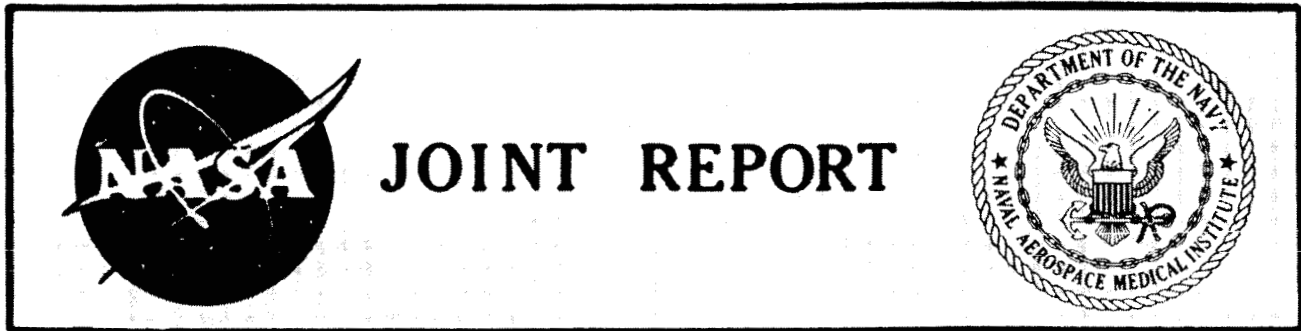


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MAGNITUDE ESTIMATIONS OF CORIOLIS SENSATIONS

James T. Reason and Ashton Graybiel

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## MAGNITUDE ESTIMATIONS OF CORIOLIS SENSATIONS\*

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Bureau of Medicine and Surgery  
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Commanding Officer

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PENSACOLA, FLORIDA 32512

## SUMMARY PAGE

### THE PROBLEM

The purpose of the first experiment was to investigate the nature of the psychophysical function relating magnitude estimates of the strength of the Coriolis vestibular reaction to the speed of platform rotation. This relationship was investigated under four experimental conditions: 1) eyes closed, head tilt to the right; 2) eyes closed, head tilt left; 3) eyes open, head tilt right; and 4) eyes open, head tilt left. A second experiment compared the relative strengths of the tilt and return motions in the right and left quadrants. In all cases, the extent of the head motion was  $30^\circ$ , and rotation was in the counterclockwise direction throughout.

### FINDINGS

Geometric mean magnitude estimates of Coriolis sensations increased as a power function of angular velocity in all four experimental conditions. Magnitude estimations obtained in the vision-present condition were generally greater than those for the vision-absent condition. For both conditions of visual reference, magnitude estimates relating to the right head tilt were greater than those for the left head tilt.

In the second experiment, it was found that the strongest reaction was produced by the return from the left shoulder and the next strongest by the return from the right shoulder. The subjective rankings did not differentiate between the right and left tilt motions. As in previous studies, individual differences were noted in ranking the strength of the subjective reactions produced by these four lateral head motions.

## INTRODUCTION

One factor which is likely to have an important influence upon human performance within a rotating environment, at least during the preadapted stages of exposure, is the subjective magnitude of the illusory Coriolis sensation that accompanies certain movements of the head. Theoretical formulations of the Coriolis stimulus (4) indicate that the magnitude of the mechanical couples developed within the semicircular canal system is directly proportional to the angular velocity of the rotating platform so long as both the rate and the extent of the effective head motion (relative to the platform) are held constant. Although the mechanics of the Coriolis vestibular reaction are now fairly well understood, the psychophysical aspects of this situation have received relatively little attention.

The most comprehensive investigation in this area was carried out by Guedry and Montague (4) who used the excursion of a simulated aircraft control stick to indicate subjects' reactions to 30° lateral head movements (to and from the right shoulder) during clockwise bodily rotation. Separate estimates were made of the apparent displacement and the apparent velocity of the target light, and in both cases the subjective reactions were linearly related to the angular velocity of the rotating device. This suggested that displacement and velocity estimates, obtained in this way, closely approximate the strength of the mechanical couples developed within the canal system. However, discrepancies were noted between spontaneous verbal reports of the strength of the sensation and the stick excursion measurements. Several of the subjects commented that returning the head to the upright position produced a stronger sensation than moving the head toward the right shoulder, a distinction that was not revealed by the stick excursion movements. This observation was confirmed by the findings of a second series of experiments in which subjects were required to compare the "disturbance" produced by 30° tilt and return movements in both the right and left quadrants. It was found that the apparent diving sensations produced by head movements contrary to the direction of rotation (i.e., the return from the right shoulder and the tilt toward the left shoulder) were more disturbing than movements in the same direction as the platform's rotation. The return of the head from the right shoulder was considered the most disturbing movement. These results, and others in the same series of experiments, suggest the possibility that the disturbing qualities or the over-all strength of the Coriolis sensation may, in certain circumstances, differ markedly from the estimates of apparent displacement and velocity obtained by the stick excursion method.

Two experiments are reported here, the first of which was concerned only with the strength or disturbance component of the Coriolis sensations produced by 30° downward tilt motions of the head (in the frontal plane) at different speeds of platform rotation. In particular, it was designed to investigate the psychophysical functions relating numerical estimates of sensation magnitude (9) to the speed of rotation under the following experimental conditions: 1) eyes closed, head tilt right; 2) eyes closed, head tilt left; 3) eyes open, head tilt right; and 4) eyes open, head tilt left. It was expected that within each condition of visual reference, the technique of magnitude estimation would reveal the directional asymmetry reported by Guedry and Montague. The design also

allowed comparisons between subjects' estimations in the vision-present and vision-absent conditions. The second experiment was concerned with comparing the relative strengths of the tilt and return movements in the right and left quadrants.

Aside from its practical implications, this study was of some theoretical interest in that it required subjects to make numerical estimates of the strength of sensations which are not normally associated with tilting movements of the head. Although the method of magnitude estimation has been widely used over the past decade (9), it has rarely, if ever, been applied to a virtually new sensory experience. Thus, the ability of subjects to quantify the subjective magnitude of these novel and bizarre sensations is likely to have a close bearing on the usefulness of this technique and on the questioned validity of Stevens' power law (10).

## EXPERIMENT I

### SUBJECTS

Eighteen male volunteer subjects, aged 22 to 33 years, were used. Of these, sixteen were junior officers in the U. S. Navy or Marine Corps undergoing preliminary flight training at the Pensacola Naval Air Station. The remaining two were scientists employed at the Naval Aerospace Medical Institute. Only the latter had had any previous experience of Coriolis sensations in a laboratory situation. Two additional subjects were tested but were unable to complete the experimental session, in one case through technical reasons, in the other through the sudden onset of vomiting. All of the subjects were in good health.

### APPARATUS

The experiment was performed within the Pensacola Slow Rotation Room (SRR). A complete description of this facility can be found elsewhere (1). The extent and direction of the head movements in the frontal plane were controlled by a biteboard arrangement attached to the subject's chair. An adjustable head and back support restrained the subject's head between judgments. The distance from the axis of rotation to the center of the subject's head was 42 inches.

### TRAINING AND INSTRUCTIONS

Before using it to quantify the strength of Coriolis sensations, each subject was familiarized with the technique of magnitude estimation by first performing the relatively simple task of estimating the loudness of a 1000-Hz tone at various sound pressure levels. The technique and instructions were essentially the same as those described by Stevens (8). The modulus or standard stimulus (equivalent to 10 units of subjective loudness) was set at 50 dB (re 0.0002 dyne/cm<sup>2</sup>) and was presented for comparison with the variable stimulus on each trial. The six variable stimuli ranged from 50 to 100 dB in 10-dB steps. Two magnitude estimates were obtained at each intensity level, and a

different random order was used for each subject. The tones were delivered binaurally through earphones and were generated by a "Maico" clinical audiometer.

On completion of these loudness estimations, subjects were seated in the SRR and instructed in the technique of estimating the strength of Coriolis sensations. A verbatim account of these instructions can be found in Appendix A.

After instruction, the subjects were practiced in making the head movements while the SRR was at rest. It was stressed that these movements should be made at a uniformly fast rate. Subjects were also informed that the movements should be made from the neck and that the trunk should remain in the upright position.

The head and back support was inclined at a slight angle from the vertical to allow clear passage for the tilt motions of the head. In order to reach the biteboard, therefore, the subject's head had to move forward in a short arc. Subjects were instructed to make these movements to and from the biteboard as slowly as possible in order to minimize the accompanying sensations. On reaching the biteboard, subjects were told to delay their tilt movement until they were sensation free. At the completion of the movement, they were to release the bite in the tilted position, make their magnitude estimate, and then move back to the headrest, straightening their heads enroute. Once settled in the support, they were to place the bite back in the horizontal position by hand. Practice was given in these procedures prior to the onset of rotation.

## OPERATING PROCEDURE

Before the experiment began, the SRR operator was provided with a list of rotation speeds in the required order. On reaching the particular operating velocity, he was requested to call, "Level at rpm," without specifying the actual speed of rotation. When the judgment was completed at that level, the on-board experimenter called, "Next rpm." The transition from one rpm to the next was made as smoothly as possible. The time for transition varied but it was rarely less than 40 seconds. During these changes in velocity, subject's head was restrained in the support.

## EXPERIMENTAL DESIGN

The standard stimulus (equivalent to 10 units of sensory magnitude) was set at 10 rpm. Six variable stimuli were used: 6, 8, 10, 12, 14, and 16 rpm. The experimental session was divided into four runs: two runs involved the left head tilt and two involved the right head tilt, each of 30°. The order of the variable stimuli within each run was randomized, and a different order was used for each subject. Within each condition of visual reference (i.e., vision present or absent), approximately half the subjects received the runs in the following order: right (tilt), left, left, right; for the remainder the order was: left (tilt), right, right, left. The SRR was rotated throughout in the counterclockwise direction.

The subjects were randomly divided into two groups of nine. In the "vision-absent" group the subjects' eyes were covered by a blindfold; in the "vision-present" group no restriction was placed upon visual reference within the illuminated SRR, although no specific fixation point was provided. The instructions to both groups were identical with the exception of those relating to the wearing of the blindfold.

The standard stimulus was presented only once at the beginning of each run, a total of four times within each experimental session. After the first presentation the subjects were informed that, on subsequent presentations, the standard may appear to be more or less intense than the preceding standards, but in either case it was to represent 10 units of sensory magnitude. After the presentation of each standard, the subjects were questioned as to the quality of their sensations. They were also requested to judge whether the current standard seemed more or less intense than the preceding standard.

## RESULTS

### Magnitude Estimates

Psychophysical functions relating to the four experimental conditions are shown in Figures 1 a and 1 b. The fact that all four plots are reasonably well fitted by single straight lines indicates that the geometric mean magnitude estimates of Coriolis sensations increased as a power function of the SRR angular velocity (i.e., "physical magnitude"). The straight lines were fitted by the method of least squares, and the regression coefficients (exponents) for each plot are set out in Table I.

Table I

Exponent Values\* for the Four Experimental Treatments

	Right Tilt	Left Tilt
Eyes open	1.86	1.74
Eyes closed	2.07	2.33

\*Derived from the geometric mean magnitude plots shown in Figures 1 a and 1 b.

It is clear that the magnitude functions derived from the four experimental conditions differed with respect to both slope and over-all height. These differences are displayed more effectively in Figure 2. In order to investigate the statistical significance of the slope differences, individual exponents were calculated for each subject for each of the two conditions to which he was exposed. To establish the significance of the "height" differences, the sum of the mean magnitude estimates for each subject was

EYES CLOSED (N=9)

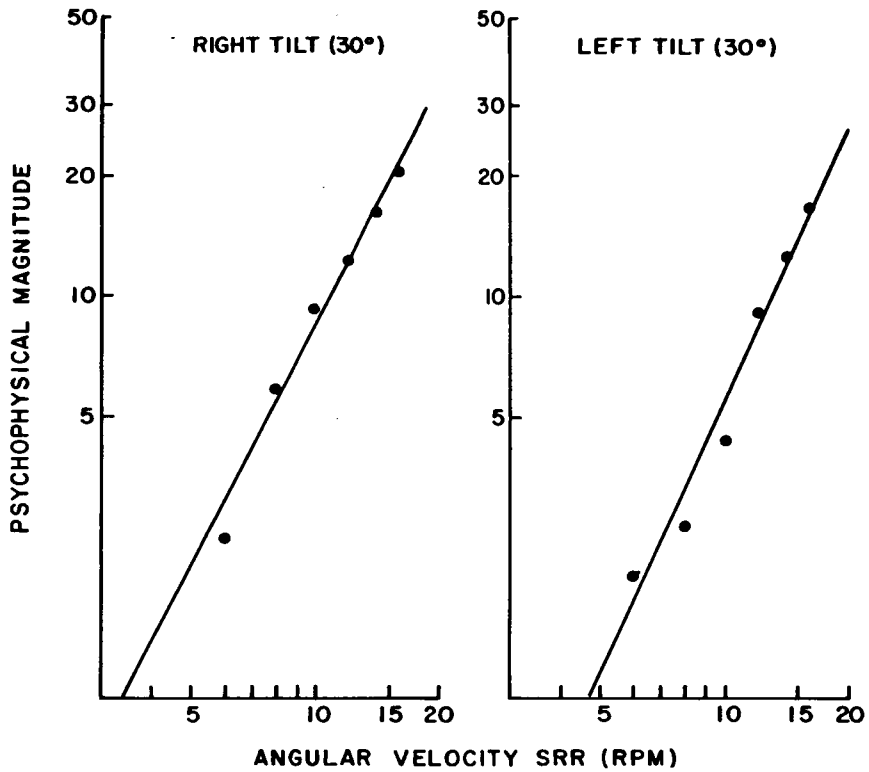


Figure 1a

Relationship between geometric mean magnitude estimates of Coriolis sensations and angular velocity for right and left tilts in the vision-absent condition. Plots are shown on logarithmic coordinates.

EYES OPEN (N=9)

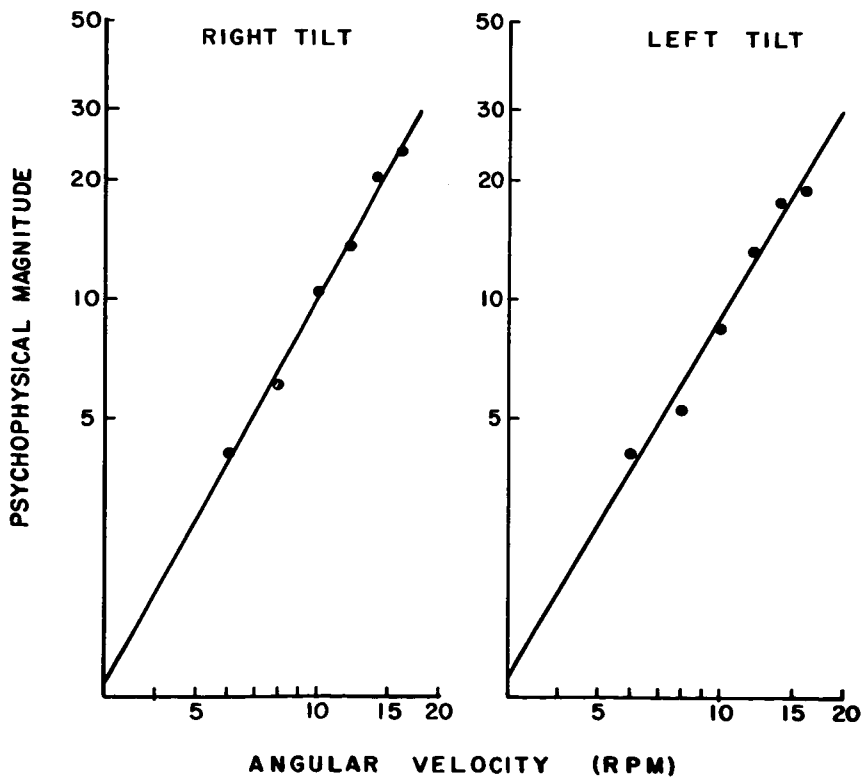


Figure 1b

Relationship between geometric mean magnitude estimates of Coriolis sensations and angular velocity for right and left tilts in the vision-present condition. Plots are shown on logarithmic coordinates.



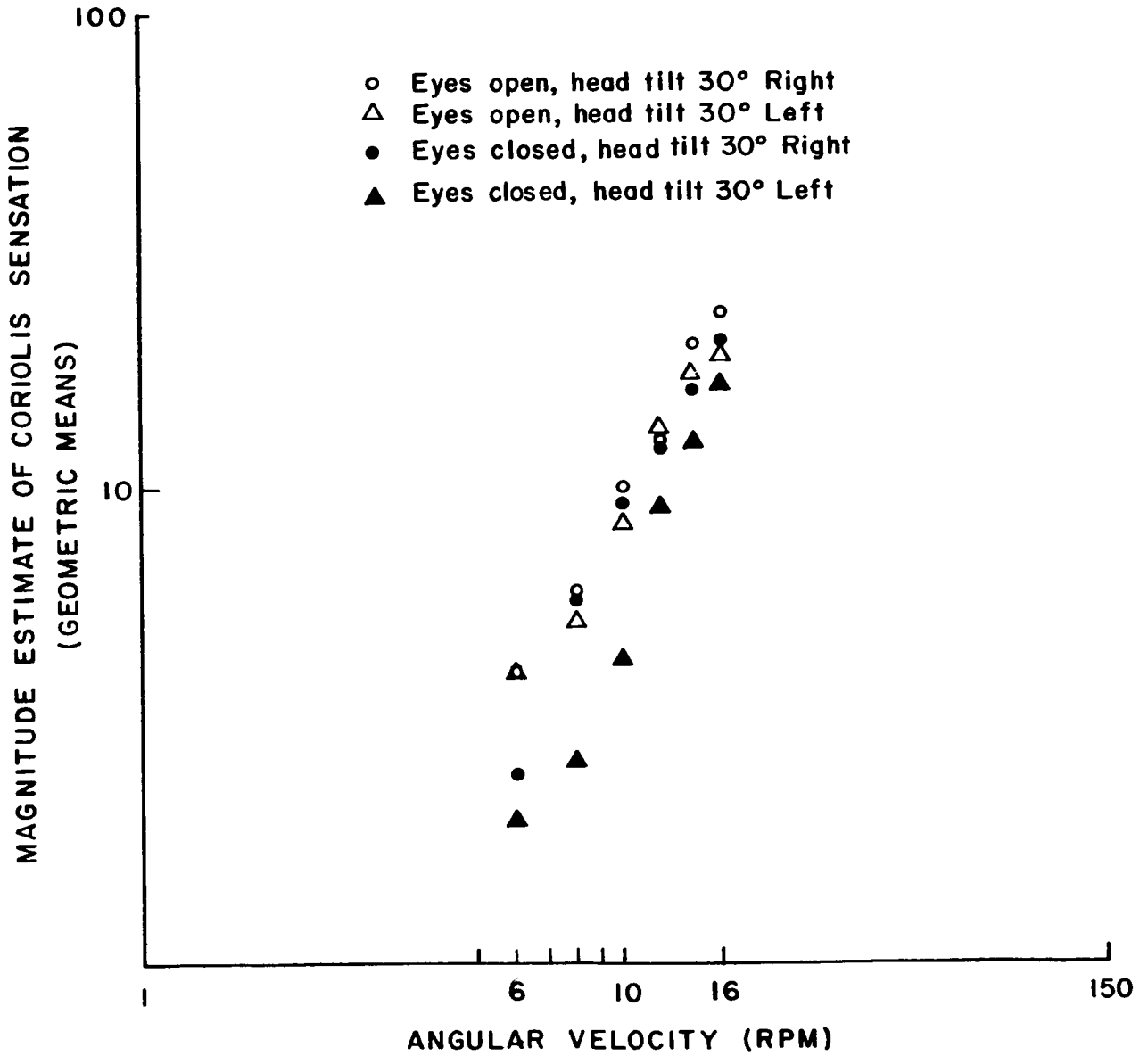


Figure 2

Comparing magnitude functions obtained under the four experimental conditions: Eyes open, tilt right; eyes open, tilt left; eyes closed, tilt right; eyes closed, tilt left.

computed for the same conditions. Summaries of these statistical analyses are shown in Table II (a) and (b).

Table II  
Summary of Statistical Analyses

Treatment Comparison*	Test	Direction of Difference	Significance Level
<u>(a) "Height" Values</u>			
ECR versus ECL	Wilcoxon <sup>+</sup>	R > L	p < .01
EOR " EOL	"	R > L	NS
ECR " EOR	Mann-Whitney <sup>#</sup>	EO > EC	NS
ECL " EOL	"	EO > EC	p < .05
ECR " EOL	"	EOL > ECR	NS
ECL " EOR	"	EOR > ECL	p < .02
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<u>(b) "Slope" (Exponent) Values</u>			
ECR versus ECL	Wilcoxon	L > R	p < .05
EOR " EOL	"	R > L	NS
ECR " EOR	Mann-Whitney	EC > EO	NS
ECL " EOL	"	EC > EO	p = .05
ECR " EOL	"	ECR > EOL	NS
ECL " EOR	"	ECL > EOR	NS

\* Experimental Treatment-Symbols: ECR = eyes closed, right tilt; ECL = eyes closed, left tilt; EOR = eyes open, right tilt; EOL = eyes open, left tilt

+ Wilcoxon matched-pairs signed ranks test

# Mann-Whitney U test

For both directions of tilt the exponents for the vision-absent group were generally greater than those for the vision-present group, although only the difference between the left tilt conditions was significant ( $p < .05$ ). Within the vision-absent group the slopes relating to the left head tilt were significantly steeper than those for the right head tilt ( $p < .05$ ). In the vision-present group no significant difference was found between the slopes for the right and left head tilts; if anything, the exponents produced by the right tilt were slightly greater than those for the left tilt.

In all comparisons, magnitude estimations obtained in the vision-present condition were generally greater than those for the vision-absent condition. For both conditions, the magnitude estimates obtained with the right head tilt were greater than those for the

left head tilt, although this difference achieved statistical significance only within the vision-absent group ( $p < .01$ ).

### Subjective Reports

Although none of the subjects found any apparent difficulty in quantifying the strength of his sensations, many of them found the task of describing the directional components virtually impossible. Thus, many tended to describe their sensations as a "feeling of dizziness" or a "buzzing in the head." Among those who were able to specify the direction of their apparent bodily displacement, the major point of agreement was that the head movements elicited a feeling of turning or "banking" in the same direction as the tilt. These turning sensations were usually accompanied by some form of pitching sensation, but there was little uniformity as to the direction. Part of this difficulty in reporting the quality of sensations may have been due to the fact that the subjects were well aware of their attachment to a rigid structure within a large room which was unlikely to execute pitching motions. Another factor may have been that they were seated at a short distance from the axis of rotation so that a pitch-forward sensation, for instance, could also be described as an upward displacement where the subject feels himself to be pivoted see-saw fashion at the axis of rotation.

The subjective reports with regard to the strength of the standard stimulus over the experimental session were relatively clear cut. Nearly all subjects reported that the stimulus diminished in strength with repeated presentations. In general, the decrement was most marked between the second and third runs (the same direction of head tilt); the fourth run standard (in the opposite direction) was frequently considered stronger than the third run standard. Some degree of adaptation may also have been indicated by the gradual falling off in the size of the magnitude estimates over the four sessions, although this interpretation is confounded by the fact that the judgments were being made in relation to a standard which was also diminishing in magnitude on repeated presentations.

### Motion Sickness Episodes

Symptoms were most commonly observed following head tilts at the higher speeds of rotation. Slightly more instances were observed in the vision-present condition (5 instances, including one of vomiting when judgments were discarded) as opposed to the vision-absent condition (3 instances). With the exception of the one case of vomiting, the symptoms never exceeded Malaise IIA (2).

## EXPERIMENT II

### SUBJECTS

Fifteen junior officers who had recently completed the initial part of the Non-Flying Officers' Course at the Pensacola Naval Air Station served as volunteer subjects. None had any previous experience of Coriolis phenomena. All were in good health.

## APPARATUS

Identical to that used in Experiment I.

## PROCEDURE

After instructions and practice in the use of the biteboard, each subject was exposed to a single angular velocity of 10 rpm. Four separate lateral head tilts were made: 1) 30° tilt to the right, 2) 30° return to upright, 3) 30° tilt to the left, and 4) 30° return to the upright. The sensations elicited by the left and right tilt movements were each assigned the arbitrary value of 10 units of strength. The subject's task was to assign a number to the sensation elicited by the return movement which reflected its strength relative to the preceding down movement. The direction of this initial down movement was alternated between subjects. An interval of at least 30 seconds elapsed between the tilt and return movements. At the completion of the four head tilts, the subjects were asked to rank the strength of the sensations produced by the four separate movements.

## RESULTS

The mean magnitude estimate ( $N = 15$ ) for the return from the right shoulder was 13.6, range 9 to 17; the corresponding mean estimate for the return from the left shoulder was 16.5, range 10 to 25. In the case of the right return movement, 13 subjects judged it greater than the preceding downward tilt, one judged it as equal, and one judged it as slightly less; in the left return, 14 subjects judged it as greater than the preceding tilt, and one judged it as being equal in strength. Thus, on average, the right return elicited a sensation that was 36 per cent greater than the preceding tilt, while the left return movement produced a sensation that was 65 per cent stronger than the preceding tilt.

A Kendall's coefficient of concordance ( $W$ ) indicated that there was a significant degree of agreement among subjects in the manner in which they ranked the sensations produced by the four movements ( $W = 0.49$ ; chi squared (3 df) = 15;  $p < .01$ ). Considering the sum of the ranks attributed to the four sensations, it was clear that the greatest magnitude was produced by the return from the left shoulder and the next greatest by the return from the right shoulder. Although the sum of ranks reflected the general trend, there were a few subjects who considered one or other of the downward tilt motions to be stronger than one or other of the return movements. Similar individual differences were also noted by Guedry (3).

In this experiment, the rankings did not differentiate between the two down movements in regard to their relative strength; the sum of ranks obtained for the right down movement was equal to that obtained for the left down movement. The lack of differentiation between these two tilt motions may have been due to the fact that the asymmetry shown to exist in Experiment I was masked (in the retrospective ranking) by the considerably greater strength of the sensations provoked by the return movements. It is also

possible that these differences may have been obscured by the fact that in Experiment I, both downward tilts were assigned the same arbitrary value of 10 units of strength.

## GENERAL DISCUSSION

The findings of Experiments I and II clearly confirm the directional asymmetries reported by Guedry and Montague. Despite a number of methodological differences between this and the earlier study, the results in both cases indicate that, in general, returning the head laterally to the upright position produces a stronger and more disturbing sensation than moving the head through the same angle to either shoulder. It was also found that for both tilt and return motions, head movements which in regard to the mechanics of the canal system should elicit a feeling of diving or pitching forward (i.e., in the present experiment these were the right tilt movement and the return from the left shoulder) tend to produce a greater magnitude of sensation than movements evoking a feeling of climbing or pitching backward.\* The fact that the directional components of the sensations were not clearly identified by the subjects did not appear to affect their ability to discriminate between the relative strengths of these two types of sensations.

The main purpose of this study--to establish the nature of the psychophysical relationship between the angular velocity of the platform and the strength of the Coriolis sensation--was clearly achieved within the limitations of the method of magnitude estimation. Although differences in experimental treatment produced systematic variation in the height and slope of the plots displayed in Figures 1 and 2, the over-all relationship between sensation strength and angular velocity was adequately described by a power curve. Of practical importance was the fact that the exponents for these four plots ranged from 1.74 to 2.33 with an average value of 2.0. The significance of these slope values can be appreciated more readily when they are compared with the exponents obtained by Stevens and his coworkers for a wide range of sensory continua. Poulton, in a recent publication (6), has listed the exponents obtained by magnitude estimation for some 21 sensory dimensions. The smallest exponent (i.e., the shallowest slope) was for brightness (0.33), the largest was for electric shock (3.50), and the next largest was for force of handgrip (1.70). Thus, within the spectrum of sensory continua so far investigated, the rate at which the Coriolis sensation increases with the physical magnitude of the stimulus is second only to the pain evoked by electric shock.

Assuming that exponents of the same order will be obtained when the z-axis of the body is orthogonal to the axis of rotation (as in projected spacecraft), it is likely that the angular velocity of the craft will be highly critical for the comfort and possibly the efficiency of astronauts during the early stages of exposure to Coriolis forces. What may be of greater significance, however, is the likelihood that the rate at which man can adapt to these bizarre sensory inputs is closely linked to the magnitude of the sensory

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\*In the Guedry and Montague studies, the device was rotated in the clockwise direction; hence, the more disturbing movements were the left tilt and the return from the right shoulder.

response that is evoked during the initial period of exposure. There is some recent experimental evidence (7) to suggest that the greater this initial sensory response, the greater the amount of stimulation required to neutralize the Coriolis sensation.

With regard to the effects of vision, the results of Experiment I showed that those subjects who were allowed an unrestricted view of the illuminated interior of the SRR tended to report stronger or more disturbing sensations at all levels of stimulus magnitude than those subjects who made their judgments in the absence of vision. It seems reasonable to suppose that the subjective strength of the Coriolis sensation is in some way dependent upon the degree of discordance existing among the various correlated sensory inputs. In the vision-absent condition there is a direct conflict within the central nervous system between orientation information derived from the otoliths and that originating from the canal system (3); but in the vision-present condition this intralabyrinthine conflict is further exacerbated by an incongruous visual input. Although the difference in the incidence of motion sickness under the two conditions of visual reference was not significant, the greater incidence of sickness observed in the vision-present condition may also have reflected this additional sensory conflict. This notion receives some support from the results of an earlier experiment (5) which investigated the effects of vision on the incidence of sickness in the SRR.

Finally, it is worth noting that predictions derived from Stevens' power law have been supported by magnitude estimations of a novel sensory experience. This result makes it difficult to accept the view expressed by Treisman (10) that the power function obtained with direct estimates of sensory magnitude is dependent upon learning derived from previous transactions with the stimulus dimension.

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## Appendix A

### Instructions to Subjects

"What we are about to do on the SRR is essentially the same as what we have just done on the loudness test. In this case, however, I am interested in the strength of the sensations you get when you move your head while the room is rotating. These are called Coriolis sensations and are a natural consequence of the mechanics of the inner ears. It is these sensations that are likely to bother astronauts when they move their heads aboard a space vehicle which is rotated to produce artificial gravity. This is why we are interested in finding out all we can about them.

"On this test, you will make two sorts of head movements: one a head tilt of  $30^\circ$  to the left shoulder, the other a tilt of  $30^\circ$  to the right shoulder. As you can see, we control the extent of these movements by this biteboard arrangement. You will be making these head tilts at each of six speeds of room rotation. At each speed, we will be making two judgments of the strength of sensation; thus, we will make four experimental runs in all, two runs for the left head tilt, and two runs for the right head tilt.

"Like the loudness test, we will have a standard stimulus level to which we have assigned the arbitrary value of 10 units of strength to the sensation it produces. But unlike the loudness test, where we presented the standard for comparison on each trial, we shall, in this test, only be able to give it to you once at the beginning of each of the four runs. In other words, you will have to make your judgments in comparison to what you remember of the standard and to what you have called the preceding stimulus. One further difference between this and the loudness test is that the standard will be somewhere in the middle of the stimulus series, so that some of the stimuli will be less intense than the standard and some will have a greater intensity. Apart from these differences in procedure, however, your task will be essentially the same as before. If the variable stimulus appears twice as great as the standard, you call it 20; if it appears to be three and a half times as great, you call it 35; if it is ten times as great, you call it 100, and so on. Conversely, if it is only half as great as the standard, you call it 5, and so on. You can use decimals or fractions, if you wish. Remember that in this way you have just as many numbers below ten at your disposal as you have above.

"It is possible that some of these head movements will make you feel peculiar-- you may begin to sweat, or you may become aware of sensations in your stomach. If this occurs, let us know and we will let you rest until these feelings pass. Some people quite enjoy these sensations--others find them disturbing and unpleasant. We can't avoid this last possibility, but we will make sure that you don't become too uncomfortable."



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13. ABSTRACT <p>This investigation was concerned with estimates of the subjective strength of the Coriolis vestibular reaction evoked by 30° lateral head motions at constant angular velocity in the Slow Rotation Room. In the first experiment, a power relation was obtained between geometric mean magnitude estimates of the Coriolis reaction and angular velocity. These estimates tended to be greater when vision was present than in its absence. In both conditions of visual reference, head motions evoking a pitch-forward sensation were more disturbing than those producing a pitch-back sensation.</p> <p>In the second experiment, it was found that the strongest reaction was produced by the return from the left shoulder (counterclockwise rotation), and the next strongest by the return from the right shoulder. Subjective rankings did not differentiate adequately between the strengths of the right and left tilt motions.</p>		

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