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PERCEPTION OF BODY POSITION AND SUSCEPTIBILITY OF MOTION SICKNESS AS FUNCTIONS OF ANGLE OF TILT AND ANGULAR VELOCITY IN OFF-VERTICAL ROTATION

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13. ABSTRACT

Four normal subjects manifested little or no susceptibility to motion sickness in a chair device tilted 10° off-vertical and rotated at 2.5 rpm or 5 rpm; with further rate increases the end-point of mild symptoms was always reached and within increasingly shorter durations. Susceptibility was maximal at either 15 rpm or 20 rpm but with higher rotational rates declined rapidly, reaching a plateau of relatively low susceptibility at 40 rpm and 45 rpm; furthermore, at these higher velocities, the subjects began to lose their sensation of being tilted off-vertical. Two subjects were asymptomatic when the chair was tilted 2.5° off-vertical and rotated at 17.5 rpm; with greater angles of tilt susceptibility of all subjects increased in ever-decreasing amounts.

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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 (2, 3). The effect can be illustrated by considering the subject stationary in an upright position, and having an acceleration vector rotate 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 and, theoretically at least, 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 a subject's susceptibility to motion sickness from otolithic stimulation and may complement those susceptibility tests in which the semicircular canals are the initial or primary etiological factor (8, 9).

Evidence from testing a few subjects highly resistant to motion sickness had indicated that a greater provocative effect was derived from increasing the off-vertical angle from 10° to 20° at various rotational rates, but the relative change in effectiveness was not explored (2, 3). In these earlier studies the method of grading susceptibility utilized a schedule of ever-increasing rotational rates, which often unnecessarily prolonged the test duration and frequently caused a very rapid rise in symptomatology when the adequately stressful rate was finally reached (2, 3). As a result, great care had to be exercised to prevent the overshoot of a preselected endpoint of mild severity, termed Malaise IIA (M IIA) by Graybiel et al. (4) and based on a numerical scale formulated by those authors. In addition, the original test method exposed the subject to periods of incremental increases in the vestibular stressor level. Low levels of stressor stimulation were usually initially compensated, 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 purpose of the present study was to explore: (a) the change in provocative effect of varying the rate of rotation from 2.5 rpm to 45 rpm about a slight (10°) off-vertical axis, and (b) 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 from 2.5° to 25°.

PROCEDURE

SUBJECTS

Four young Navy enlisted men, ranging in age from 19 to 21 years, who had previously demonstrated motion sickness susceptibility to off-vertical rotation volunteered as subjects. Each was found to be healthy by a comprehensive Navy medical examination, given prior to his acceptance as a research subject, and remained so during the experimental procedure, as reported daily in his pre-examination questionnaire (8). Functional tests of the semicircular canals (5) and otolith organs (6,7) plus those of postural equilibrium (1) proved further that those specific systems were functioning well within normal limits.

METHOD

A standard Stille rotating chair, Model RS-3, mounted on a motor-driven tilt base served as an off-vertical rotation (OVR) chair (Figure 1). The degree of tilt relative to the gravitational upright was registered on a large protractor scale. The subject's head was centered over the axis of rotation and held rigidly against the headrest by an adjustable strap across his forehead. A seat belt further secured him to the chair. His eyes were covered with a small padded goggle which did not interfere with an observer's being able to note facial flushing, pallor, and sweating. The combined weight of the subject and the chair superstructure was statically balanced in a 20° off-vertical position to ensure constant speed rotation ($\pm <0.1\%$) during the OVR tests. The chair was then returned to upright and accelerated at $5°/sec^2$ until the selected terminal velocity was reached. After no less than 60 seconds' duration the chair was quickly tilted at 5°/sec to the selected tilt position and off-vertical rotation was continued until moderate malaise (M IIA) (4) was manifested or the time limit of 60 minutes 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 $5°/sec^2$.

Initially, the effect of the chair velocity in an off-vertical position was tested by exposing each subject to a schedule of several test velocities (2.5, 5.0, 10.0, 15.0, 20.0, 30.0, 40.0, 45.0 rpm), while maintaining in each case a 10° 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 several tilt angles (2.5, 5.0, 7.5, 10.0, 15.0, 20.0, and 25.0 degrees) during 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 that 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 (4) quickly disappeared, at least 24 hours separated the individual trials.

RESULTS

Tolerance of 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 of Figure 2) only between 10 rpm and 25 rpm since the M IIA endpoint was not reached at the other velocities by all subjects. This curve section was, however, 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

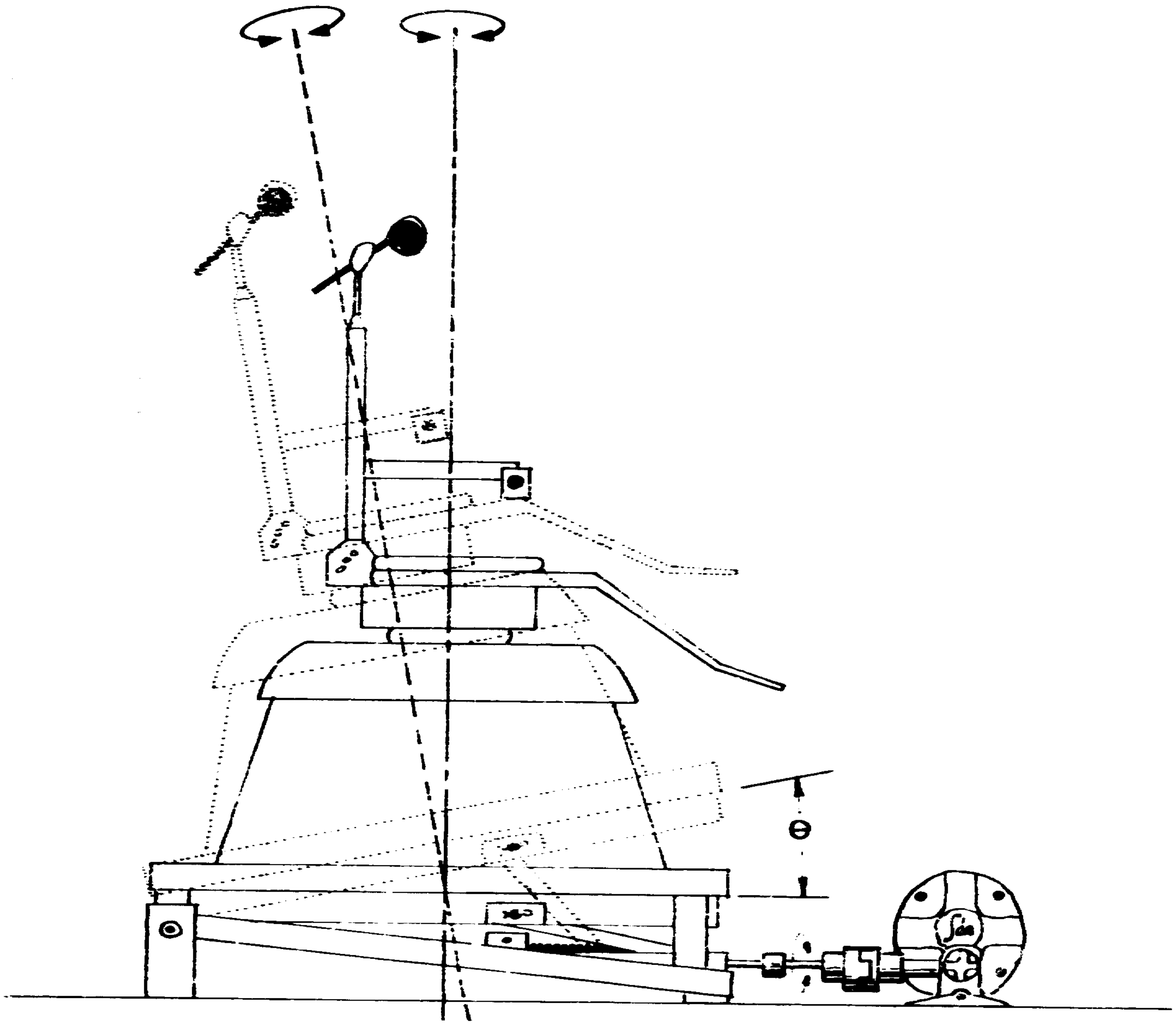

Figure 1

Off-Vertical Rotating Chair Device

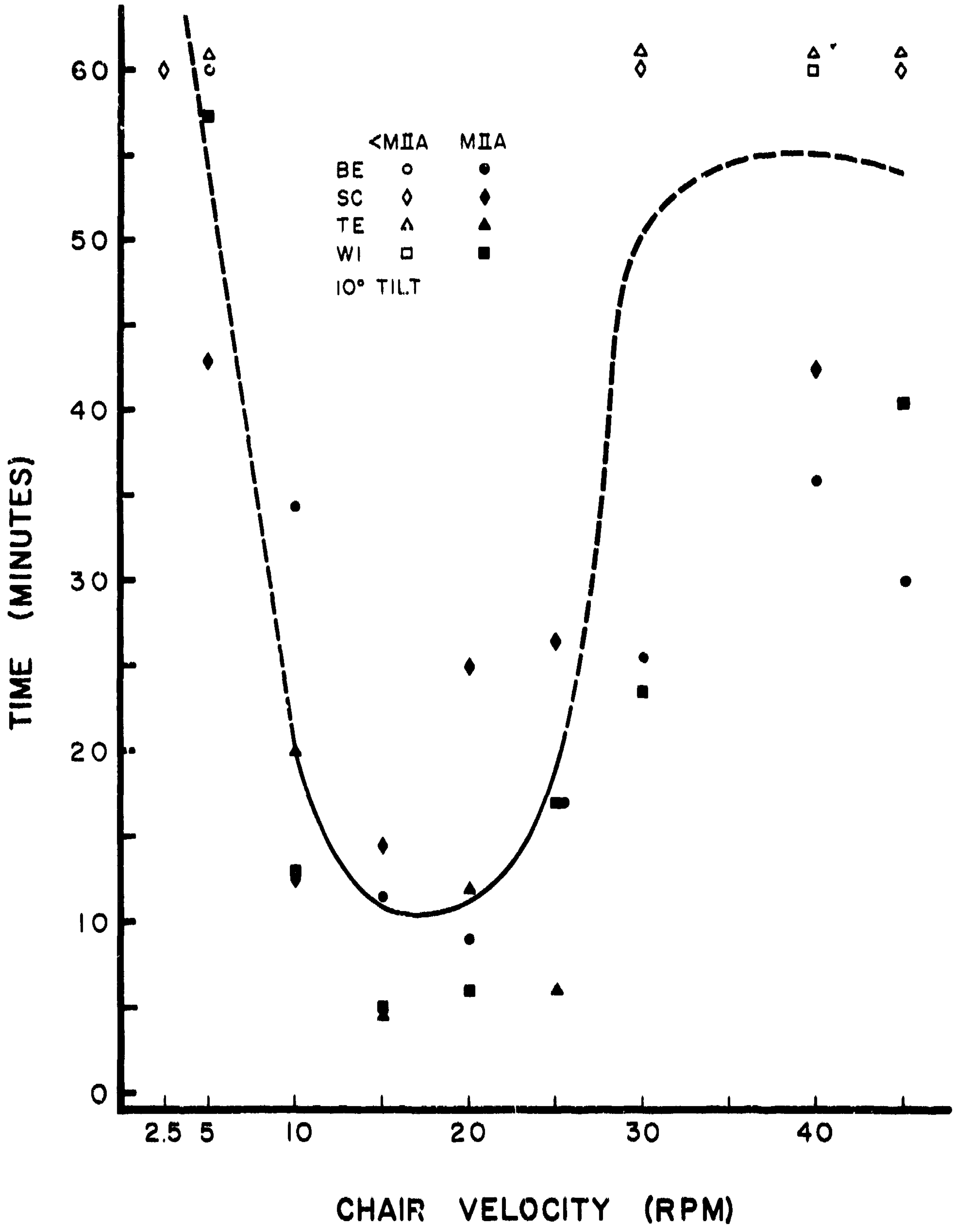

Figure 2

Subject's Motion Sickness Susceptibility Measured in Terms of Duration of Off-Vertical (10°) Rotation Required to Reach the Test Endpoint (Malaise IIA (M IIA) or 60 minutes) As a Function of Rotational Rate (rpm) susceptible subject, reached the endpoint criterion (Malaise IIA) with an average of 43 minutes' exposure at 5 rpm but remained symptomless throughout the 60-minute maximum test period at 2.5 rpm. With 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 rpm to 10 rpm evoked the endpoint in all subjects, three within 20 minutes. An even greater provocative effect was found at 15 rpm and 20 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 beginning at about 25 rpm the stressor effect appeared to decrease. This trend continued in progressing to 45 rpm as increasingly longer durations were required to evoke the endpoint which was not always reached even in the most susceptible subject (SC).

The subjects' impressions of the bodily movement and position 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; i.e., his head appeared to move 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 the apex usually was located within the area of contact with the chair's 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 rpms. 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° from the upright. With greater off-vertical angles, the provocative effect of rotation generally increased in ever-decreasing amounts.

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 subjects was changed with the degree of tilt.

The remarkable increase then paradoxical decrease in susceptibility that resulted from step increases in off-vertical rotational rate provided another example of the importance of the frequency as well as of the intensity and pattern of the stimulus

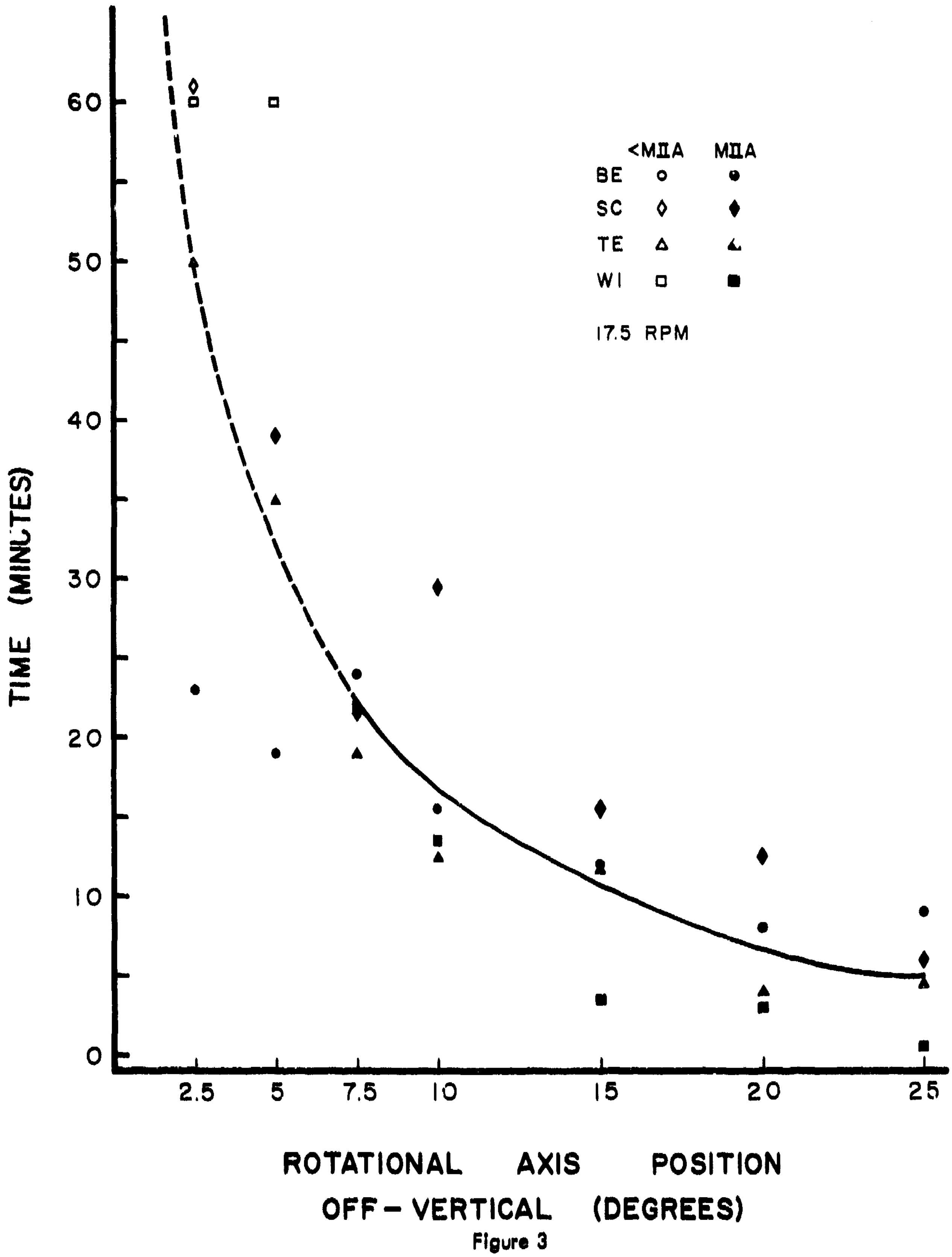

Figure 3

Subject's 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 in the production of motion sickness. Wendt (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 stressor effect. 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 in part of the subjects, may indicate the possible contribution of nonotolithic proprioceptors which were also stimulated by the RLAV. It is noteworthy, however, that the most susceptible subject (SC) who reached the Malaise IIA endpoint even at 5 rpm was symptom free at 30 rpm and at higher rates of rotation.

Figure 4 displays on a logarithmic scale 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 slow constant speed (17.5 off-vertical rotations per minute) 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 (3,9). 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 that would tend to respond slavishly to the everchanging direction of the acceleration vector sweep. If such otolithic activity was the basis for the Fechnerian relationship found, then it would follow that the stressor effect under our test conditions is in direct proportion to the integrated change in the amount of deformation of the macular sensory hairs, coded in logarithmic terms.

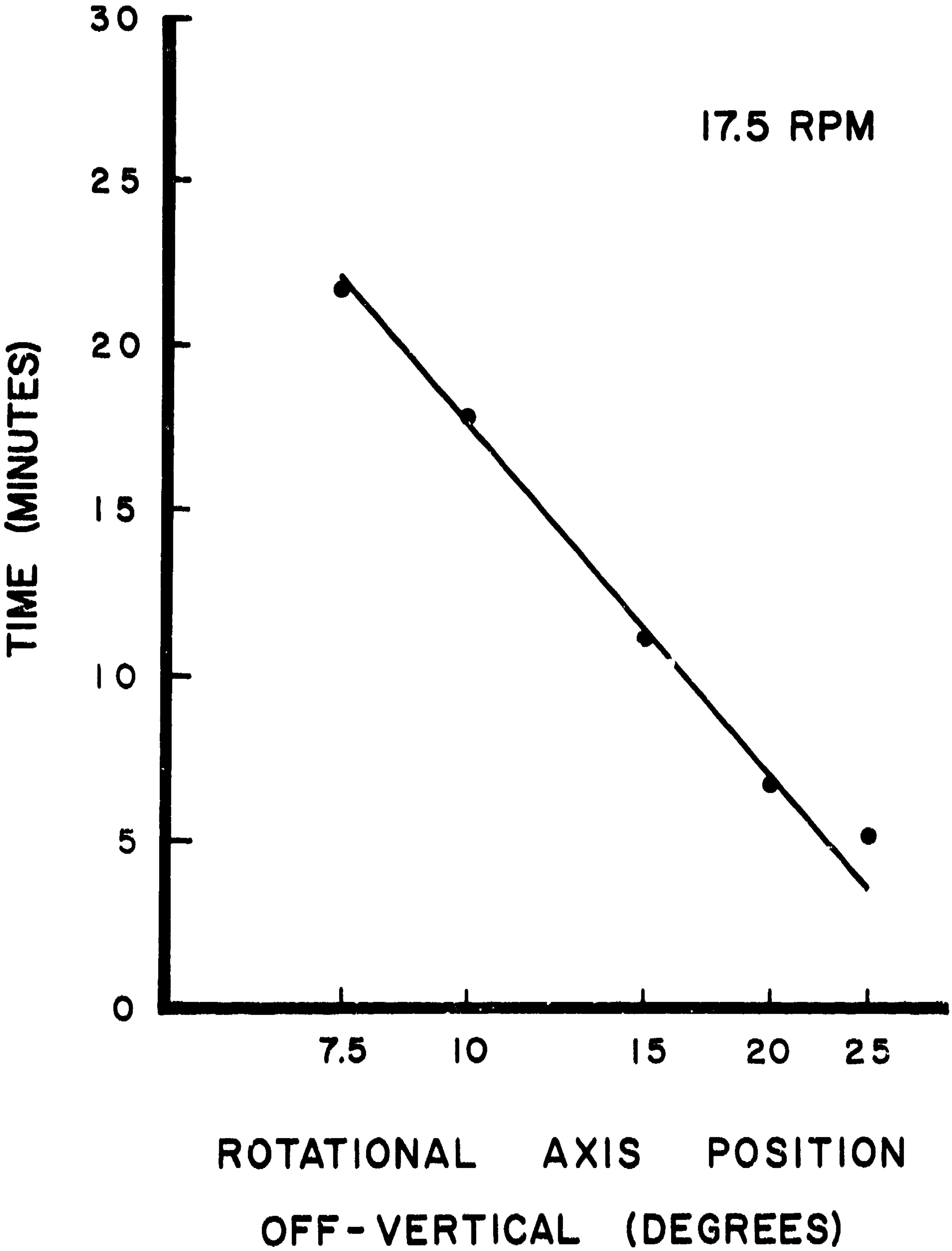

Figure 4

Data of Figure 3 Expressed as a Linear Relationship Between Duration of Exposure Required to Evoke Malaise IIA and Logarithmically Scaled Off-Vertical Position of Axis of Constant Speed Rotation (17.5 rpm)

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