

274-18763

# Perception of the Upright and Susceptibility to Motion Sickness as Functions of Angle of Tilt and Angular Velocity in Off-Vertical Rotation\*

EARL F. MILLER II and ASHTON GRAYBIEL  
*Naval Aerospace Medical Research Laboratory*

## SUMMARY

Motion sickness susceptibility of four normal subjects was measured in terms of duration of exposure necessary to evoke moderate malaise (MIIA) as a function of velocity (2.5 to 45 rpm) in a chair rotated about a central axis tilted  $10^\circ$  with respect to gravitational upright. The subjects had little or no susceptibility to this type of rotation at 2.5 and 5.0 rpm, but with further increases in rate, the MIIA endpoint was always reached and with ever shorter test durations. Minimal provocative periods for all subjects were found at 15 or 20 rpm. Higher rotational rates dramatically reversed the vestibular stressor effect, and the subjects as a group tended to reach a plateau of relatively low susceptibility at 40 and 45 rpm. At these higher velocities, furthermore, the subjects essentially lost their sensation of being tilted off vertical. In the second half of the study, the effect of tilt angle was varied while the rotation rate was maintained at a constant 17.5 rpm. Two subjects were completely resistant to symptoms of motion sickness when rotated at  $2.5^\circ$  off vertical; with greater off-vertical angles, the susceptibility of all subjects increased sharply at first, then tapered off in a manner reflecting a Fechnerian function. The marked changes in these measured responses were attributed primarily to the macular organs being unnaturally stimulated by off-vertical rotation.

## INTRODUCTION

Constant-speed rotation of a subject about his longitudinal axis which has been slightly tilted with respect to gravity produces an unusual and ever-changing pattern of stimulation (refs. 1 and 2). The effect is equivalent to holding the subject stationary in an upright position, with the ability to rotate an acceleration vector around him at an off-vertical angle of incidence equal to the chair's tilt. This mode of stimulation has proven to be highly effective in evoking symptoms that characterize motion sickness. Theoretically, it provides adequate stimulation to the otolith and other gravireceptor organs, but probably not to the semicircular canals. This technique may therefore offer a simple, precise, and highly controllable method of grading motion

sickness susceptibility to otolithic stimulation and one that complements those susceptibility tests in which the semicircular canals are the primary or the only otic structures involved (refs. 3 and 4).

Evidence from testing a few highly resistant subjects indicated that a greater provocative effect was derived from increasing the off-vertical angle from  $10^\circ$  to  $20^\circ$  at various rotational rates, but the relative change in effectiveness was not explored (refs. 1 and 2). With the initial method of grading susceptibility a schedule of ever-increasing rotational rates was employed, which often unnecessarily prolonged the test duration and frequently caused a very rapid rise in symptomatology when the adequately stressful rate was finally reached (refs. 1 and 2). As a result, great care had to be exercised to prevent the overshoot of a preselected endpoint, a motion-sickness diagnostic criterion of mild severity (MIIA) (ref. 5). In addition, the original test method exposed the subject to periods of incremental increases in the vestibular stressor level. Low

\*This study was supported by contract T-81633, Biomedical Research Office, Manned Spacecraft Center, and by order L-43518, Office of Advanced Research and Technology, NASA.

levels of stressor stimulation were usually compensated initially, and in the process might have served as training toward increasing adaptation, an undesirable factor when determining baseline and relative measurement of susceptibility among subjects.

The purposes of this study were: first, to explore the change in provocative effect of varying the rate of rotation from 2.5 to 45 rpm about a slight ( $10^\circ$ ) off-vertical axis; and second, by using a velocity within the range of maximum effectiveness, to measure the relationship between motion sickness susceptibility and varying degrees of off-vertical tilt up to  $25^\circ$ .

## PROCEDURE

### Subjects

Four young Navy enlisted men, ranging in age from 19 to 21 years, who had demonstrated motion sickness susceptibility to off-vertical rotation, volunteered as subjects. Each was found to be healthy by a comprehensive Navy medical examination, given before his acceptance as a research subject, and remained so during the experimental procedure, as reported daily in his preexamination questionnaire (ref. 3). Functional tests of the semicircular canals (ref. 6) and otolith organs (refs. 7 and 8) plus those of postural equilibrium (ref. 9) proved further that these specific systems were functioning well within normal limits.

### Methods

A standard Stille rotating chair (model RS-3), mounted on a motor-driven tilt base served as an off-vertical rotation (OVR) chair (fig. 1). The degree of tilt relative to the gravitational upright was registered on a large protractor scale. The subject's head was centered on the axis of rotation and held rigidly against the headrest by adjustable straps across his forehead. Seat belts further secured him to the chair. His eyes were covered with a small padded goggle which prevented vision but did not interfere with the observation by the test conductor of flushing, pallor, and sweating, which are most clearly manifested on the face. The combined weight of the subject and the chair superstructure was statically balanced in a  $20^\circ$  off-vertical position to ensure constant-speed rotation ( $\pm 0.1$  percent) during the OVR test. The chair was then returned to

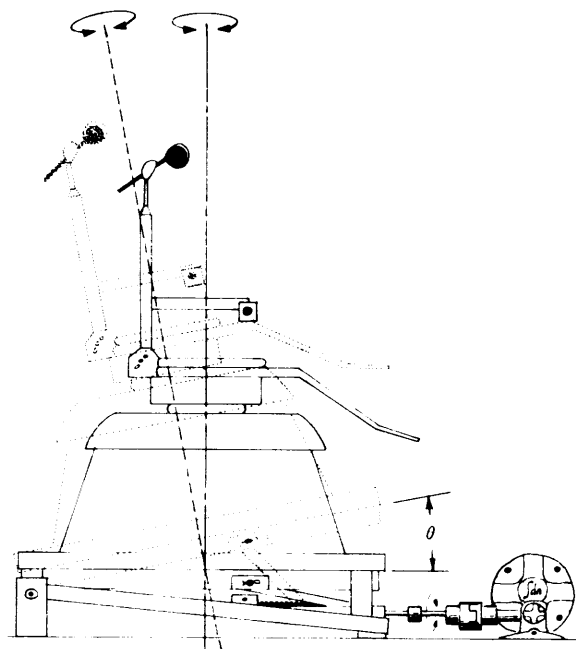


FIGURE 1.—Diagram of apparatus used in off-vertical rotation test.

upright and accelerated at  $5^\circ/\text{s}^2$  until one of several selected terminal velocities (2.5, 5, 10, 15, 20, 25, 30, 40, or 45 rpm) was reached. After no less than 60 seconds' duration the chair was tilted at  $5^\circ/\text{s}$  to a tilt position selected from among 2.5, 5, 7.5, 10, 15, 20, and 25 degrees. Off-vertical rotation was continued until moderate malaise (M IIA) was manifested or the time limit of 1 hour had elapsed. If the malaise endpoint was reached, the chair was quickly tilted to the upright, which immediately abolished the stressor stimulus, and decelerated at  $5^\circ/\text{s}^2$ .

Initially, the effect of the chair velocity in an off-vertical position was tested by exposing each subject to a random schedule of the listed test velocities, while maintaining in each case a  $10^\circ$  tilt of the rotational axis from upright. Each subject was tested twice, once in the clockwise and once in the counterclockwise direction of rotation, at each velocity. This procedure was followed by one in which the same subjects were tested once at each of the tilt angles, introduced in random order, while rotating at a constant velocity of 17.5 rpm. That value, based upon an ongoing analysis of results from the first half of this study, was selected

as representing the best estimate of a single rate of rotation which would produce a nearly maximum provocative effect. The scheduled order of presentation of each velocity and tilt angle was randomized not only for each subject, but also among subjects. Although the overt symptoms of M IIA quickly disappeared, at least 24 hours separated the individual trials.

### RESULTS

Tolerance of subjects to off-vertical rotation as reflected by the duration required to evoke M IIA is plotted for the four subjects in figure 2 as a function of chair velocity (rpm). It was possible to draw an average subject response curve (solid line) only between 10 and 25 rpm, since the M IIA endpoint was not reached at the other velocities by all subjects. This curve section, however, was extended in an idealized fashion (dotted lines) in both directions in figure 2 to portray the marked general changes in response throughout the entire range of

test velocities. SC, the most susceptible subject, reached the endpoint criterion (M IIA) with an average of 43 minutes' exposure at 5 rpm but remained symptomless throughout the 1-hour maximum test period at 2.5 rpm. At 5 rpm subjects TE and BE were unaffected and subject WI reached M IIA just prior to the end of the test. Increasing the velocity from 5 to 10 rpm evoked the endpoint in all subjects, three within 20 minutes. An even greater provocative effect was found at 15 rpm, with all subjects manifesting M IIA within 15 minutes' exposure. The provocative effect, however, could not be enhanced substantially by greater rates of rotation, and in fact at 25 rpm the stressor effect appeared to be lessened. This trend continued while progressing from 30 to 45 rpm. Increasingly longer durations were required to evoke the endpoint, which was not always reached even in the most susceptible subject (SC).

The subject's impressions of bodily movement in space also varied with the rate of rotation. Each subject had the sensation of revolving rather than rotating and in a direction opposite the actual rotation. That is, his head seemed to be moving in a circular path centered on the rotational axis and to be directed always essentially in the same compass direction. At rates below 30 rpm, the subjects reported a smooth revolving bodily movement that generated an inverted cone; the base was traced by the head, and apex usually was located within the area of contact with the chair seat. At a rate of 30 rpm, all subjects felt tilted to some extent, as with the slower rates, but complained that this rate provided substantially "the most difficult ride," with a more pronounced sensation of rocking front to back or side to side as compared to the lower or higher rates. At rates higher than 30 rpm, all subjects began to lose their feeling of being tilted, and at 40 and 45 rpm, they reported "much easier" and "very smooth rides," with the sensation of being at or near upright throughout the period of exposure.

Figure 3 is a plot of the provocative effect, measured in the same terms as figure 2, as a function of the off-vertical angle of tilt at a constant rotation of 17.5 rpm. Two subjects were completely symptom free when rotated about an axis positioned  $2.5^\circ$  from the upright. With greater off-vertical angles, the provocative effect of rotation increased dramatically at first, then leveled off.

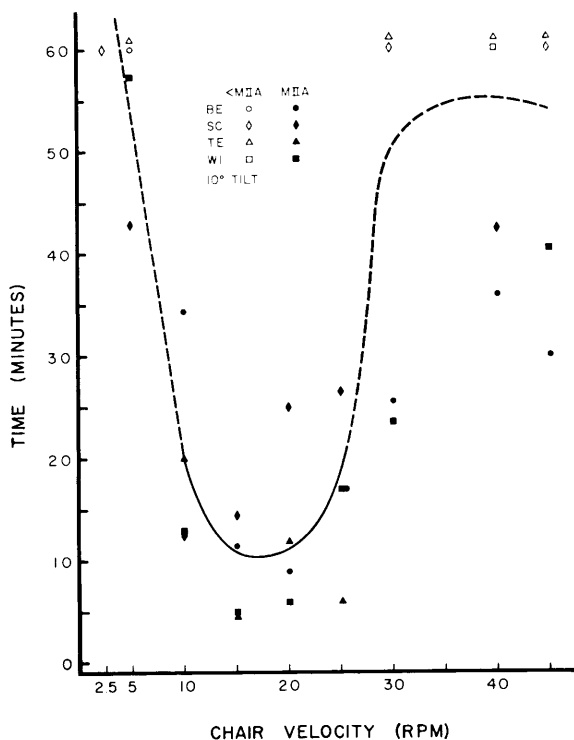


FIGURE 2.—Subjects' motion sickness susceptibility measured in terms of duration of off-vertical ( $10^\circ$ ) rotation required to reach the test endpoint (malaise IIA or 60 minutes) as a function of rotational rate (rpm).

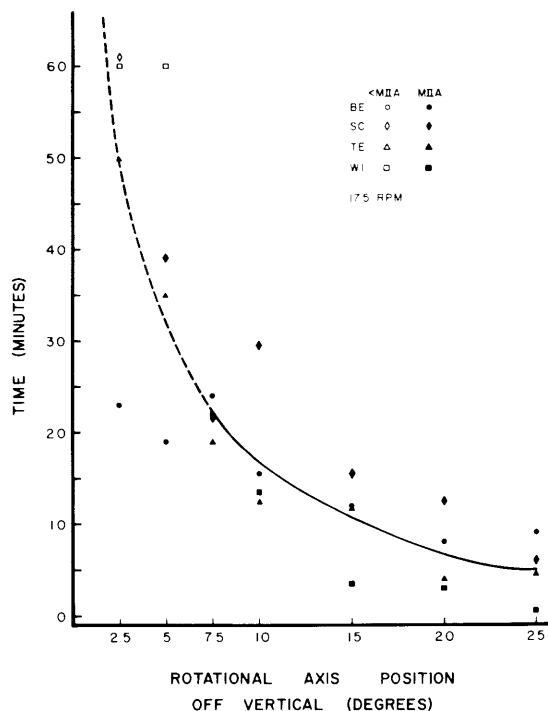


FIGURE 3.—Subjects' motion sickness susceptibility measured in terms of duration of a constant rotational rate (17.5 rpm) required to reach the test endpoint (malaise IIA or 60 minutes) as a function of off-vertical placement of the rotational axis.

### DISCUSSION

The sweep of the rotating linear acceleration vector (RLAV) stimulated all gravireceptors, but the provocative effect of the RLAV was probably primarily dependent upon its unusual activation of the otolith organs. In a constant off-vertical position the rotational velocity was changed to vary the sweep rate of a constant force in an essentially identical spatial pattern. In the complementary situation a constant velocity was maintained while the angle of incidence of the RLAV with respect to the subject varied with the degree of tilt.

The remarkable decrease and subsequent increase in tolerance that resulted from step increases in off-vertical rotational rate provided another example of the importance of the frequency as well as the intensity and pattern of the stimulus in the production of motion sickness. Wendt (ref. 10) found, for example, that a medium-frequency linear wave motion of 16 to 22 cpm was most effective in making

men sick, but that there was a sharp decrease at subsequent higher frequencies. At the low rotational rates used in our study, normal physiological conditions were approximated, and, as expected, most subjects experienced little or no vestibular stress effect. With moderate rates all subjects were found to be susceptible, and their susceptibility over a narrow span of velocities increased precipitously to a critical value. With higher rotational velocities the paradoxical increase in tolerance to off-vertical rotation was found. The slight increase in the provocative effect at 45 rpm from that seen at 40 rpm and the extent to which the more rapid rotational rates failed to eliminate the evocation of motion sickness symptomatology may indicate the possible contribution of nonotolithic proprioceptors that were also stimulated by the RLAV. It is noteworthy, however, that the most susceptible subject (SC), who reached the M IIA endpoint even at 5 rpm, was symptom free at 30 and 45 rpm.

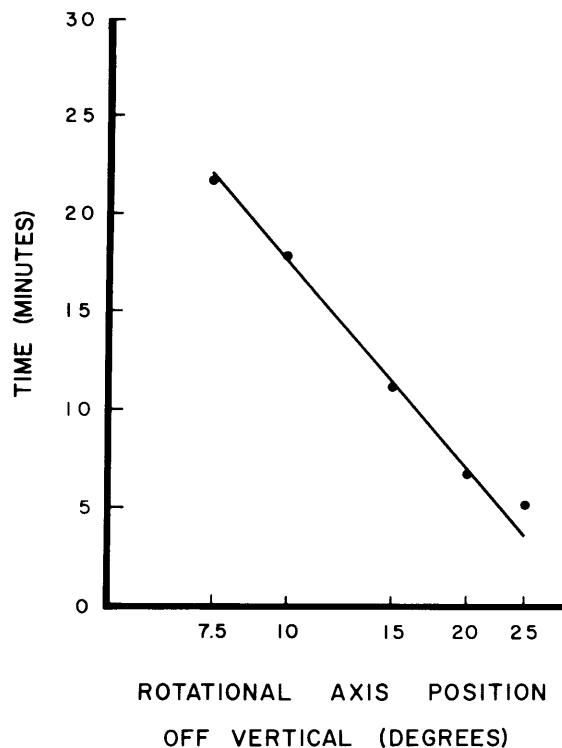


FIGURE 4.—Linear relationship between duration of exposure required to evoke malaise IIA and logarithmically scaled off-vertical position of axis for constant rotation at 17.5 rpm.

Figure 4 displays on a logarithmic base the response data of figure 3 within the range of off-vertical angles that was found effective in evoking M IIA in all subjects. The excellent empirical fit of these data with a straight line indicates that the stressor value of a relatively low constant speed (17.5 rpm) varies directly with the axis tilt angle in accordance with Fechner's Law. The nonotolithic receptors, which are also responsive to these experimental conditions, represent secondary stressor influences since they, per se, cannot evoke motion sickness (refs. 2 and 4). The primary genesis of the changes in the provocative effect as a function of off-vertical displacement of the rotational axis (RLAV angle) must therefore be vestibular. More specifically, this effect very likely involves the bizarre activity of cilio-otolith elements, which would tend to respond slavishly to the ever-changing direction of the acceleration vector sweep. If such otolithic activity is the basis for the Fechnerian function found, then it would follow that the change in stressor effect that occurs with simply a shift in off-vertical rotational position (at least within the range tested in this study) would be dependent upon the integrated change in the amount of deformation of the macular sensory hairs, coded in logarithmic terms, in response to the constant dynamic pattern of stimulation.

### REFERENCES

1. GRAYBIEL, A.: AND MILLER, E. F. II: Off-Vertical Rotation: A Convenient Precise Means of Exposing the Passive Human Subject to a Rotating Linear Acceleration Vector. *Aerospace Med.*, vol. 41, 1970, pp. 407-410.
2. GRAYBIEL, A.: AND MILLER, E. F. II: The Otolith Organs as a Primary Etiological Factor in Motion Sickness: With a Note on "Off-Vertical" Rotation. Fourth Symposium on the Role of the Vestibular Organs in Space Exploration, NASA SP-187, 1970, pp. 53-64.
3. MILLER, E. F. II: AND GRAYBIEL, A.: A Provocative Test for Grading Susceptibility to Motion Sickness Yielding a Single Numerical Score. *Acta Oto-Laryngol.*, suppl. 274, 1970, pp. 1-20.
4. MILLER, E. F. II: AND GRAYBIEL, A.: The Semicircular Canals as a Primary Etiological Factor in Motion Sickness. Fourth Symposium on the Role of the Vestibular Organs in Space Exploration, NASA SP-187, 1970, pp. 69-82.
5. GRAYBIEL, A.: WOOD, C. D.: MILLER, E. F. II: AND CRAMER, D. B.: Diagnostic Criteria for Grading the Severity of Acute Motion Sickness. *Aerospace Med.*, vol. 39, 1968, pp. 453-455.
6. McLEOD, M. E.: AND MEEK, J. C.: A Threshold Caloric Test: Results in Normal Subjects. NSAM-834, Naval School of Aviation Medicine, Pensacola, Fla., 1962.
7. MILLER, E. F. II: Counterrolling of the Human Eyes Produced by Head Tilt With Respect to Gravity. *Acta Oto-Laryngol.*, vol. 54, 1962, pp. 479-501.
8. MILLER, E. F. II: Ocular Counterrolling. *The Vestibular System and Its Diseases*, R. J. Wolfson, ed., University of Pennsylvania Press, 1966, pp. 229-241.
9. GRAYBIEL, A.: AND FREGLY, A. R.: A New Quantitative Ataxia Test Battery. *Acta Oto-Laryngol.*, vol. 61, 1966, pp. 292-312.
10. WENDT, G. R.: Experiences With Research on Motion Sickness. Fourth Symposium on the Role of the Vestibular Organs in Space Exploration, NASA SP-187, 1970, pp. 29-32.

