

NYSTAGMUS RESPONSES DURING ROTATION ABOUT A TILTED AXIS

Captain Charles W. Stockwell, USAR, Gene T. Turnipseed, and Fred E. Guedry, Jr.

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SUMMARY PAGE

THE PROBLEM

A persistent horizontal nystagmus response is elicited when a man is rotated at constant velocity about an Earth-horizontal axis. This response comprises two components: a directional bias and a cyclic modulation of the bias level. Observations were made of the effects on these response components of three stimulus variables: rate of initial acceleration, rate of steady rotation, and angle of tilt of the rotation axis.

FINDINGS

The magnitudes of both components were directly related to the angle of tilt of the rotation axis.

Cyclic modulation became stronger as rotation rate increased and remained constant throughout the rotation period. Bias decayed during steady rotation, and its decay rate became faster as rotation rate increased.

Neither component was affected during constant speed rotation by the rate of initial angular acceleration.

Differences in the behavior of these two response components suggest the presence of two separate response mechanisms. Previous experiments indicate that both mechanisms depend upon the otolith system, although the possibility of a semicircular canal contribution remains. Thus it is reasonable to conclude that these response components provide a means of assessing the dynamics of otolith regulated responses.

The findings in this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

INTRODUCTION

Experiments conducted independently by Guedry (12) and by Benson and Bodin (5) first showed that, when a man is rotated about an Earth-horizontal axis, his horizontal nystagmus response persists as long as rotation continues. According to these authors, the persistence of nystagmus in this situation is not due to the initial angular acceleration used to achieve rotation speed; it is caused instead by the sensory input provided by continuous reorientation of the body relative to gravity. Their conclusion was supported by subsequent experiments in which the same kind of persistent nystagmus was elicited from subjects who were counterrotated at the end of a centrifuge arm (3, 18). In the latter case, the rotating linear acceleration vector was produced by centripetal acceleration, and angular acceleration was not present.

Analysis of the response reveals two components. The first is a bias in slow phase eye velocity opposite the direction of head velocity, and the second is a modulation of the bias level, which occurs within each cycle of rotation. This report describes the behavior of these two response components as parameters of the stimulus are varied. Observations are made concerning the effects of three stimulus variables: rate of initial angular acceleration (α), rate of constant speed rotation (ω), and angle of tilt of the rotation axis (ϕ). Tilting the rotation axis provides a means of systematically varying the magnitude of the linear acceleration vector component acting in the horizontal head plane (i.e., the plane of stimulation of the horizontal semicircular canals and of utricular shear). As the tilt angle of the rotation axis (ϕ) is changed, the vector component in the horizontal head plane varies as $g \sin \phi$. This stimulus variable is of particular interest in this experiment, because it has not previously been studied with other stimulus variables held constant.

In the discussion of results, various hypotheses that have been advanced to account for this response are considered, and potential clinical applications of procedures developed in this study are evaluated.

PROCEDURE

SUBJECTS

Thirty men with normal vestibular function served as subjects. They were between 20 and 30 years of age and were in good physical condition. An additional 20 subjects withdrew from the experiment because they experienced symptoms of motion sickness during the tests.

APPARATUS

The rotary device used in this experiment has been described previously (12). The device, as used here, consisted of a padded platform upon which the subject was positioned with his longitudinal body axis aligned at the desired angle relative to gravity. The subject was firmly secured to the platform by means of safety straps across

his head, chest, thighs, knees, and feet. He wore an orthopedic neck brace to minimize movements of the head relative to the body. After the subject was secured to the platform, he was exposed to a constant angular acceleration about his longitudinal body axis until he reached the desired velocity, which was thereafter maintained within 5 per cent until deceleration.

Appropriately placed Beckman electrodes were used to record corneoretinal potentials during rotation. The potentials were amplified and filtered by a "nystagmus signal conditioner" (14) and led through sliprings to a Sanborn 964 recording system.

METHOD

The effects of two stimulus variables, rotation rate and angle of tilt of the rotation axis, were studied in three groups of eight subjects each. Three rotation rates were used: $\omega = 66, 102, \text{ and } 138 \text{ deg/sec}$. These were combined with four angles of tilt of the rotation axis: $\phi = 0, 10, 30, \text{ and } 90 \text{ deg}$ from vertical, as illustrated in Figure 1. When the rotation axis was tilted in this manner, the force acting in the shear plane of the utricle varied as $g \sin \phi$ (assuming that the average plane of utricular surface lies in the horizontal plane of the head). Figure 1 shows the utricular shear forces produced by the four angles of tilt used.

Each group received a different series of stimuli as shown in Table I.

Table I
Treatments by Groups

	Stimulus	ϕ (deg)	Direction of Rotation
Group 1 $\omega = 66 \text{ deg/sec}$	1	0	CW
	2	0	CCW
	3	10	CW
	4	10	CCW
	5	30	CW
	6	30	CCW
	7	90	CW
	8	90	CCW
Group 2 $\omega = 102 \text{ deg/sec}$	1	30	CW
	2	30	CCW
Group 3 $\omega = 138 \text{ deg/sec}$	1	30	CW
	2	30	CCW

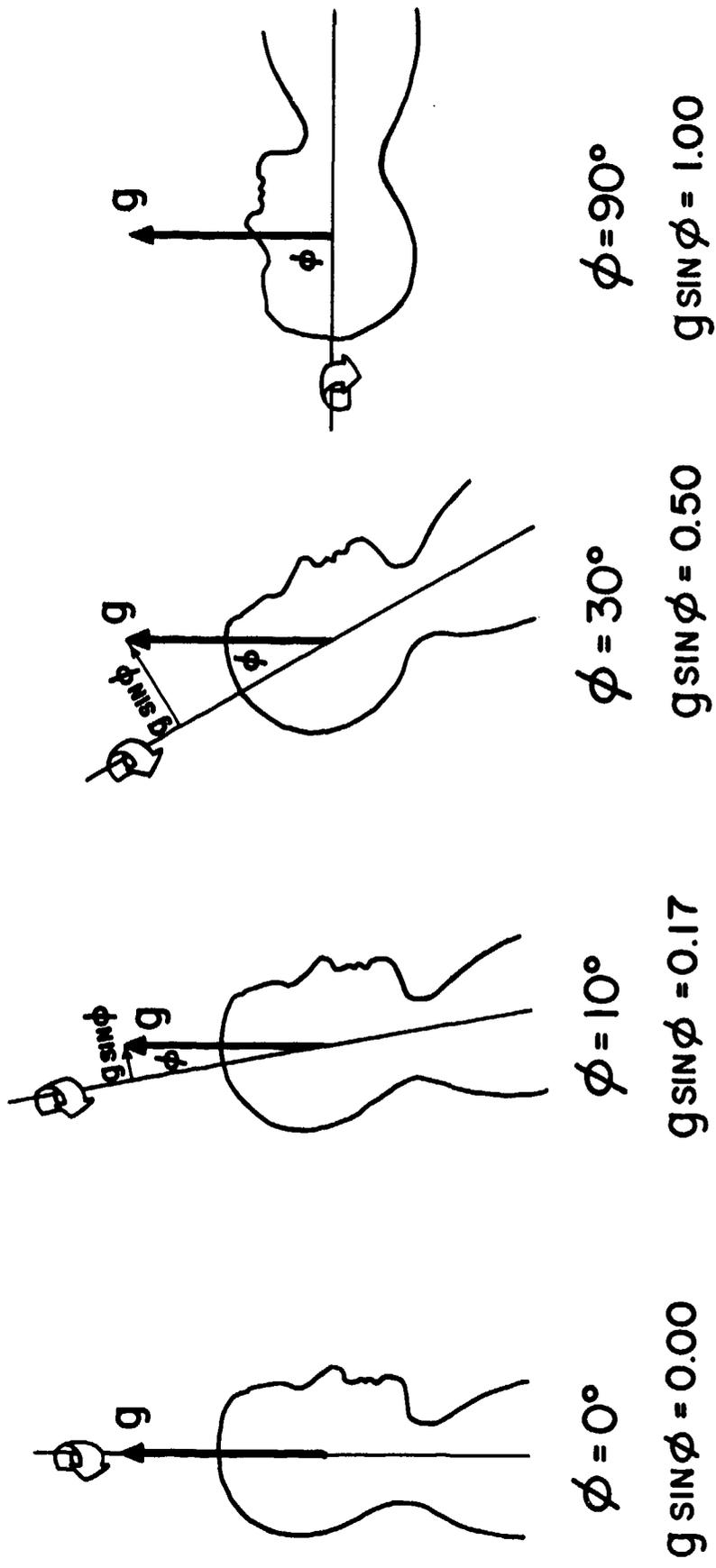


Figure 1

Utricular shear forces ($g \sin \phi$) produced by tilting the rotation axis at four angles relative to gravity. Forces are given in g units.

Each stimulus comprised angular acceleration at approximately 25 deg/sec^2 to the specified rotation rate, maintenance of this rotation rate for 90 seconds, and deceleration to a stop. At least 5 minutes were allowed between stimuli. An order effect was anticipated; so, for each group of subjects, the order of administration of stimuli was randomized under the restriction of balance required by the Latin square design (21).

A fourth group of six subjects was tested to determine the effects of initial angular acceleration rate. Subjects in this group were accelerated in the clockwise direction at 0.7 and at 25 deg/sec^2 to a constant velocity of 102 deg/sec . The total period of rotation was 210 seconds in either case. The order of administration of stimuli was randomized across subjects in this group as well.

Horizontal eye movements were recorded for all subjects during, and for 1 minute after, each stimulus. The subjects were kept alert by continuous presentation of mental arithmetic problems while eye movements were being recorded.

RESULTS

Nystagmus slow phase velocity always reached a peak at the end of the initial angular acceleration and declined during the period of constant speed rotation. When the rotation axis was Earth-vertical, nystagmus disappeared within 60 seconds. In contrast, nystagmus during rotation about a tilted axis persisted throughout the rotation period. Figure 2 reveals the two components of this persistent response, directional bias and cyclic modulation. Directional bias can be seen as the average amplitude of slow phase eye velocity, and cyclic modulation appears as the cyclic change in eye velocity about the bias level.

Large differences were found among subjects in both response measures. Therefore, sampling error was large, and the mean values that were obtained must be regarded as only approximate estimates of population values, since sample sizes were relatively small.

EFFECTS OF TILT ANGLE (ϕ)

Nystagmus responses of subjects in Group 1, who were rotated at 66 deg/sec and at tilt angles of 0, 10, 30, and 90 deg, are shown in Figures 2 and 3. Nystagmus produced by tilted-axis rotation comprised both the response to the initial angular acceleration and the response to the rotating linear acceleration vector. However, the Earth-vertical axis response for the same subjects showed the effects of the initial angular acceleration alone; so, for comparison, this response is plotted in each graph in Figure 2. It is reasonable to attribute the difference between the Earth-vertical axis response and the tilted-axis responses to the effects of the rotating linear acceleration vector. Assuming that the responses to angular and to linear accelerations are additive, it appears that the linear acceleration vector rotating at 66 deg/sec produced a response bias that increased during the first 30 seconds of rotation and thereafter remained fairly constant. Moreover, the magnitude of the bias component was directly related to the angle of tilt of the rotation axis.

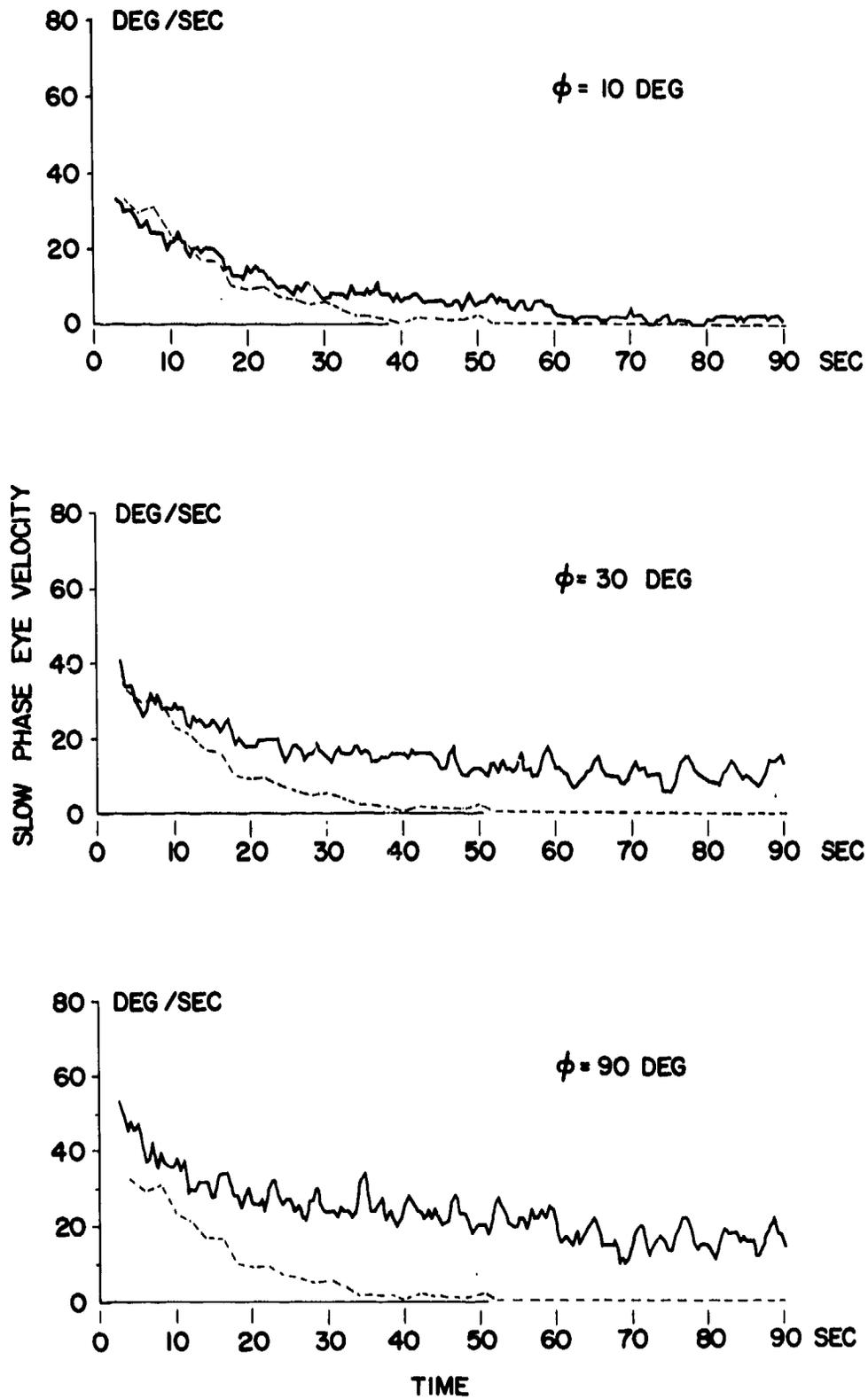


Figure 2

Mean nystagmus responses of subjects in Group 1 during tilted-axis rotation (solid lines). For comparison, the Earth-vertical axis response is shown in each graph for the same subjects (dashed lines). Rotation rate was 66 deg/sec. Responses for clockwise and counterclockwise rotation are combined. Values above the zero baseline indicate nystagmus slow phase velocity opposite the direction of rotation. 5

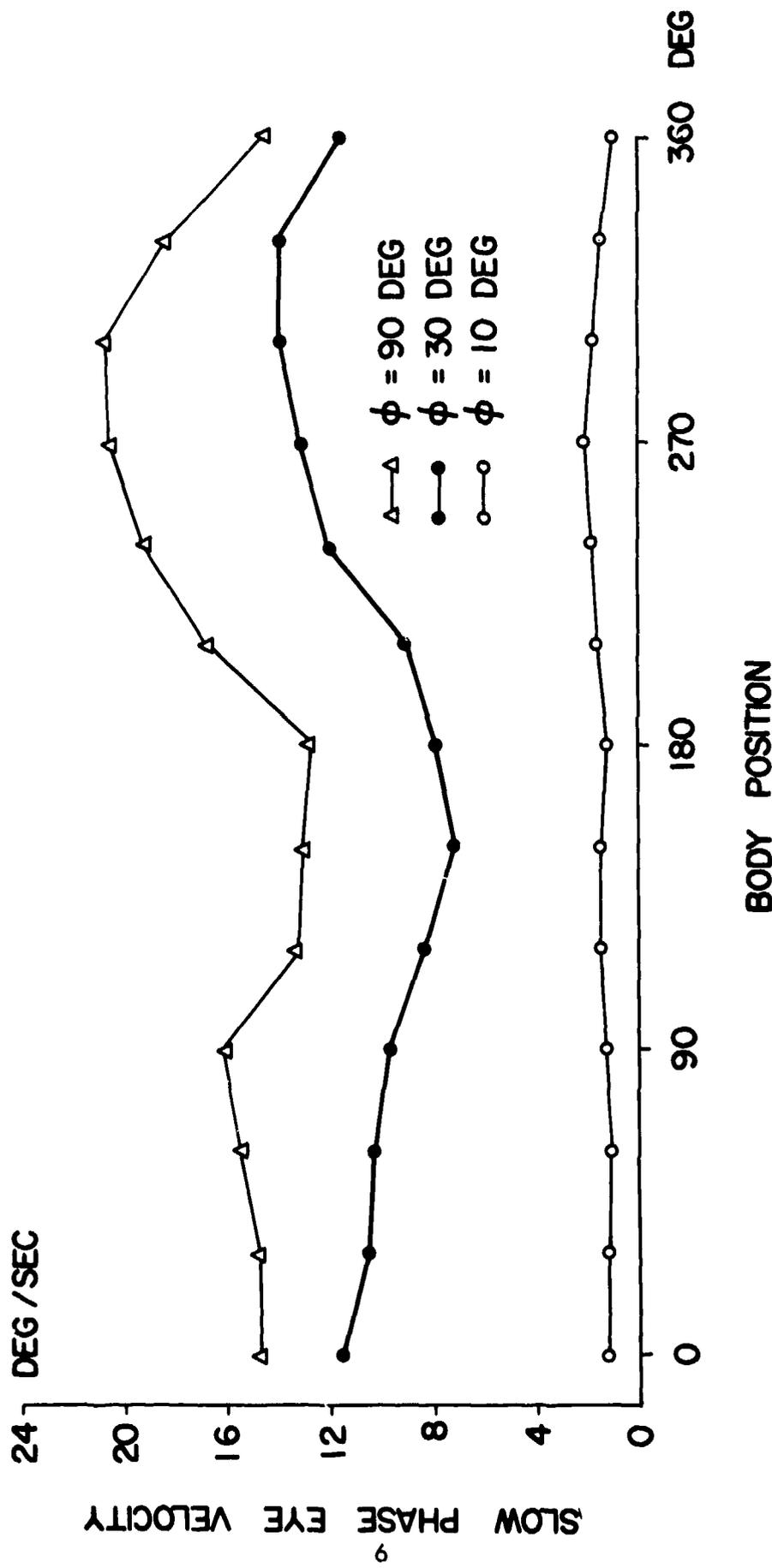


Figure 3

Mean cyclic modulation for subjects in Group 1 during the final 30 seconds of steady rotation about tilted axes. Rotation rate was 66 deg/sec. Responses from clockwise and counterclockwise rotation are combined. Body position is given in degrees of rotation (either clockwise or counterclockwise) from nose-up.

The magnitude of directional bias can also be expressed as a function of the utricular shear force (see Figure 1). Bias magnitude was approximately 17 deg/sec/g in shear, a value that agrees reasonably well with those obtained by Benson and Bodin (5) and by Correia and Guedry (7) of 15.4 and 14.1 deg/sec, respectively, for Earth-horizontal axis rotation at 60 deg/sec.

The other response characteristic, cyclic modulation, was keyed to the position of the subject's body relative to gravity. Nystagmus slow phase velocity was minimum just before he reached the nose-down position and maximum just before he reached nose-up. The mean amplitude of cyclic modulation is shown in Figure 3 for the cycles occurring during the last 30 seconds of constant speed rotation. Modulation amplitude was influenced by the angle of tilt of the rotation axis. It was barely discernible when the rotation axis was tilted at 10 deg, but increased to 6 deg/sec (peak to peak) when tilt was increased to 30 deg, and to 9 deg/sec (peak to peak) when tilt was 90 deg.

EFFECTS OF ROTATION RATE (ω)

The nystagmus response for each of the three rotation rates is shown in Figures 4 and 5. In each case, the axis of rotation was tilted at 30 deg from vertical, producing an utricular shear component of 0.50 g. Responses during Earth-vertical axis rotation are also shown in Figure 4. Earth-vertical axis responses were not available for subjects in Groups 2 and 3 rotated at $\omega = 102$ deg/sec or $\omega = 138$ deg/sec, respectively; so, the estimates shown in Figure 4 for those subjects were based on predictions arising from the torsion pendulum theory, assuming $\Pi/\Delta = 16$ seconds and $K_n(\theta/\Delta) = 10$ seconds (13).

The higher rotation rates were achieved by increasing the duration of the 25 deg/sec² angular acceleration. These longer angular accelerations produced increases in peak nystagmus slow phase velocity as expected from the classical concepts of cupular mechanics (9). According to these same concepts, the time constant of nystagmus decay is the same irrespective of rotation speed, but this was not the case when the rotation axis was tilted. The time constant of nystagmus decay, measured from the onset of constant velocity rotation, was 77 seconds when $\omega = 66$ deg/sec, but was only 45 seconds when $\omega = 102$ deg/sec and 37 seconds when $\omega = 138$ deg/sec. In a previous study (7) where $\omega = 180$ deg/sec, the time constant of nystagmus decay was 18 seconds.

At the rotation rate of 66 deg/sec, it appears that nystagmus bias reached a constant level, but at higher speeds it probably would have eventually disappeared if rotation had continued for longer than 90 seconds. This was demonstrated in the responses of subjects in Group 4 when they were rotated at 102 deg/sec for 210 seconds (Figure 6, upper panel). Directional bias for that group disappeared after 135 seconds of constant speed rotation.

Cyclic modulation increased in amplitude and approached a more nearly sinusoidal form as ω increased. Cyclic modulation during the last 30 seconds of constant speed rotation is shown in Figure 5 for each of the three rotation rates. Maximum slow

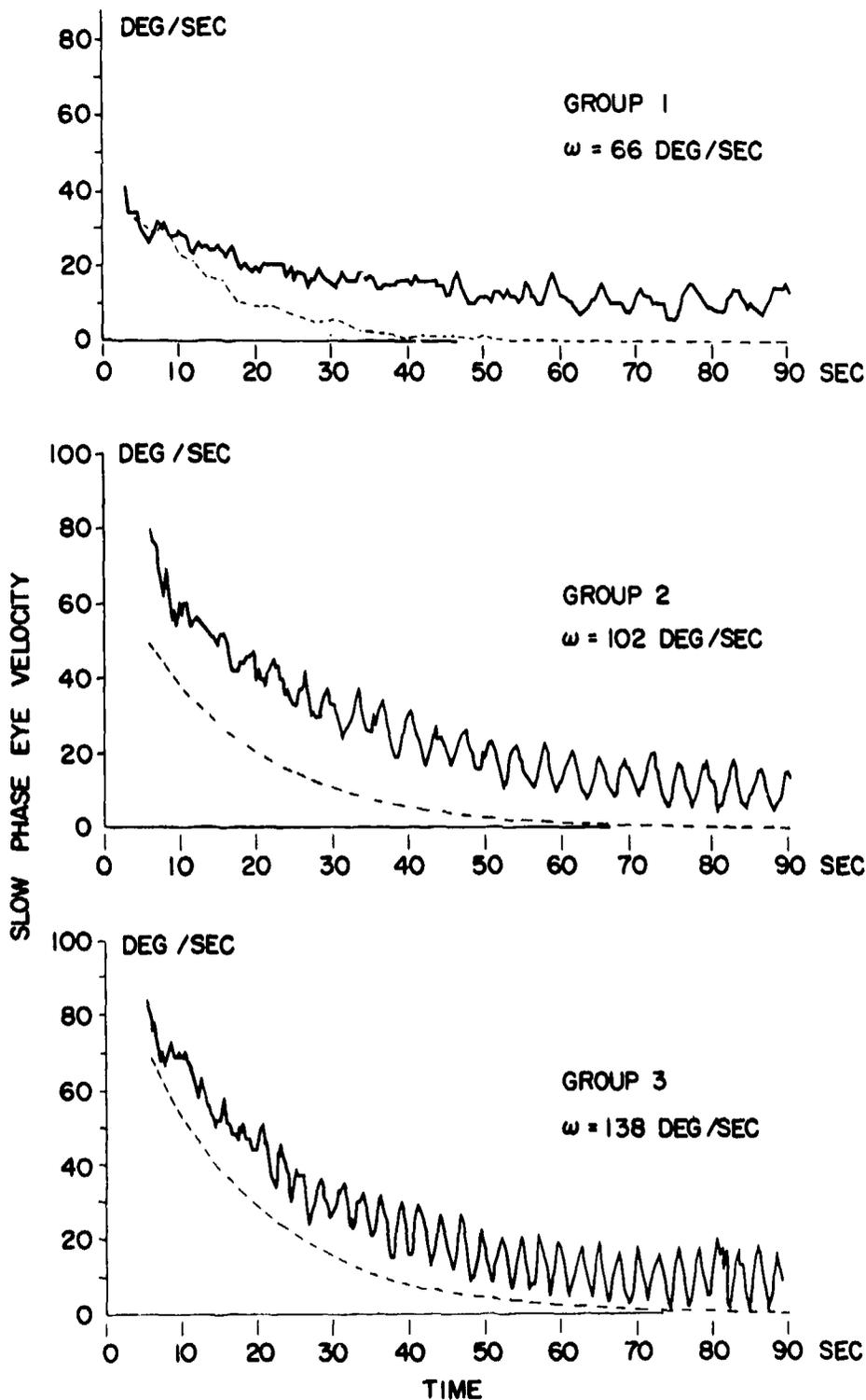
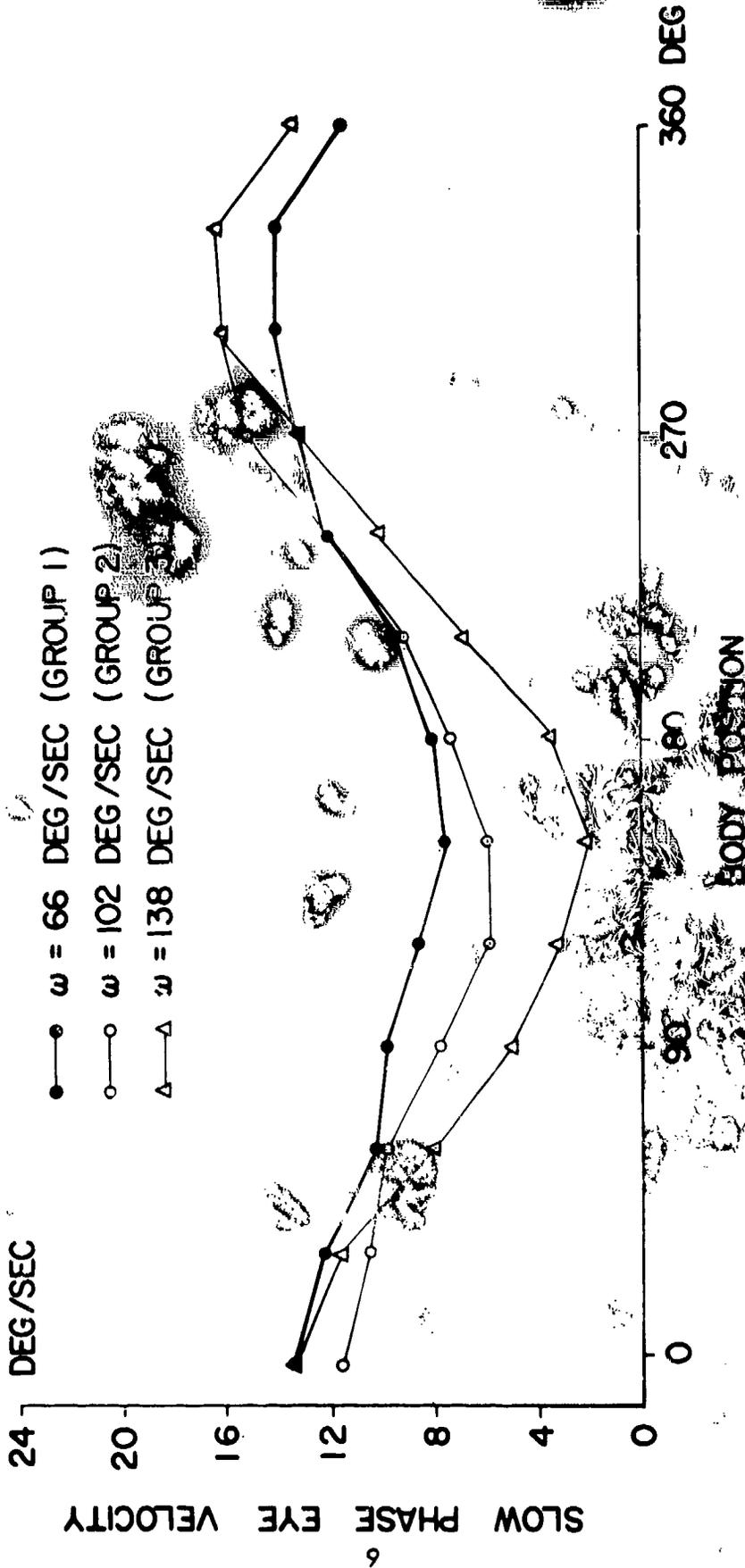


Figure 4

Mean nystagmus responses during tilted-axis rotation at three rotation rates (solid lines). Angle of tilt of rotation axis was 30 deg. For comparison, actual Earth-vertical axis response is shown for subjects in Group 1, and estimated vertical-axis responses are shown for subjects in Groups 2 and 3 (dashed lines). Responses for clockwise and counterclockwise rotation are combined. Values above zero baseline indicate nystagmus slow phase velocity opposite the direction of rotation.



Mean cyclic modulation during final 30 seconds of steady rotation at three rotation rates. Angle of tilt of rotation axis was 30 deg. Responses from clockwise and counterclockwise rotation are combined. Body position is given in degrees of rotation (either clockwise or counterclockwise) from nose-up.

phase velocity occurred approximately 45 deg before the nose-up position was reached and minimum occurred approximately 45 deg before nose-down. No phase shift was apparent with changes in rotation rate. Peak-to-peak amplitude was 6 deg/sec when $\omega = 66$ deg/sec, 10 deg/sec when $\omega = 102$ deg/sec, and 14 deg/sec when $\omega = 138$ deg/sec. There was no evidence that cyclic modulation amplitude decreased during the period of constant speed rotation.

The relation between cyclic modulation amplitude and rotation rate can be seen in a different way in Figure 6 (lower panel), which shows the responses of subjects in Group 4 when they were accelerated at 0.7 deg/sec² to a final angular velocity of 102 deg/sec. For those subjects, the amplitude of cyclic modulation increased in a regular manner with increases in rotation velocity.

EFFECTS OF INITIAL ANGULAR ACCELERATION RATE (α)

Figure 6 shows the responses of subjects in Group 4 who were accelerated at both 0.7 deg/sec² and 25 deg/sec² to an angular velocity of 102 deg/sec. Peak-to-peak modulation amplitude was similar (after constant speed rotation was reached) for both acceleration rates. It was 18 deg/sec when $\alpha = 0.7$ deg/sec² and 19 deg/sec when $\alpha = 25$ deg/sec². These values are much larger than the peak-to-peak modulation amplitude of 10 deg/sec found for subjects in Group 2 who were also rotated at 102 deg/sec under the same conditions (see Figure 4, middle panel). However, this difference was not statistically significant at $p < 0.10$.

The magnitude of directional bias was influenced by initial angular acceleration rate, but the time constant of bias decay was not. During acceleration at $\alpha = 0.7$ deg/sec², the bias increased slowly for about 90 seconds until it reached a level of 17 deg/sec and thereafter remained stable. When angular acceleration ceased, bias decayed to zero with a time constant of 22 seconds. When $\alpha = 25$ deg/sec², the response also decayed to zero with a time constant of 22 seconds. Note that this time constant of bias decay is much shorter than the time constant for the other group of subjects who were tested under identical conditions (Figure 4, middle panel), indicating again the large range of individual differences for this response.

MOTION SICKNESS

Despite efforts to minimize the incidence of motion sickness, these symptoms were so severe in 40 per cent of the original group of 50 subjects that they requested to withdraw from the experiment. A continuous distribution seemed to exist from subjects who experienced no symptoms at all to those who reported acute distress after the first few cycles of tilted-axis rotation. This range in sensitivity to motion sickness is remarkable in view of the fact that these subjects were drawn from a population of Navy pilot candidates, but it is comparable to findings in another series of experiments (1,2).

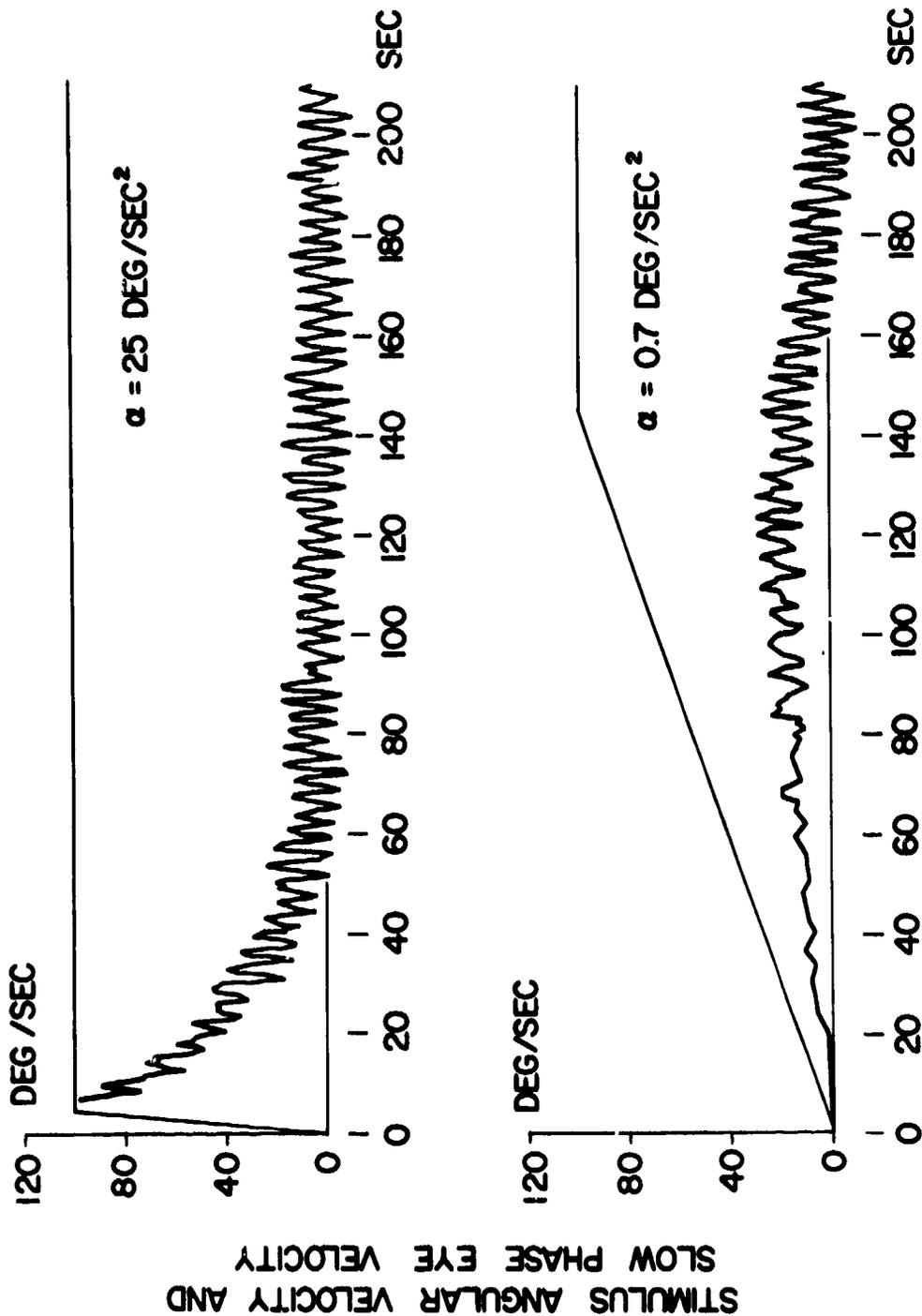


Figure 6

Mean nystagmus responses for subjects in Group 4 utilizing two rates of initial angular acceleration. Direction of rotation was clockwise, angle of tilt of rotation axis was 30 deg, and final rotation rate was 102 deg/sec. Values above zero baseline indicate nystagmus slow phase to the left (counterclockwise).

No obvious relationship was noted between sensitivity to motion sickness and either of the response components measured. However, such relationships were not explored systematically because nystagmus recordings from subjects who became motion sick were necessarily incomplete.

DISCUSSION

The amplitudes of both the bias and cyclic components were found to be directly related to the angle of tilt of the rotation axis and, by inference, to the magnitude of the vector component acting in the horizontal head plane. In other respects, these two response components differed in their relations with stimulus variables. Cyclic modulation became stronger as rotation rate increased and always remained essentially constant throughout the period of rotation. The relationship between the bias component and rate of rotation was more complex. Benson and Bodin (5) showed that bias became stronger as rotation rate increased, up to 60 deg/sec, and that it remained constant during steady rotation. In the present study, it was found that bias no longer remained constant when rotation rates above 66 deg/sec were used. Instead, it decayed during steady rotation, and its rate of decay became faster as rotation rate increased. Correia and Guedry (7) found that, when subjects were rotated at 180 deg/sec, the rate of bias decay was so rapid that it approached the decay rate of the semicircular canal response to the initial angular acceleration.

These differences in the behavior of the two response components suggest that two response mechanisms are involved. Apparently both depend upon the vestibular system, because Guedry (12) failed to elicit any nystagmus during Earth-horizontal axis rotation from men with bilateral loss of labyrinthine function. The nature of the vestibular subsystems responsible for these two components is as yet incompletely known, although cyclic modulation appears more readily attributable to stimulation of the otolith organs. The cyclic modulation is clearly keyed to body position, and position indication is a widely accepted otolithic function. As pointed out by Niven et al. (18) and by Benson and Barnes (4), cyclic modulation appears to reflect a compensatory response to the transverse (left-right) component of the otolithic shear force. Such an interpretation is supported by the fact that the cyclic change in transverse shear force is the same during tilted-axis rotation as it is when the subject experiences linear oscillation along his transverse body axis. Niven et al. (18) exposed men to a transverse linear oscillation and obtained a direction-reversing nystagmus analogous to the cyclic component of nystagmus observed during tilted-axis rotation.

The bias component cannot be so easily interpreted. According to an hypothesis originally postulated by Benson and Bodin (5) and elaborated by Steer (20), bias is the result of semicircular canal stimulation by an unusual mode. Canal stimulation supposedly occurs because the rotating linear acceleration vector causes a traveling constriction in the flexible semicircular canal wall. As the linear vector rotates about the head, this constriction moves in phase around the coplanar semicircular canal duct, forcing fluid ahead of it in the direction of rotation, like a roller pump. When the pumping force is balanced by the cupula restoring force, a constant cupula displacement results and causes a unidirectional nystagmus.

An alternative view (12) ascribes the bias to a dynamic otolithic mechanism capable of extracting information regarding both the rate and direction of the rotating linear acceleration vector. The utricle lies approximately in the plane of rotation; so, during rotation about a tilted or horizontal axis the utricular statoconial mass would undergo a circular orbital motion relative to the underlying hair cells. Owing to the pattern of hair cell orientation in the utricular macula (19), this movement would yield sequential patterns of firing, signifying rotation about the z-axis to central analyzers. That otolithic "movement receptors," described by Lowenstein and Roberts (16), might have some special role in providing rate information which would enhance perceptual discriminations beyond those permitted by central differentiation of sequential position information alone is an intriguing possibility.

This explanation for the bias component is consistent with several mechanisms that might account for cyclic modulation: 1) with higher rotation rates the circular orbit may change to an elliptical transverse orbit so that eventually only the cyclic component remains, or 2) the utricular input may be positively reinforced at one point in the cycle and negatively reinforced in another by saccular inputs. Since saccular planes are roughly normal to the utricular planes, the saccular statoconial masses would oscillate in approximately a linear path during rotation about a tilted z-axis rather than in a circular orbital movement. With both the utricular and saccular masses in cyclic motion, it is reasonable that the utricular-controlled bias component might receive one saccular facilitation and one saccular suppression during each cycle. This would mean that the cyclic component is attributable to the saccule while the bias component depends upon utricular information. If so, the procedure provides a means of assessing both utricular and saccular function.

Another hypothesis to account for the bias component was recently introduced by Benson and Barnes (4). This hypothesis is based on the notion that deflection of the statoconia lags the rotating linear acceleration vector, causing the statoconia to twist with respect to the macula. Twisting of the statoconial membrane in turn excites receptors that are sensitive in the direction tangential to the macula, generating a constant signal proportional to the angle of twist. These authors have derived predictions from their model that are in fair ordinal agreement with experimental observations.

None of these hypotheses has, as yet, received direct experimental verification; so, the issue is unresolved. However, a relevant observation was provided by Benson et al. (6) when they recorded action potentials from neurons in the medial vestibular nucleus of the cat. These units had been rigorously diagnosed as "canal-dependent," yet they also responded to a rotating linear acceleration vector. Benson et al. interpreted this result as evidence of semicircular canal sensitivity to linear acceleration, but they did not exclude the alternative possibility that these "canal-dependent" units also receive impulses from the otolith organs. Two other recent studies tend to support the latter interpretation. Correia and Money (8) reported that a clear unidirectional nystagmus during rotation about an Earth-horizontal axis was still present in cats after all six semicircular canal ducts had been blocked, although nystagmus frequency and slow phase eye velocity were reduced. Jancke et al. (15) found that utricular nerve

section abolished sustained nystagmus in rabbits during rotation about an Earth-horizontal axis. Taken together, these two experiments strongly suggest that the sustained nystagmus response is provoked by the otolith system and that, if the semicircular canals are involved, they play only a secondary role.

If both response components depend upon otolith mechanisms, they may provide a potentially useful supplement to present tests of otolithic function, such as those based on ocular counterrolling (17) and the oculogravic illusion (10). Since these components are elicited by dynamic stimulation, they may be used to assess response characteristics of the otolith system which are not elicited by static test conditions alone. Cyclic modulation is perhaps a more appropriate clinical measure for this purpose than directional bias, because at present it can be more readily assigned to a specific otolith mechanism. However, measurement of both components is feasible. For example, two 50-second periods of rotation about an Earth-vertical axis (one clockwise and one counterclockwise) and two 50-second periods of rotation about a tilted axis (clockwise and counterclockwise) should constitute an adequate test regimen. By using a rotation rate of 102 deg/sec and an axis tilt of 30 deg, both cyclic modulation and bias can be assessed. An index of directional bias can be obtained by comparing mean slow phase velocity per cycle of the response during tilted-axis rotation with the response during Earth-vertical axis rotation. An adequately stable measure of cyclic modulation can be gained from the mean peak-to-peak modulation over, say, the last eight cycles of rotation. An indication of any directional imbalance can be obtained by comparing responses during clockwise rotation with those during counterclockwise rotation.

Large individual differences in bias, bias decay, and cyclic modulation were found in this study among apparently normal subjects. Directional preponderance was also present in some subjects. These differences complicate establishment of representative stimulus-response curves especially when data points from several small groups of subjects are used. They also indicate the need for obtaining normative data from fairly large subject samples in order to prepare this procedure for any kind of clinical application. However, for potential application of the procedure to such problems as predicting flight adaptability, a large range of variation among flight candidates is desirable, and from this point of view the variations found are favorable. Moreover, there is evidence that the procedure may have clinical value despite the range of normal variation. Graybiel et al. (11) evaluated a patient with symptoms of idiopathic progressive vestibular degeneration. When the patient was tested, his loss of semicircular canal function was virtually complete, although several tests involving static otolithic stimulation indicated otolith function within a normal range. However, during rotation about an Earth-horizontal axis, the patient displayed no directional bias and a cyclic component which was clearly outside the range of normal variation.

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