and the present one showed that at very low frequency, the VOR could be properly enhanced with a stationary target (G = 1) and suppressed with a mobile target (G = 0).

Of particular interest is the 6 to 30 Hz frequency range. To our present knowledge, this range had not been previously investigated in man. With a stationary target, the gain curves increased continuously from 6 to 30 Hz to values up to 3 around 25 to 30 Hz. These results obviously suggest that for high frequency rotations, the VOR cannot be significantly mediated by visual inpu

Our results, showing a gain much larger than unity for frequencies beyond 15 Hz raised a serious problem. These somewhat surprising VOR dynamical characteristics may be due to high acceleration response of the semi-circular canals or to the intrinsic properties of the 3 neurones arc or, as suggested by Dupuis and Hartung (1980) in an experiment with head translation, to mechanical resonance of the eyeballs.

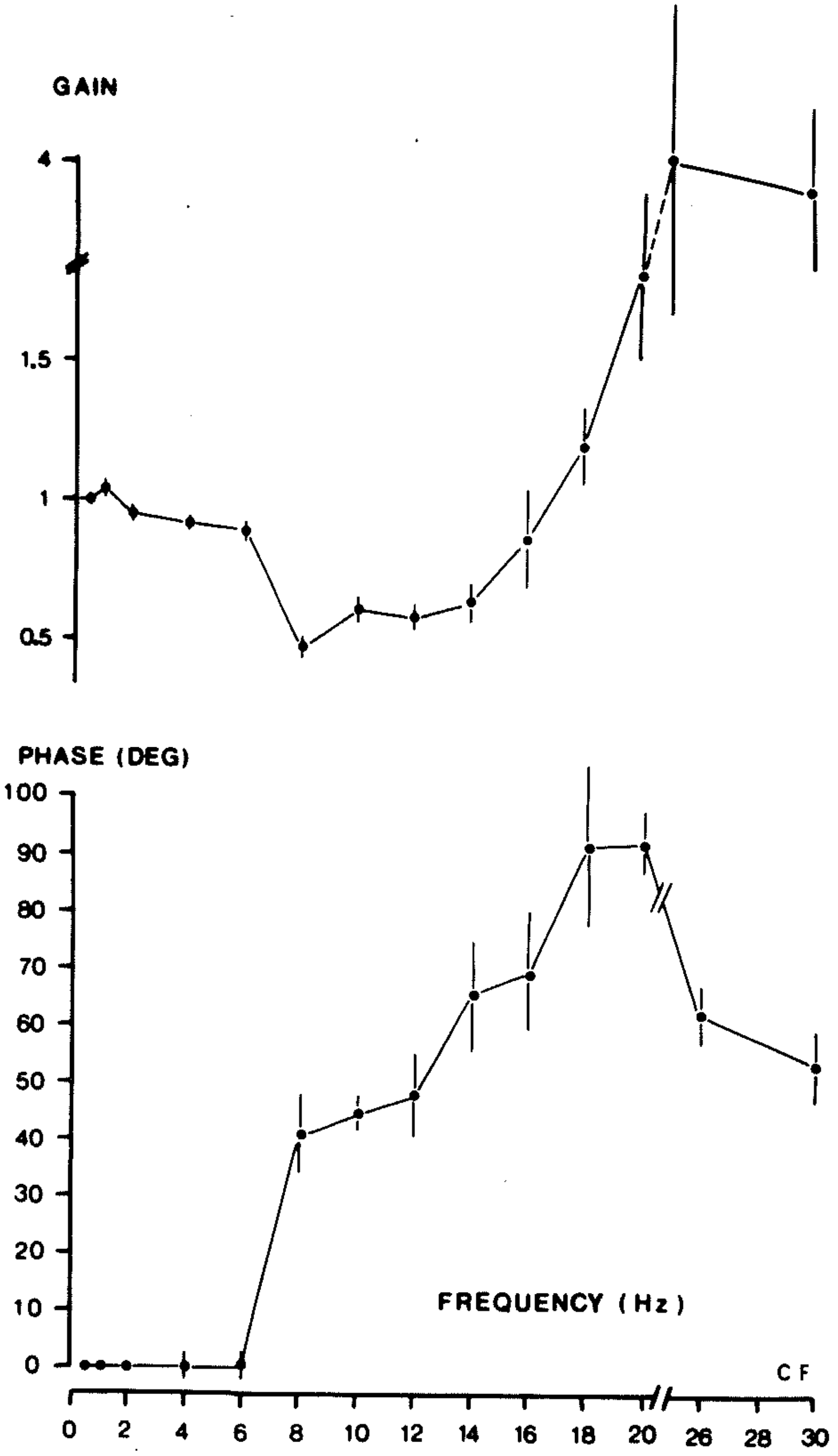

Fig. 7 - VOR gain and phase as a function of head rotation frequency during stationary targetfixation. The gain decreases from 2 to 6 Hz then re increases towards 2-3 around 25 Hz. The phase curve remains flat up to 6 Hz then raise slowly towards 90 °.

The study of the mecanisms responsible for the high gain response of the VOR at high frequency deserves further interest. A definite description of the phenomenon might be provided by correlating the ocular muscle activity to the rotation amplitude or by submitting a labyrinthectomized subject to the stimulation. The results of either experiment should show whether the high amplitude response is due to eyeball mechanical resonance or to highly non-linear vestibular reflex activation.

Whatever the outcome of these suggested experiments, it is obvious that the VOR may be activated by high frequency rotations. We used passive rotations but active situations show similar subjective and objective results. As opposed to what is usually described in the literature, the gain curve increases continuously beyond 8 Hz. The phase variation follows a bell-shape curve culminating at 90° around 20 Hz. The inadequacy of gain and phase at high rotation frequency may be in part responsible for the perceived instability of the visual field and also for the observed decrease of performance in visual manual tracking tasks performed in vibrating environment.

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