# Effects of Exposure to a Rotating Environment (10 RPM) on Four Aviators for a Period of Twelve Days

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**Four carefully selected military personnel undergoing flight training were exposed to constant rotation at a speed of 10 RPM for 12 days in the Pensacola Slow Rotation Room. Environmental and working conditions simulated in many respects those which might obtain in a rotating orbiting spacecraft. The findings are discussed under three headings: clinical symptoms, clinical laboratory findings and psychophysiological performance. The experiment has demonstrated that countermeasures in addition to adaption are needed if there is immediate exposure to rotational velocities of 10 RPM and that the rotating room is a useful device for further exploration of vestibular and central nervous system mechanisms.**

THE CHIEF PURPOSE of this investigation was to measure the effects of prolonged exposure in a rotating room under environmental and working conditions which simulated in many respects those which might obtain in a rotating, orbiting spacecraft. The rate of rotation selected, 10 RPM, was considered to be near the upper limits of angular velocity to which man might adapt without impractical side effects. The duration of the run, twelve days, seemed sufficient for studying adaptive changes noted in previous studies of a similar nature.[1,2] Because it was recognized that the angular velocity was near the upper feasible limits participants were carefully selected from officers in the Navy flight training program. The primary objectives in the study were to determine (1) whether or not these selected individuals could remain on board for the planned duration without the need for medical treatment, (2) whether or not any of a wide variety of physiological and biochemical tests would reflect any adverse effects of prolonged rotation and (3) whether or not the performance of tasks designed to test different abilities would be adversely affected. The findings are discussed both from their theoretical and practical aspects.

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Sponsored by the Office of Life Science Programs, National Aeronautics and Space Administration (Order No. R-93), this task was a joint project of the U. S. Naval School of Aviation Medicine and the U. S. Army Institute of Research.

In previous reports from this laboratory the widespread symptomatology which normal persons have manifested in the Pensacola Slow Rotation Room (SRR) has been designated "canal sickness" to distinguish this etiologic type of motion sickness. The symptoms are not experienced by individuals who have lost vestibular function and are reduced or even absent in those with a partial loss of function.[3] The symptomatology is dependent not only on unnatural stimulation of the canals *per se* but also on many other factors, e.g., conflict among normally synergic inputs, lack of fitness and past conditioning. Symptoms range in severity from mild malaise to prostration. They include dizziness, headache, apathy, drowsiness and fatigue. Objective signs include pallor, cold sweating, vomiting, inactivity and ataxia. First order effects apparently give rise to secondary effects of still greater diversity which are declared by biochemical changes and other objective signs, e.g., compensatory nystagmus.[4] The time-course for changes in one symptom may reveal little of the over-all complexity of the adjustment, e.g., nausea may persist after nystagmus has declined. If perrotation adaptation has taken place a return of symptoms may be expected following cessation of rotation. There is evidence of habituation with repeated exposure.[5] Countermeasures, including drug therapy, are demonstrably beneficial.

Prior experiments involving prolonged exposure of man to continuous rotation at 10 RPM are relevant to the present report. Of three subjects who lived in the Pensacola Slow Rotation Room for two days at 10 RPM two were normal subjects adjudged to be of differing sensitivities to canal sickness and the third was a control subject who had lost vestibular function.[1,2] The control subject did not report sickness and exhibited only slight difficulty in walking heel-to-toe, a difficulty to be anticipated as a result of conflicting visual and proprioceptive clues in this unusual environment. Of the two normal subjects neither appeared to have motivation to continue beyond the two-day run, despite the fact that there was evidence of some adaptation in both subjects. The less susceptible "normal subject," who had had previous experience in the room, appeared less affected than the other "normal subject."

A series of short runs conducted primarily to evaluate susceptibility to canal sickness has involved angular velocities higher than 10 RPM. Systematization of stimulation was accomplished by means of an experimenter-paced Dial Test which necessitated different head and trunk movements in setting the needles of five dials arranged around a chair.[1] It was found that 7.5 RPM was a convenient velocity for screening tests but that in some cases velocities up to and including 20 RPM were required to produce symptoms of sickness. Occasionally subjects on repeated testing showed little evidence of malaise at the latter velocity for periods up to an hour.[6]

Similar results were obtained by Stone and Letko[7] whose subjects were placed in a spine position, feet outboard and supported by a "floor" 15 feet from the center of rotation, thus simulating the orientation in a rotating spacecraft. Short periods of rotation were used, and maximum angular velocities were 17 RPM. The authors encountered malaise in all subjects at 10 RPM and above and rightly concluded that more simulation studies should be conducted.

The present experiment was undertaken in the light of this background, with subjects purposely selected to be resistant to motion sickness and instructed to avoid unnecessary head movements until adaptation ensued. Effort was made to ensure motivation of the subjects by (1) explaining the importance of their participation to the space effort, (2) selecting two Marine and two Navy officers in the hopes of engendering a competitive spirit, (3) arranging for publicity in the local news media and (4) impressing upon the subjects that the objective was to succeed in all tests without getting sick, if possible.

## PROCEDURE

*Subjects.*—Two Navy and two Marine officers who had completed the acrobatic stage of flight training were chosen as subjects. Additional factors influencing selection were their youth, high motivation, good general fitness, good mental discipline and a history of less than average susceptibility to motion sickness.

TABLE I. GENERAL CLINICAL FINDINGS ON EXPERIMENTAL SUBJECTS

| Subj. | Age Ht. (in) Wt. (lbs) | Past Hist. | Gen'l. Fitness | Phy. Exam. B. P. | X-ray Chest | Work ECG* Ht. Rate† | BCG | Blood Morph. Hemat. PBI | Urin. Micro. |
|---|---|---|---|---|---|---|---|---|---|
| LI | 24<br>70.5<br>162 | Pilo-nidal cyst | Ex. | Sys. Mur. G II base<br>126/54 | N-L | N-L<br>58/76 | N-L | N<br>40 | N<br>N |
| MO | 23<br>72<br>153 | Not sig. | Very good | Left varico-cele<br>120/64 | N-L | N-L<br>77/109 | N-L | N<br>45 | N<br>N |
| SH | 22<br>74<br>190 | Not sig. | Ex. | N-L**<br>120/64 | N-L | N-L<br>52/88 | Grade 1 Abnorm. | N<br>42 | N<br>N |
| WI | 21<br>76<br>191 | Low T waves ECG | Ex. | N-L<br>134/78 | N-L | N-L‡<br>68/84 | Too tall for bed | N<br>47<br>4.2 | N<br>N |

*20 inch step up; 20 × per min. for 3 min.
**N=normal; N-L=normal limits.
†Ventricular rates before and immediately after exercise.
‡Basal ECG normal; resting ECG diphasic. $T_2$, $V_5$, $V_6$, inverted $T_3$ fasting-normal.

The general clinical findings of the subjects are summarized in Table I. The systolic murmur in the case of LI was of doubtful pathological significance; the varicocele in the case of MO was not troublesome; the ballistocardiogram in the case of SH revealed normal and abnormal complexes, the latter predominating but their pathological significance was doubtful in the absence of any other cardiovascular abnormality; the T wave alterations in the case of WI led to a thorough cardiovascular evaluation on two different occasions and it was concluded that there was small likelihood that they had pathological significance.

The special findings, mainly referable to the sensory organs of the inner ear, are summarized in Table II.

TABLE II. SPECIAL CLINICAL FINDINGS

| Subject | History of Deafness Otitis, Vertiginous Attacks | Otoscopic Exam R | Otoscopic Exam L | Hearing R | Hearing L | Threshold Caloric Test (°C) R | Threshold Caloric Test (°C) L | Parallel Swing* |
|---|---|---|---|---|---|---|---|---|
| LI | No | N | N | N | N | 36.2 | 36.4 | Normal response |
| MO | No | N | N | N | N | 34.6 | 35.8 | Normal response |
| SH | No | N | N | N | N | 36.2 | 36.4 | Normal response |
| WI | No | N | N | N | N | 36.2 | 36.4 | Normal response |

*This is a measure of otolith function.

The "threshold caloric tests"[8] were conducted with the subject's head so positioned that a line between the tragus and outer canthus was vertical. The ear was irrigated for 40 seconds with 100 cc of water at an outlet-controlled temperature of 36.4° C. Nystagmograms were recorded while the eyes were observed through Frenzel lenses. In the absence of any response the temperature of the water was lowered in 0.2° C steps until nystagmus appeared on the trace. McLeod and Meek[8] found that 95 per cent of 104 normal subjects manifested nystagmus when the irrigating temperature was 35.4° C or higher; hence the value of 34.6° C for the right ear in the case of MO represents, probably, abnormally low sensitivity.

The subjects were evaluated in several ways with regard to susceptibility to motion sickness and the results are summarized in Table III.* The first approach was based on responses to the Rorschach test but scored in an unusual way[9,10] for specific dimensions, viz., anxiety, dependency, drive, hostility and rigidity. The second was based on a lengthy interview emphasizing the "social history" and the reaction of initial exposure to an unusual force environment. Two provocative tests were employed. The first consisted of

*We are indebted to Commander Allen E. McMichael, MSC, USN for the first two evaluations and to Miss Rosalie Ambler for carrying out the vestibular test.

TABLE III. EVALUATION OF SUSCEPTIBILITY TO MOTION SICKNESS IN EXPERIMENTAL SUBJECTS.

| Tests | Subjects: LI | | MO | | SH | | WI | |
|---|---|---|---|---|---|---|---|---|
| Rorschach | Rank | Score | Rank | Score | Rank | Score | Rank | Score |
| Anxiety | 2.5 | +2 | 1.0 | +3 | 2.5 | +2 | 4.5 | +1 |
| Dependency | 4.5 | 0 | 4.5 | 0 | 2.0 | +3 | 3.0 | +2 |
| Drive | 3.0 | 0 | 3.0 | 0 | 3.0 | 0 | 3.0 | 0 |
| Hostility | 5.0 | —2 | 1.5 | +3 | 1.5 | +3 | 3.0 | +1 |
| Rigidity | 1.5 | +2 | 4.0 | +1 | 4.0 | +1 | 4.0 | +1 |
| Over-all | 5.0 | +2 | 2.0 | +7 | 1.0 | +9 | 4.0 | +3 |
| Interview | | | | | | | | |
| Age at reaction | 4 or 5 | | 8 or 9 | | — | | — | |
| Type of reaction | Sick | | Nausea | | None | | None | |
| Place of reaction | Car | | Ocean | | — | | — | |
| Over-all susc. rank order | 2 | | 1* | | 3 | | 4 | |
| Vestibular Test | | | | | | | | |
| Over-all score | 46 | | 58 | | 53 | | 36 | |
| Rank order | 3 | | 1* | | 2 | | 4 | |
| Acrobatics | | | | | | | | |
| Motion sickness | Nil | | Nil | | Nil | | Nil | |

*Most susceptible.

a brief exposure to "Coriolis vestibular stimulation"[11] and the second test, which was probably equivalent to a standardized pattern of acrobatics designed to induce motion sickness[6] consisted of the acrobatic stage of flight training.

It was concluded that all four subjects were less susceptible than the average person to motion sickness. Only two had a history of motion sickness and this was limited to a single instance. All were insusceptible to airsickness but significant differences were revealed in the vestibular test

## APPARATUS AND METHODS

The Pensacola Slow Rotation Room (SRR), described in an earlier report,[1] was used in this experiment. It is a multisided windowless room about 15 feet in diameter and 7 feet high with a nearly square (15¾" x 12½") center post. The motive power is supplied by a gas burning engine geared to a rubber-tired wheel in contact with the driving band of a flywheel to which the superstructure (SRR) could be clutched or unclutched. Slip rings provided the means of transmitting power and electrical signals. The room contained laboratory equipment and living facilities. Despite the crowded conditions there was room to provide for relatively comfortable bunking, recreation (including television) and exercise. Particular attention was given to creature comforts, including the preparation of foods to suit individual tastes.

At the angular velocity of 10 RPM the centripetal force generated at different radii and the deviation of the gravitoinertial upright from the visual upright (direction of gravity) are given in Table IV. This was the force environment to which the subject was exposed when motionless. Movements of the subject resulted in changes in the force environment caused in part by the generation of inertial forces and in part by variations in the level of centripetal force with changing distance from the center of rotation. Linear motions generated Coriolis forces and rotary motions gyroscopic forces. The former, which would affect the direction and magnitude of the resultant linear force vector (gravitoinertial upright), were not large; a few "instantaneous" values are given in Table IV. Gyroscopic forces generated by simultaneous rotations about two axes were extremely small and are significant only when discussing rotary motions of the head and stimulation of the semicircular canals.

TABLE IV. CERTAIN PARAMETERS OF THE FORCE ENVIRONMENT IN THE SLOW ROTATION ROOM WITH AN ANGULAR VELOCITY OF 10 RPM

| Radius in ft. | Centripetal Force (G units) | Gravito-Inertial Force (G units) | Gravito-Inertial Upright (angle Φ) | Coriolis force in % of centripetal force** with man walking at: 1 ft./sec. | 2 ft./sec. |
|---|---|---|---|---|---|
| 2 | .0682 | 1.0021 | 3°54" | 95.4% | 190.9% |
| 3 | .1023 | 1.0050 | 5°50" | 63.6% | 127.2% |
| 4 | .1364 | 1.0092 | 7°46" | 47.7% | 95.4% |
| 5 | .1705 | 1.0144 | 9°41" | 38.1% | 76.2% |
| 5.5 | .1876 | 1.0179 | 10°37" | 34.7% | 69.4% |
| 6 | .2046 | 1.0207 | 11°34" | 31.8% | 63.6% |
| 7 | .2387 | 1.0281 | 13°26" | 27.3% | 54.5% |

**This would be "in % of apparent weight" in an orbiting rotating spacecraft.

The changes in the total force environment caused by the motions of the subject were incredibly complex. They were not measured but an estimate of their principal effects was obtained in terms of the subject's movements. It was convenient to distinguish between two types of motions of the subject even though they were not always separate, namely, rotary movements of the head out of the plane of rotation of the room (head movements) and movements of the body which affected the linear force vector (body movements).

The head movements resulted in unusual or bizarre stimulations of the semicircular canals and were the essential factor in causing canal sickness, although additional etiological factors also were operating. The number of these head movements depended on voluntary restriction, imposed by the subject, and activities with which the subjects were inescapably associated. Each subject was fitted with a modified orthopedic collar which when worn greatly minimized head tilt with reference to the thorax.

Body movements were associated with changes in the linear force vectors, and the disposition of the laboratory equipment and living facilities was such that the subjects carried out most of their activities in a zone varying in radius from 2.0 to 5.5 feet (Table IV). These changes increased the difficulty in maintaining postural equilibrium, thereby adding to the muscular work which was also augmented by the increased gravitoinertial force. In the absence of head movements this was not an important factor in causing canal sickness.

Although the lack of precise measurements of the force environment was a handicap, nevertheless past experience revealed that the movements of subjects, unless restricted, tended to be sufficiently constant so that the severity of symptoms was directly related to the velocity of rotation.[1,2] Thus if deviations from the usual pattern of activities are noted a rough measure of the change in stressful stimuli is afforded. Nearly always this was estimated in terms of restriction in head or body movements.

The methods used in studying the time-course of responses to stress are conveniently, though somewhat arbitrarily, grouped under three headings: clinical symptoms and signs, clinical laboratory findings and psychophysiological measurements. Here only a general description will be given; the necessary details will be added below when discussing specific tests.

A record was kept of body weight, oral temperature, pulse rate and blood pressure. Each subject kept his own log in which he described his changing subjective symptomatology. The onboard experimenter kept a record of the significant manifestations of canal sickness in each subject and their overt behavior in terms of daily activities and interpersonal relations. Moreover, he recorded his own experiences, which were of particular interest in that he was active during the brief periods when the room had to be stopped for experimenters to go on board and off; in other words, he was intermittently adapting to stationary and rotating conditions. Electrocardiograms were obtained and tilt tests conducted throughout the entire experiment. In measuring adaptation during rotation much reliance was placed on the Coriolis oculogyral illusion[5] and the "walking test."[12] Pre- and postrotation tests included the Graybiel-Fregly Posture Test[13] and the nystagmic response to head movements while the subjects were rotated clockwise and counterclockwise at 10 RPM, utilizing the Stille-Werner chair. Three visual tests were included: critical flicker fusion, visual fields and ocular imbalance.

Biochemical measurements were designed to study water balance, acid-base balance, intestinal absorption, excretion of electrolytes, release of stress hormones, glucose metabolism and changes in certain serum enzymes. The basic composition of the diet was about the same for each man for each day, with fluids recorded as taken. The conditions of the experiment precluded weighing of individual portions; however, these were estimated as closely as possible. All excreta, including feces, urine and vomitus, were collected. The period of collection extended from 0800 one day through 0800 the following. There were four urine collection periods: 0800-1300, 1300-1800, 1800-2300 and 2300-0800. Collections began three entire days prior to rotation. Fasting blood specimens were collected at 0900 each day of sampling. All of the chemical measurements were made on the plasma.

Performance measures included hand dynamometry, spoke test (eye-hand coordination), tracking test, speed of tapping, reaction time, time estimation, digit span, complex counting task, reading and mathematics tests and four "vigilance" tests.

*Routine*—The experiment fell naturally into three periods, namely, prerotation, perrotation, and postrotation. The "day" extended from 0900 to 0900. When necessary to avoid confusion three designations are used: From 0900 to 0900 is termed the "entire day," from 0900 to 2400 "Day 1" and from 2400 to 0900 "end of Day 1." The prerotation period was approximately four days which are numbered backward minus four (−4) through minus one (−1). This was a period for practice and for obtaining baseline measurements. The latter were obtained mainly on Day −2 and −1 when the four subjects and the onboard experimenter remained in the SRR. The perrotation period was 12 days, numbered 1-12. At 0900 on the morning of Day 1, after the final prerotation tests were completed, the room was set in motion at 10 RPM and, except for three short stops daily, continued to rotate for the 12 days. During the stops the subjects sat with their heads fixed in order not to lose their adaptation. The daily schedule of events was as follows: 0745, awakened; 0800, brief stop to take experimenters aboard; 0900, stop; experimenters offboarded; 0905, light breakfast; 0910, morning testing program; 1130, brunch and relaxation; 1230, afternoon testing program; 1600, begin "free" period; 1820, stop for evening specimens; 1830, dinner; 2030, begin night watch.

The postrotation period began at 0900 on Day +1. On cessation of rotation certain tests were conducted outside the SRR after which the subjects returned to and remained in the room for two days.

## RESULTS

### Clinical Symptoms and Signs

With the sudden onset of rotation all of the subjects immediately experienced difficulty in walking and in carrying out tasks involving bodily movements. The full impact was not felt at once, typical symptoms of canal sickness appearing only after a delay.

LI experienced only mild symptoms referable to the nausea syndrome, probably due in large part to the great restriction of head movements which he imposed from the early minutes of the run. He did not vomit but lost two pounds during Day 1 because of nausea and consequent food and fluid restriction. He slept at every opportunity during Days 1 and 2 and fell asleep during his "watch" on end of Day 1. He regained his appetite on Day 3.

MO was the first to become sick and in retrospect he said that he wished he had restricted his head movements earlier than he did. The first of his eight vomiting episodes occurred within 35 minutes and the last during the evening of Day 2. He carried out the performance tests but minimized all other activities. There was a weight loss of six pounds during Days 1 and 2 which was regained by Day 8. He discarded the head brace on Day 3 and that evening his appetite had returned. Thereafter he did not restrict his head movements but continued to restrict body movements.

SH experienced typical symptoms of canal sickness within the first hour and vomited once the afternoon of Day 1. He wore the brace on Day 1, restricted head movements through Day 2 and his appetite returned by the evening of Day 3. There was a weight loss of three pounds which was regained by Day 4.

WI experienced slight nausea and this was limited to the first three hours. He did not wear the brace but restricted head movements through Day 2. He was the only one of the four subjects to gain weight during the early perrotation period; he gained two pounds during Days 1 and 2 but lost one pound during Days 3 and 4.

Even after symptoms of nausea and anorexia disappeared and no further head restrictions were enforced all of the subjects continued to experience drowsiness and fatigue and to restrict their physical activity which in turn minimized their head movements. LI had his "first real desire" to work on Day 5. During the remainder of the run he continued to nap occasionally during leisure periods and complained in the morning of excessive drowsiness and fatigue, even after eight or nine hours of sleep. The feelings of drowsiness and fatigue in MO, although less prominent after Day 4, persisted throughout the run. On Day 6 he "exercised a little" for the first time but his comment on Day 7 was "tired again, feel normal though." Leisure time was occupied either with activities that required little mental effort or by resting or sleeping. SH had "no desire to work" on Day 4 and slept during the late afternoon and evening of Day 5. On Day 6 he was in "good spirits" and his first desire to exercise was satisfied with "a few push-ups." With the exception of Day 8 his log contained references to fatigue, such as "very tired at end of the day" (Day 11) and "very tired despite more sleep" on the morning of Day 12. WI found it "difficult to stay awake" on Day 2, was "tired and sleepy" on Day 3, had a "good day" although "no desire to work" on Day 4. He complained of fatigue on Days 5 and 6 and on Day 10 stated "typical day, the tests are becoming tiresome and fatigue is a big problem."

None of the subjects had fully adapted to the experimental conditions by the end of Day 12. The common complaint was "fatigue" and although they were carrying out all of their assignments the employment of their free time was directed toward rest and relaxation rather than toward things which required mental alertness or physical work. MO complained most and WI least but the differences between the subjects were not pronounced.

Cessation of rotation created an impact but far less than at the start of rotation. The immediate effect was on neuromuscular coordination and was evidenced by ataxia which diminished rapidly during the first hour or two. Additional symptoms were mainly a mixture of excitement and pleasure on stopping and residual perrotation effects. None complained of nausea although SH experienced "stomach awareness" which usually precedes frank nausea. SH also complained of slight lightheadedness and was "very tired" in the evening of Day + 1. MO was "impressed" with the effects on coordination but adaptation was "quicker than expected." Additional comments were "not at all tired" and "we made the news." WI reported "no ill effects" and "after about one hour I could walk straight without difficulty."

*Cardiovascular Measurements*—The values for pulse rate and blood pressure obtained while the subjects were recumbent did not change significantly throughout the entire experiment. The maximum changes in

TABLE V. MAXIMUM CHANGES IN PULSE RATE AND BLOOD PRESSURE VALUES ON ASSUMING TILT POSITION

| SUBJ. | | | DAY | —2 | —1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 11 | 12 | † |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| LI | PULSE RATES | | SUPINE | 66 | 60 | 66 | 60 | 66 | 66 | 66 | 72 | 72 | 66 | 72 | 66 | 66 |
| | | | TILT | 78 | 84 | 84 | 84 | 96 | 96 | 96 | 96 | 100 | 84 | 96 | 90 | 96 |
| | | | △ | +12 | +24 | +18 | +24 | +30 | +30 | +30 | +24 | +28 | +18 | +24 | +24 | +30 |
| MO | | | SUPINE | 78 | 60 | | | 72 | 84 | 72 | 78 | 78 | 72 | 72 | 72 | 78 |
| | | | TILT | 90 | 96 | | | 114 | 108 | 102 | 90 | 102 | 84 | 102 | 102 | 84 |
| | | | △ | +22 | +36 | | | +42 | +24 | +30 | +12 | +24 | +12 | +30 | +30 | + 6 |
| SH | | | SUPINE | 60 | 54 | | 60 | 60 | 60 | 60 | 70 | 66 | 78 | 66 | 78 | 72 |
| | | | TILT | 90 | 70 | | 84 | 96 | 90 | 96 | 102 | 102 | 108 | 114 | 126 | 84 |
| | | | △ | +30 | +16 | | +24 | +36 | +30 | +36 | +32 | +36 | +30 | +48 | +48 | +12 |
| WI | | | SUPINE | 72 | 60 | 60 | 54 | 66 | 66 | 57 | 60 | 66 | 60 | 72 | 72 | 66 |
| | | | TILT | 96 | 90 | 84 | 90 | 96 | 90 | 90 | 96 | 102 | 96 | 102 | 102 | 108 |
| | | | △ | +24 | +30 | +24 | +36 | +30 | +24 | +33 | +36 | +36 | +36 | +30 | +30 | +40 |
| MEAN | | | △ | +22 | +26 | +21* | +28** | +36 | +27 | +35 | +28 | +29 | +24 | +43 | +43 | +24 |
| LI | BLOOD PRESSURES | Syst. | S | 110 | | 117 | 121 | 112 | 115 | 130 | 125 | 112 | 128 | 124 | 110 | 122 |
| | | | △T | —20 | | +27 | + 6 | —10 | —21 | —22 | —17 | +14 | —28 | —16 | —10 | —10 |
| | | Diast. | S | 66 | | 49 | 70 | 60 | 70 | 78 | 74 | 60 | 75 | 68 | 60 | 64 |
| | | | △T | + 6 | | +29 | —22 | —10 | —12 | —25 | —13 | +16 | —27 | —20 | —14 | + 6 |
| MO | | Syst. | S | | 100 | | | 113 | 114 | 125 | 119 | 113 | 109 | 112 | 106 | |
| | | | △T | | — 8 | | | —17 | —16 | —23 | —23 | +11 | + 5 | —22 | —16 | |
| | | Diast. | S | | 70 | | | 83 | 75 | 90 | 81 | 78 | 70 | 70 | 76 | |
| | | | △T | | +10 | | | + 7 | +15 | —16 | + 9 | +12 | +10 | —12 | — 8 | |
| SH | | Syst. | S | 126 | | | 126 | 117 | 124 | 130 | 126 | 127 | 135 | 138 | 129 | 121 |
| | | | △T | —14 | | | —16 | —19 | — 4 | —20 | —23 | —21 | —35 | —22 | —19 | — 9 |
| | | Diast. | S | 84 | | | 87 | 79 | 77 | 85 | 80 | 87 | 82 | 85 | 82 | 79 |
| | | | △T | +20 | | | — 9 | — 9 | +25 | + 7 | + 6 | —11 | —14 | —15 | + 8 | +15 |
| WI | | Syst. | S | | 120 | 117 | 114 | 124 | 120 | 130 | 116 | 140 | 127 | 133 | 127 | 120 |
| | | | △T | | —17 | —25 | +14 | + 4 | —16 | —14 | — 4 | —34 | —21 | —23 | —27 | —10 |
| | | Diast. | S | | 78 | 78 | 79 | 76 | 76 | 90 | 77 | 65 | 76 | 82 | 81 | 72 |
| | | | △T | | +14 | +24 | +11 | +22 | +20 | +12 | +19 | + 1 | +18 | —12 | — 9 | +18 |
| MEAN △ | | Syst. | TILT | | +25 | +53 | —20 | +10 | +58 | —22 | +21 | +18 | —13 | —69 | —23 | +39 |
| MEAN △ | | Diast. | TILT | | +13 | +27 | — 7 | + 3 | +27 | — 6 | + 5 | + 5 | — 3 | —17 | — 6 | +10 |

*Mean of 2, **Mean of 3, †Days 1 and 2 combined.

these values on actively assuming a position of tilt 15 degrees from the upright are given in Table V. With regard to pulse rate every subject manifested a significant increase (>10 beats) on every test throughout the entire experimental period. In only three instances, however, were the increases significantly greater during the per- or postrotation periods when compared with the maximal increase on either Day –2 or Day –1, SH on Days 11 and 12 and WI on Day + 1.

Systolic blood pressure dropped in the single test carried out on each subject before rotation and in three of the four the drop was significant, i.e., greater than 10 mm Hg. During rotation increases as well as decreases were observed. All of the increases were meaningful; they occurred on Day 1 (LI), Days 7 and 8 (MO) and Days 2 and 3 (WI). Most of the decreases were salient ones but in only six instances were they significantly greater during than before rotation and all occurred on or after Day 5.

Diastolic blood pressure increased in the single test carried out before rotation and the increase was important in three of the four subjects; similar changes were observed on Day +1 in the three subjects on whom measurements were made. During rotation both increases and decreases in diastolic pressure were noted. Most of the significant increases occurred early and the decreases late in the perrotation period but there were enough exceptions to minimize the significance of this trend. During rotation, when comparison is made with prerotation periods, there were only five instances in which there was either a concomitant significant rise in pulse rate and a significant fall in systolic or diastolic pressure or a concomitant fall in both systolic and diastolic pressures, all occurring on or after Day 5.

A standard 12-lead electrocardiogram was taken each day during the experiment and there were no significant changes when compared with the control tracings. Electrocardiograms (Lead 2) obtained supine and during tilt-up revealed only minor changes in addition to variations in heart rate. All four subjects demonstrated an increase in P wave on assuming the upright position and this was present on all tracings before, during and after the rotation. The maximum T wave changes are shown in Table VI. Subjects LI, MO and SH demonstrated a decrease in T wave amplitude of 1.5 mm in Lead 2 during the tilt test. This finding was present during the control test as well as during the entire perrotation period. Subject WI showed the most striking changes during the tilt test, his ECG having S-T segment depression of 0.5 to 1.0 mm and negative T waves, but these changes were present before rotation and did not change perrotation. R wave amplitude was included to evaluate relative as well as absolute changes in the T wave.

*Tests of Postural Equilibrium and Ataxia*—These fell into two categories: the regular test battery used in comparative measurements before and after rotation and a modified version for use under the restrictions imposed in the SRR.

Two tests were carried out daily in the perrotation period. In the first test the subject was required to stand heel-to-toe with eyes closed and arms folded in front of him for sixty seconds, for two trials. If the sixty-second criterion was not met a third trial was given and the score was the best of three (with a maximum of 120). In the second test the subject was required to walk five steps heel-to-toe (without deviating from the line on the floor) from the wall to the center column with arms folded for two trials. If he did not complete five steps on each trial (score of 10) a third trial was given and the score was the best two of three.

The scores for "walking" are summarized in Figure 1. All of the subjects were able to achieve a maximum score prior to rotation. On Day 1 there was a decrement in performance but the subjects improved on Day 2 and Day 3 and all were able to achieve a maximum score by the fourth day of rotation.

The Graybiel-Fregly postural equilibrium tests administered on Day –7 and Day +3 were (1) walking with eyes open on a ¾″ wide rail (8′ long), (2) standing with eyes open on the ¾″ wide rail and (3) standing with eyes closed on a 2¼″ wide rail (30″ long). The

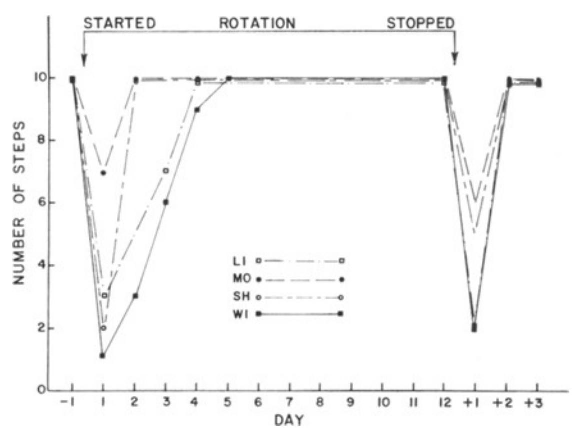


Fig. 1. Heel-to-toe walking scores for four subjects.

TABLE VI. MAXIMUM T WAVE CHANGES

| Subj. | AMP of T (mm) | Day –2 | –1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 11 | 12 | +1 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| LI | SUP. | 4.5 | 5 | 4.5 | 3 | 4 | 4 | 4.5 | 4 | 4 | 3.5 | 4 | 3.5 | 4 |
| | TILT | 3 | 3 | 3 | 2 | 2.5 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| MO | SUP. | 6 | 5 | | | 5 | 3.5 | 4 | 4 | 2 | 4 | 4 | 4 | 4 |
| | TILT | 4 | 2.5 | | | 1.5 | 2 | 2 | 2.5 | 2 | 1.5 | 1 | 1.5 | 2 |
| SH | SUP. | 4 | 4.5 | | 4 | 3.5 | 3 | 3.5 | 3 | 3 | 3 | 3 | 3 | 3 |
| | TILT | 2.5 | 3 | | 3 | 2 | 1 | 3 | 2 | 2 | 2 | 2 | 2 | 2 |
| WI | SUP. | .5 | 1.5 | 2 | 1 | .5 | 1 | 1 | 1.5 | .5 | 1 | .5 | .5 | 1 |
| | TILT | –2 | –1.5 | –1.5 | –2 | –2.5 | –2 | –2 | –1.5 | –2 | –1.5 | –1.5 | –1.5 | –1.5 |

TABLE VII. RESULTS OF GRAYBIEL-FREGLY POSTURAL EQUILIBRIUM TEST BEFORE AND AFTER ROTATION

| | Before Rotation | | | | | | After Rotation | | | | | | Rotation Effects | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Subj. | Walking Test | Per Cent* | Stand Eyes Open Test | Per Cent | Stand Eyes Closed Test | Per Cent | Walking Test | Per Cent | Stand Eyes Open Test | Per Cent | Stand Eyes Closed Test | Per Cent | Walk | Stand Open | Stand Closed |
| LI | 11 | 31 | 18 | 27 | 129 | 61 | 11 | 31 | 21 | 36 | 40 | 26 | 0 | + | - |
| MO | 8 | 11 | 21 | 36 | 82 | 46 | 13 | 56 | 38 | 68 | 52 | 32 | + | + | - |
| SH | 10 | 26 | 16 | 20 | 33 | 17 | 13 | 56 | 23 | 45 | 23 | 12 | + | + | - |
| WI | 8 | 11 | 9 | 3 | 14 | 6 | 8 | 11 | 10 | 4 | 14 | 6 | 0 | + | 0 |

* Percentile rank in a distribution of scores on several hundred normal males.

subject was required to stand erect, or nearly erect, with shoes on, arms folded against the chest and feet in heel-to-toe position. The dynamic (walking) test was scored in terms of the number of correct steps and the static (stand) tests were scored in terms of number of seconds without "falling" off the rail. The results of the tests are shown in Table VII. Performance on the walking test was unchanged in two subjects (LI and WI) and improved in two. The Stand Eyes Open Test performance was improved in all four subjects. The Stand Eyes Closed Test Performance was unchanged in one subject (WI) but decreased slightly to markedly in the other three. It should be noted that initially the performance of all of these subjects was at low average or below average on the two visually influenced tests (Walking and Stand Eyes Open) and that two of the subjects scored below average on the nonvisual influenced test (Stand Eyes Closed). The postrotation Stand Eyes Closed Test findings suggest that the subjects had not fully recovered from the effects of exposure in the SRR.

*Coriolis Oculogyral Illusion*—This was elicited by requiring the subject to tilt his head quickly (1.0 - 1.25 sec) toward the shoulder and, after a delay, to return to the upright while fixating the dimly illuminated outline of a box in the dark. The scoring consisted of the subjective perception of apparent movement estimated in inches and the direction of the movement. The results are summarized in Table VIII.

TABLE VIII. MAGNITUDE OF THE CORIOLIS OCULOGYAL ILLUSION

| Day | Subj. | Head Left | Return | Head Right | Return |
|---|---|---|---|---|---|
| 1 | LI | 7 ↑ | 7 ↓ | 9 ↓ | 0 |
| | MO | 2 ↑ | 3 ↓ | 2 ↓ | 2 ↑ |
| | SH | 3 ↑ | 3 ↓ | 3 ↓ | 3 ↑ |
| | WI | 18 ↑ | 18 ↓ | 12 ↓ | 12 ↑ |
| 3 | LI | 12 ↑ | 18 ↓ | 12 ↓ | 0 |
| | MO | 0 | 0 | 0 | 0 |
| | SH | 0 | 0 | 0 | 0 |
| | WI | 0 | 0 | 1 ↓ | 1 ↑ |
| 6 | LI | 0 | 0 | 0 | 0 |
| | MO | 0 | 0 | 0 | 0 |
| | SH | 0 | 0 | 0 | 0 |
| | WI | 0 | 0 | 0 | 0 |
| 10 | LI | 0 | 0 | 0 | 0 |
| | MO | 0 | 0 | 0 | 0 |
| | SH | 0 | 0 | 0 | 0 |
| | WI | 0 | 0 | 0 | 0 |
| +1 | LI | 4 ↑ | 6 ↓ | 3← | 5 ↓ |
| | MO | 2 ↓ | 4 ↑ | 3 ↑ | 4 ↓ |
| | SH | 0 | 0*→ | 0 | 0 |
| | WI | 6 ↓ | 6 ↑ | 0 | 2 ↑ |

*No apparent displacement—just velocity.

Despite the fact that this illusion is difficult to quantify and that, with continued elicitation it appears to diminish even in one who is not well adapted to a rotational environment, it remains a good indicator of a certain kind of vestibular adaptation.[5] As may be seen in the table, on Day 1 the illusions experienced by LI and WI were of relatively large magnitude and those of MO and SH, relatively small. At the next test period (Day 3) the illusion had disappeared for MO and SH, was negligible for WI but prominent for LI. On Day 6 and Day 10 the illusion was absent for all men.

When the test was repeated after cessation of rotation the stimulus to the canals was angular acceleration in the frontal plane, a normal stimulus, and perception of the illusion was evidence of a conditioned response. The illusion was perceived by all subjects except SH. MO reported almost a perfect reversal, both in terms of magnitude and direction, implying that the perrotation adaptation was in the nature of a compensatory phenomenon.[4,5] LI and WI also reported apparent movement, indicating conditioned responses but not always was movement in the opposite direction.

*Nystagmography*—Rotation tests, with subjects seated upright in a Stille-Werner Chair, were conducted just before and after the twelve-day run. Nystagmus elicited by head movements was recorded during clockwise (CW) and counterclockwise (CCW) rotation of the chair at 10 RPM. Subjects were instructed to carry out silent arithmetic computation throughout each rotation in an effort to induce artificial arousal. The tests after the twelve-day run were given at three different intervals:

(1) Post-Test I. Within the first two hours after the twelve-day run the men exhibited a greatly reduced nystagmus and no subjective reaction to recorded head movements during rotation in the accustomed direction of rotation (CCW); in the unaccustomed direction of rotation (CW), the average nystagmus and subjective reactions elicited by head movements were about the same intensity as they had been prior to the twelve-day period of rotation. In some cases responses during clockwise rotation were greater than their prehabituation counterparts. This was probably attributable to a conditioned compensatory nystagmus which had been detected by static tests given five to 30 minutes after the prolonged rotation.

(2) Post-Test II. Two days after the twelve-day rotation subjects were again given 10 RPM tests on the Stille-Werner chair. In the interim period (about 46 hours) they were not exposed to rotation but participated in other tests which required them to remain

active throughout each normal work day. In the unaccustomed rotation direction, nystagmus elicited by head movements during Post-Test II generally was less than responses to equivalent stimuli in the prehabituation tests, and it was also less than that elicited during Post-Test I. In the accustomed rotation direction nystagmus had recovered, although not to its initial level. Reports of sensation indicated a similar course. Hence, the accustomed rotation direction still yielded weaker responses, nystagmus, and subjective but the responses to head movements with the two directions of rotation had begun to equalize.

(3) Post-Test III. Three weeks after the habituation run nystagmus output elicited by head movements was nearly equal for the two directions of rotation and was still less than the prehabituation level. Subjects indicated that the subjective effects had returned although comparisons with initial response intensities are obviously difficult due to the length of the intervening time.

Nystagmus produced by the acceleration and deceleration of the Stille-Werner chair showed little or no decline as a result of the twelve-day run. Hence the habituation appeared to be specific to the bizarre vestibular stimulation of the concomitant rotation about two axes.

The amount of nystagmus produced during either the head tilt tests or the passive angular acceleration did not serve as a good indicator of the amount of sickness and apparent discomfort experienced by the four subjects. MO yielded the least nystagmus, yet showed the greatest neurovegetative symptoms. However, the sample of only four subjects is not sufficient to test for the possibility of a low positive correlation between nystagmus output during initial testing and susceptibility to motion sickness.

*Visual Tests*

*Critical Flicker Frequency*—Monocular (right eye) flicker thresholds were determined with a standard CFF measuring device (Ivy-Krasno) in which the test field, viewed against a dark background, subtended a visual angle of approximately 11 minutes of arc. With the use of a method of limits three ascending and three descending thresholds of fusion and flicker, respectively, were determined daily for each subject. The average of these six values served as the indicator of CFF for each day tested (Figure 2). Two of the subjects (MO, SH) revealed a significant decrease in performance relative to initial control levels during the early per-rotation period. This apparent decrement in visual function lasted for about three to four days, after which time a gradual yet complete recovery took place. The other two subjects (LI, WI), on the other hand, who manifested fewer symptoms, had an apparent increase in CFF during the rotational phase of the experiment. Following rotation the CFF level decreased

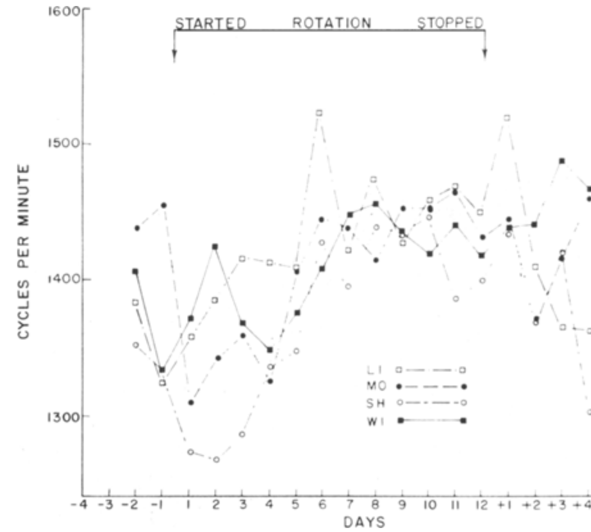


Fig. 2. Critical flicker frequency for four men.

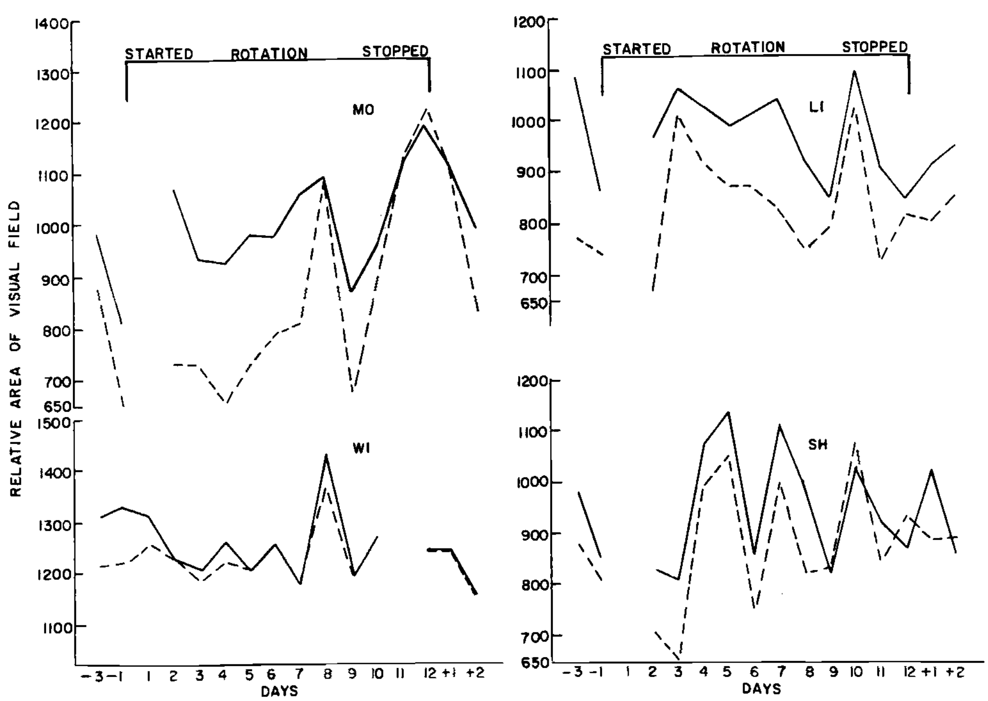


Fig. 3. Peripheral fields for four men.

to its basic prerotational level in subject LI but not in subject WI.

*Visual Fields*—The visual field of the right eye of each subject was explored daily in the classical way, using a meter tangent screen. Detection of a red (2/1000) and blue (2/1000) test-object was recorded in each of four meridians (vertical, horizontal and the two intermediate). The data were plotted on standardized forms and the areas contained within the isopter lines for red and blue were measured with a polar planimeter. The resultant relative areal size served to indicate over-all visual field sensitivity for a given test period.

The results obtained with the red (2/1000) and blue (2/1000) target correlated satisfactorily, indicating that there were no selective visual field changes in the regions tested. In general the average over-all size of the visual field (Figure 3) remained essentially at the same level. Variability on this test appeared to be directly related to the symptomatology of motion sickness; i.e., the subjects who exhibited the most symptoms (viz., 8 and 1 vomiting episode, respectively) had the greatest fluctuations.

*Eye Muscle Imbalance*—The near (40 cm.) heterophoria of each subject was determined daily by a modified von Graefe technique. The stimulus to accommodation was controlled by requiring the subject to resolve a vertical row of 20/20 Snellen letters while he aligned vertically the double image of this target. The surroundings of the target were free from fusional cues. Fixation of the head using a dental bite device prevented any movement. As revealed in Figure 4, there

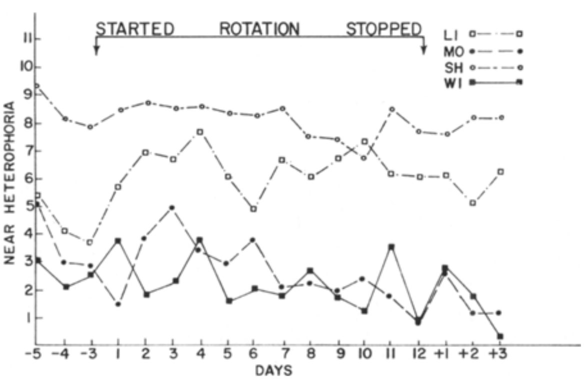


Fig. 4. Muscle imbalance for four men.

were slight day-to-day fluctuations in the latent deviation manifested by each subject. These variations were not unexpected; the important general finding is that there were only small changes in magnitude (and therefore direction) of the habitual muscle imbalance as a result of prolonged rotational stimulation.

*Discussion of Clinical Findings*—Three major periods were distinguishable in terms of the manifestations of stress: (1) the early perrotation period characterized by ataxia and the nausea syndrome, (2) the late perrotation period characterized by the fatigue syndrome and (3) the postrotation period characterized by ataxia. In addition, it is sometimes convenient to distinguish the periods immediately associated with the onset and cessation of rotation.

The sudden transition from the stationary to the rotating environment had an immediate and maximal impact on bodily activities involving neuromuscular coordination. This was emphasized by the initial period of freedom from canal sickness which encouraged all except LI to move about until voluntary restrictions were imposed. At that point all of the subjects were handicapped in varying degrees either because of canal sickness or the self-imposed restrictions in bodily movements, or both. The cardinal symptoms were nausea, drowsiness and salivation, although additional complaints included dizziness, headache, sweating, anorexia and general discomfort and fatigue. The time-course of summation and adaptation effects with regard to the nausea syndrome differed for each subject. It should be pointed out that while "subject-paced" stimulation is advantageous in terms of preventing symptoms, the "feed back control" is not perfect in the case of nausea which is characterized by a build-up that involves second order effects.

The subjects' rankings in terms of increasing severity of symptoms were WI, LI, SH, and MO. Their ranking in terms of susceptibility was complicated by the fact that the number of head movements, the essential stimulus, differed. MO and WI represented the two wide extremes in susceptibility and LI and SH fell in between. The vestibular test, which was a brief performance test, had the best predictive value. Acrobatics, something to which they were accustomed, did not discriminate among the four subjects. The interview was not very helpful in that only two had a history of motion sickness and there was only one episode in each case. The anxiety dimension in the Rorschach evaluation was the only item which ranked the subjects satisfactorily. It is worth noting that the slight depression of the right semicircular canal response indicated by the caloric test did not confer any benefit on MO.

With the disappearance of certain symptoms, particularly nausea, the subjects cautiously increased their "head movements," which marked the end of the early phase of adaptation. The symptomatology of motion sickness in general is so often dominated by the nausea syndrome that not only its disappearance but also concern over its reappearance seemed an important landmark in adaptation to the rotating environment; consequently, for descriptive purposes this period was given a special designation. It is necessary to point out that, except for a short time immediately after onset of rotation, this period was also characterized by physical inactivity which affected a number of physiological and psychophysiological parameters.

The lifting of restrictions on head movements increased the bizarre stimulation to the semicircular canals. This "increase" involved *number* of stimuli or movements and, insofar as this increase affected velocity of head movement, it was equivalent to increasing the RPM of the room, i.e., intensity of stimulation. Head movements associated with bodily movements were still reduced because the latter were restricted. The reason for this restriction was the apathy, drowsiness and fatigue which characterized the subjective symptomatology. These symptoms were present in the early perrotation period but were overshadowed by the nausea syndrome. This suggests that they were not simply the result of confinement and boredom. With increasing length of exposure the total stimulus situation was complicated by the time-dependent cumulative effects of boredom and confinement as well as those of the force environment. In retrospect it is unfortunate the experiment was not continued until the men either were fully adapted or had demonstrated in what respects they would not fully adapt. Their best day was the last, Day 12, although the anticipation of return to a stationary environment may have been a factor.

The total clinical picture was complicated by the residual effects both of long confinement and perrotation stress. In general the symptoms appearing after cessation of rotation were neither severe nor long-lived and constituted an elegant demonstration of our habituation to the stationary environment.

The only positive cardiovascular findings were the alterations in pulse rate and blood pressure manifested during the tilt test. It is important to emphasize two shortcomings in carrying out the test in the SRR; the subject was not passively tilted and the tilt period was only five minutes. The former shortcoming and the fact that the subjects were relatively inactive for at least four days prior to rotation are the only explanations for the unexpectedly large increase in pulse rate and decrease in systolic blood pressure manifested before the onset of rotation. A comparison of these values obtained on Days —1 and +1 reveals surprisingly few significant differences. Allowance must be made for the fact that the tilt test was not carried out during rotation when MO (Days 1 and 2) and SH (Day 1) were sick; this minimizes the significance of group trends on these days. The most significant change was in diastolic blood pressure although the downward trend was erratic. All of the observed instances of mild orthostatic intolerance occurred in the later perrotation period.

The results of the ataxia test carried out in the SRR were clear-cut and were similar to findings in previous experiments.[12] The uniformity of the subjects' rate of adaptation which in all equaled their prerotation level on Day 4 contrasts with their differing rates of adaptation to the nausea syndrome and the oculogyral illusion. Unfortunately the results provide no information regarding either the several etiological factors involved or the mechanisms of adaptation. The findings in the tests carried out before, and three days after, rotation are of interest. The improvement in the scores in tests carried out with "eyes open" might be explained by the fact that "learning" was a more important factor than "residual ataxia." With "eyes closed" the residual ataxia was now a more important factor than learning. Stated differently, the role of vision was very great and only with eyes closed was it possible to demonstrate that postrotation adaptation, in the case of ataxia, was incomplete.

The Coriolis or gyroscopic oculogyral illusion is a unique, immediately evoked response to which subjects readily adapt.[5] They adapt so readily, in fact, that an "order effect" may be demonstrable with successive tests on a single occasion. It is interesting that LI, who greatly minimized head movements, was the only subject who had not adapted by Day 3. The close relationship of the illusion to the nystagmus response is shown in the similarity of the mechanisms underlying adaptation.[4] In both cases in this experiment there was evidence of perrotation adaptation and a conditioned compensatory response, post-rotation.

With regard to the visual tests the only significant changes observed involved the flicker fusion test. In the early perrotation period MO and SH manifested significant temporary decreases in performance and in the late period all except MO demonstrated an increase. The decreases were consistent with the fact that MO and SH experienced more severe symptoms than the other two subjects, and the question arises whether this was a specific response to stimulation of the semicircular canals or a nonspecific effect. Simonson, Fox, and Enzer[14] found that thermal stimulation of the semicircular canal using 5 cc of water at a temperature of 70° to 76° F caused a depression in CFF in sixteen normal subjects and they implied at least that it was a specific effect. Our failure to demonstrate a decrease in CFF in two subjects is readily explicable if the subsequent increases in the later perrotation period are regarded as practice effects which were delayed in their appearance by the depressing effect of vestibular stimulation. It is noteworthy that in the later period increases in performance occurred despite increases in head movements and symptoms of fatigue.

Whatever the explanation for the observed changes in CFF they are of interest in demonstrating the readiness with which CFF can be influenced.

## CLINICAL LABORATORY FINDINGS

*Urine Volume and Electrolytes*—The findings are summarized in Table IX and Figure 5. There were significant individual differences in patterns of urinary output, although in the early perrotation period all subjects showed a decrease followed by an increase and all except possibly SH showed a second decrease in the later period. No other observations on urine, in-

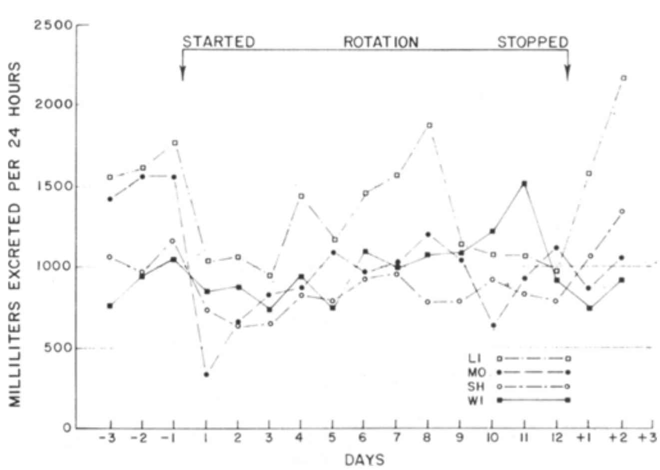


Fig. 5. Urine volume—twenty-four hours—for four men.

cluding specific gravity, PH and total solids, reflected any variations not accounted for merely by changes in volume per collection period.

The changes in urinary excretion of sodium, potassium and chloride during each collection period were essentially parallel for all four subjects as shown in Table IX. The changes in excretion of sodium were greatest (Figure 6) and reflect the greater severity of symptoms in MO and SH. Urinary calcium and phosphate excretion varied throughout the experiment with a clear tendency toward a decrease in excretion associated with nausea and vomiting.

*Microscopic Examination of Blood*—Hematocrit determinations and blood findings are shown in Table X. Hematocrit values varied within a narrow range. There were no significant variations in the WBC counts, although mean value was lowest on Day 4. A tendency toward a decrease in lymphocytes was manifested in the case of MO.

*Total Protein and Acid-Base Values*—Total protein was determined using the refractive index method and the results are shown in Table XI. None of the variations throughout the experiment were significant.

Serum pH was measured on venous blood using the Beckman pH electrode. Nearly all of the values were consistently in the low normal range (normal 7.36-7.46) or slightly below. The fact that distinct patterns did not emerge suggests technical difficulties.

TABLE IX. URINE-EXCRETION OF IONS

| Determination | Subj. | —3 | —2 | —1 | * | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | * | +1 | +2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Day of Experiment | | | | | | | | | | | |
| Volume (mc) | LI | 1573 | 1605 | 1787 | | 1020 | 1068 | 957 | 1443 | 1178 | 1485 | 1565 | 1895 | 1137 | 1075 | 1071 | 988 | | 1585 | 2180 |
| | MO | 1426 | 1590 | 1570 | | 325 | 675 | 812 | 865 | 1100 | 985 | 1010 | 1202 | 1063 | 613 | 945 | 1110 | | 863 | 1078 |
| | SH | 1038 | 987 | 1192 | | 765 | 618 | 633 | 825 | 795 | 937 | 969 | 788 | 797 | 931 | 818 | 796 | | 1086 | 1445 |
| | WI | 780 | 985 | 1015 | | 820 | 882 | 720 | 950 | 784 | 1100 | 1010 | 1097 | 1093 | 1202 | 1528 | 907 | | 735 | 910 |
| | | | | | Mean | | | | | | | | | | | | | Mean | | |
| Sodium MEq/24 hr | LI | 239 | 209 | 210 | 219 | 138 | 190 | 113 | 129 | 126 | 158 | 97 | 219 | ...... | 136 | 155 | 173 | 149 | 421 | 227 |
| | MO | 166 | 270 | 177 | 204 | 41 | 32 | 61 | 61 | 174 | 112 | 119 | 165 | 140 | 161 | 208 | 201 | 123 | 137 | 149 |
| | SH | 147 | 168 | 194 | 170 | 63 | 55 | 75 | 119 | 96 | 171 | 143 | 116 | 131 | 190 | 165 | 163 | 124 | 262 | 155 |
| | WI | 115 | 192 | 189 | 165 | 149 | 186 | 120 | 159 | 153 | 189 | 181 | 168 | 168 | 179 | 203 | 120 | 165 | 138 | 153 |
| Potassium MEq/24 hr | LI | 82 | 110 | 93 | 95 | 100 | 85 | 65 | 93 | 95 | 87 | 66 | 133 | ...... | 95 | 89 | 99 | 92 | 136 | 83 |
| | MO | 44 | 86 | 109 | 80 | 41 | 46 | 61 | 54 | 91 | 80 | 64 | 71 | 73 | 95 | 79 | 94 | 71 | 70 | 60 |
| | SH | 60 | 69 | 80 | 70 | 74 | 31 | 47 | 61 | 66 | 83 | 67 | 60 | 68 | 88 | 70 | 79 | 66 | 91 | 79 |
| | WI | 53 | 82 | 98 | 78 | 87 | 74 | 63 | 69 | 85 | 71 | 61 | 65 | 69 | 70 | 84 | 77 | 73 | 40 | 64 |
| Chloride MEq/24 hr | LI | 207 | 159 | 218 | 195 | 137 | 186 | 130 | 138 | 148 | 140 | ...... | 163 | ...... | 127 | 166 | 152 | 149 | 150 | 305 |
| | MO | 155 | 237 | 157 | 183 | 54 | 45 | 74 | 50 | 140 | 120 | 108 | 167 | 129 | 166 | 206 | 169 | 119 | 122 | ...... |
| | SH | 174 | 177 | 192 | 181 | 85 | 50 | 74 | 122 | 117 | 162 | 122 | 118 | 125 | 149 | 164 | 125 | 118 | 189 | 197 |
| | WI | 139 | 165 | 216 | 173 | 146 | 153 | 125 | 168 | 156 | 183 | 166 | 154 | 166 | 153 | 196 | 129 | 158 | 123 | 145 |
| Calcium MEq/24 hr | LI | 5.9 | 7.6 | 7.5 | 7.0 | 7.8 | 7.9 | 7.8 | 7.6 | 4.9 | 6.7 | ...... | 10.7 | ...... | 9.1 | 9.5 | 7.5 | 8.0 | 10.6 | 11.0 |
| | MO | 10.1 | 8.6 | 8.9 | 9.2 | 0.8 | 12.1 | 8.3 | 8.2 | 6.2 | 6.4 | 10.3 | 10.7 | 9.1 | 9.4 | 8.3 | 9.3 | 8.3 | 12.3 | ...... |
| | SH | 2.2 | 3.2 | 3.4 | 2.9 | 2.6 | 6.2 | 4.3 | 7.6 | 3.2 | 6.8 | 7.1 | 6.5 | 7.7 | 9.5 | 9.0 | 6.5 | 6.4 | 7.1 | 9.6 |
| | WI | 7.0 | 7.8 | 9.1 | 8.0 | 7.8 | 8.1 | 9.2 | 12.4 | 6.6 | 11.1 | 16.2 | 14.2 | 8.7 | 9.1 | 11.7 | 7.5 | 10.2 | 7.6 | 9.3 |
| Phosphate mg/24 hr | LI | 105 | 94 | 115 | 105 | 110 | 125 | 116 | 118 | 81 | 103 | ...... | 91 | ...... | 140 | 110 | 95 | 109 | 122 | 173 |
| | MO | 102 | 112 | 108 | 107 | 25 | 115 | 63 | 84 | 74 | 75 | 90 | 95 | 106 | 112 | 90 | 117 | 87 | 101 | ...... |
| | SH | 113 | 150 | 110 | 124 | 105 | 74 | 102 | 124 | 79 | 123 | 122 | 94 | 125 | 120 | 96 | 86 | 104 | 87 | 193 |
| | WI | 103 | 130 | 120 | 118 | 103 | 110 | 105 | 130 | 84 | 108 | 127 | 125 | 116 | 128 | 154 | 104 | 116 | 90 | 112 |

The "phosphate" excretion must be expressed as phosphorus in mg per day with the last digit left off. Normal excretion is 1000 to 2000 mg per day, mean 1100.

TABLE X. HEMATOCRIT DETERMINATIONS AND MICROSCOPIC EXAMINATION OF BLOOD

| Day | Hct. | WBC | Neu. | Lymphs | Eos. | Basos | Bands | Monos. | Hct. | WBC | Neu. | Lymphs | Eos. | Basos | Bands | Monos |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Subject LI | | | | | | | | Subject MO | | | | | |
| -1 | 45 | 10,100 | 62 | 32 | 0 | 1 | 0 | 5 | 45 | 8,600 | 62 | 80 | 0 | 1 | 0 | 0 |
| 1 | 44 | 11,200 | 70 | 25 | 2 | 0 | 0 | 3 | 46 | 8,200 | 67 | 31 | 0 | 0 | 0 | 2 |
| 2 | 45 | 10,100 | 78 | 20 | 0 | 0 | 0 | 2 | 45 | 6,800 | 70 | 25 | 2 | 0 | 0 | 3 |
| 4 | 44 | 7,800 | 64 | 34 | 1 | 0 | 0 | 1 | 43 | 7,200 | 78 | 18 | 2 | 0 | 0 | 2 |
| 7 | 43 | 9,900 | 55 | 38 | 2 | 0 | 0 | 5 | 41 | 8,700 | 67 | 25 | 3 | 0 | 1 | 4 |
| 11 | 45 | 11,700 | 65 | 24 | 4 | 1 | 0 | 6 | 49 | 7,600 | 75 | 23 | 0 | 0 | 0 | 2 |
| 12 | 44 | 9,700 | 61 | 35 | 1 | 0 | 0 | 3 | 45 | 9,400 | 66 | 29 | 2 | 0 | 0 | 3 |
| +1 | 45 | 6,500 | 54 | 38 | 4 | 0 | 0 | 4 | 43 | 12,300 | 54 | 41 | 5 | 0 | 0 | 0 |
| +2 | 45 | 9,300 | 66 | 29 | 2 | 0 | 0 | 3 | 49 | 5,800 | 50 | 42 | 3 | 0 | 0 | 5 |
| | | | Subject SH | | | | | | | | Subject WI | | | | | |
| -1 | 44 | 9,300 | 70 | 25 | 1 | 0 | 1 | 3 | 44 | 6,900 | 73 | 23 | 2 | 0 | 0 | 2 |
| 1 | 44 | 6,000 | 62 | 33 | 2 | 1 | 0 | 2 | 43 | 8,300 | 59 | 37 | 3 | 0 | 0 | 1 |
| 2 | | 6,100 | 41 | 52 | 4 | 0 | 0 | 3 | 41 | 9,000 | 60 | 34 | 3 | 0 | 0 | 3 |
| 4 | 39 | 5,600 | 57 | 37 | 1 | 0 | 1 | 4 | 43 | 6,400 | 59 | 34 | 4 | 0 | 0 | 3 |
| 7 | 42 | 8,900 | 65 | 30 | 3 | 1 | 0 | 1 | 41 | 5,800 | 62 | 32 | 2 | 1 | 0 | 3 |
| 11 | 45 | 6,700 | 56 | 37 | 2 | 0 | 0 | 5 | 43 | 10,100 | 65 | 33 | 1 | 0 | 0 | 1 |
| 12 | 45 | 5,700 | 55 | 41 | 1 | 0 | 0 | 3 | 44 | 8,500 | 58 | 36 | 1 | 0 | 0 | 5 |
| +1 | 44 | 7,000 | 56 | 38 | 2 | 1 | 0 | 3 | 44 | 9,200 | 52 | 40 | 3 | 0 | 1 | 4 |
| +2 | 46 | 6,100 | 60 | 37 | 0 | 0 | 0 | 3 | 48 | 8,000 | 53 | 42 | 4 | 0 | 0 | 1 |

Serum $pCO_2$ was measured using the Clark electrode. Some of the obtained values (Table XI) were outside the normal range. In the case of MO a clear tendency toward alkalosis is seen in the early perrotation period, while in the other subjects some values indicate slight acidosis.

Serum sodium and potassium were measured using a Technico autoanalyzer flame photometer with a

TABLE XI. TOTAL PROTEIN ACID-BASE VALUES (SERUM)

| Determination | Subj. | Pre-rot.* | Day of Rotation 2 | 3 | 5 | 8 | 12 | Mean† | +1 | +2 | +3 | Mean‡ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Total Prot. (gm/100 ml) | LI | 6.8 | 6.3 | 7.4 | 6.9 | 6.3 | 6.0 | 6.6 | 6.4 | 6.4 | 6.4 | 6.4 |
| | MO | 7.2 | 7.1 | 7.0 | 6.7 | 6.9 | 6.8 | 6.9 | 7.0 | 6.6 | 7.0 | 6.9 |
| | SH | 6.8 | 7.1 | 6.9 | 6.7 | 6.7 | 6.8 | 6.8 | 6.8 | 6.4 | 6.6 | 6.6 |
| | WI | 6.8 | 7.7 | 6.9 | 6.9 | 7.5 | 6.6 | 7.1 | 6.8 | 6.4 | 7.0 | 6.7 |
| | | M6.9 | 7.0 | 7.0 | 6.8 | 6.8 | 6.5 | | M6.7 | 6.4 | 6.7 | |
| pH | LI | 7.30 | 7.33 | 7.31 | 7.30 | 7.34 | 7.49 | 7.35 | 7.36 | 7.33 | 7.35 | 7.35 |
| | MO | 7.34 | 7.34 | 7.39 | 7.35 | 7.35 | 7.37 | 7.36 | 7.34 | 7.35 | 7.33 | 7.34 |
| | SH | 7.33 | 7.35 | 7.32 | 7.37 | 7.32 | 7.37 | 7.35 | 7.36 | 7.32 | 7.32 | 7.33 |
| | WI | 7.33 | 7.35 | 7.27 | 7.33 | 7.31 | 7.34 | 7.32 | 7.36 | 7.31 | 7.35 | 7.34 |
| | | M7.32 | 7.34 | 7.32 | 7.34 | 7.33 | 7.39 | | M7.35 | 7.33 | 7.34 | |
| $CO_2$ ($pCO_2$) | LI | 46.2 | 49.0 | 55.5 | 54.6 | 49.2 | 50.2 | 51.7 | 47.8 | 47.5 | 51.6 | 49.0 |
| | MO | 49.0 | 33.5 | 40.6 | 47.3 | 49.5 | 46.8 | 43.5 | 52.8 | 49.5 | 51.9 | 51.4 |
| | SH | 48.0 | 52.1 | 52.8 | 45.3 | 56.2 | 49.1 | 51.1 | 49.7 | 53.7 | 58.3 | 53.9 |
| | WI | 49.1 | 48.0 | 62.7 | 50.1 | 55.3 | 53.7 | 54.0 | 50.3 | 57.5 | 45.6 | 51.1 |
| | | M48.1 | 45.7 | 52.9 | 49.3 | 52.5 | 49.9 | | M50.1 | 52.0 | 51.8 | |
| Na (MEq/L) | LI | 134 | 138 | 132 | 136 | 135 | 135 | 135 | 141 | 136 | 136 | 138 |
| | MO | 130 | 132 | 133 | 138 | 137 | 136 | 135 | 137 | 138 | 139 | 138 |
| | SH | 135 | 139 | 134 | 136 | 136 | 139 | 137 | 141 | 140 | 140 | 140 |
| | WI | 135 | 135 | 135 | 138 | 137 | 141 | 137 | 138 | 139 | 138 | 138 |
| | | M133 | 136 | 133 | 137 | 136 | 138 | | M139 | 138 | 138 | |
| K (MEq/L) | LI | 3.9 | 3.7 | 3.3 | 3.7 | 4.1 | 4.1 | 3.8 | 3.7 | 3.5 | 3.8 | 3.7 |
| | MO | 3.8 | 3.8 | 4.0 | 3.8 | 4.2 | 4.3 | 4.0 | 4.1 | 3.8 | 3.9 | 3.9 |
| | SH | 4.5 | 4.2 | 4.4 | 4.0 | 4.1 | 4.2 | 4.2 | 4.1 | 3.6 | 3.9 | 3.9 |
| | WI | 4.4 | 4.2 | 3.9 | 3.9 | 4.2 | 4.5 | 4.1 | 3.9 | 4.1 | 4.0 | 4.0 |
| | | M4.1 | 4.0 | 3.9 | 3.8 | 4.1 | 4.3 | | M3.9 | 3.7 | 3.9 | |
| CL (MEq/L) | LI | 99 | 99 | 98 | 97 | 99 | 103 | 99 | 103 | 100 | 98 | 100 |
| | MO | 99 | 94 | 96 | 103 | 98 | 98 | 98 | 96 | 98 | 99 | 98 |
| | SH | 99 | 97 | 96 | 98 | 94 | 100 | 97 | 101 | 98 | 96 | 98 |
| | WI | 98 | 98 | 93 | 99 | 95 | 98 | 97 | 100 | 100 | 99 | 100 |
| | | M99 | 97 | 96 | 99 | 96 | 100 | | M100 | 99 | 98 | |
| Ca (MEq/L) | LI | 4.8 | 4.9 | 4.6 | 4.9 | 4.7 | 4.6 | 4.7 | 4.9 | 4.6 | 5.0 | 4.8 |
| | MO | 4.9 | 5.0 | 4.7 | 4.6 | 5.0 | 4.9 | 4.8 | 5.1 | 5.0 | 5.3 | 5.1 |
| | SH | 4.9 | 4.2 | 4.6 | 5.0 | 4.6 | 4.8 | 4.6 | 4.9 | 4.8 | 4.9 | 4.9 |
| | WI | 5.1 | 4.7 | 4.8 | 5.1 | 4.4 | 5.1 | 4.8 | 5.1 | 4.9 | 4.9 | 5.0 |
| | | M4.9 | 4.7 | 4.7 | 4.9 | 4.7 | 4.9 | | M5.0 | 4.8 | 5.0 | |
| Inorg. Phos. (mg/100 ml) | LI | 3.7 | 4.0 | 3.8 | 3.4 | 3.5 | 3.3 | 3.6 | — | — | 3.7 | 3.7 |
| | MO | 3.7 | 3.6 | 3.4 | 3.4 | 4.0 | 3.8 | 3.6 | 3.5 | 3.1 | 4.6 | 3.7 |
| | SH | 4.3 | 4.1 | 3.8 | 3.1 | 3.9 | 3.4 | 3.7 | 4.2 | 3.5 | 4.5 | 4.1 |
| | WI | 4.0 | 3.5 | 3.4 | 3.1 | 3.5 | 4.2 | 3.5 | 3.7 | 3.3 | 3.6 | 3.5 |
| | | M3.9 | 3.8 | 3.6 | 3.3 | 3.7 | 3.7 | | M3.8 | 3.3 | 4.1 | |

*Mean of values days —3, —2, —1.
†Mean of values 5 experimental days.
‡Mean of values days +1, +2, +3.

TABLE XII. BLOOD CATECHOL DETERMINATIONS

| Determination | Subject | -3 | -2 | -1* | 2 | 3 | 5 | 8 | 12** | +1** | +2 | +3 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Adrenalin (Micrograms per liter of serum) | LI | - | × | × | × | × | × | 1.3 | 0.9 | 1.2 | 1.1 | * |
| | MO | 1.8 | × | × | × | × | 0.3 | 0.4 | 0.1 | 0.2 | 1.1 | 0.2 |
| | SH | 0.1 | × | × | × | × | × | × | × | 0.1 | 0.1 | × |
| | WI | 0.3 | × | × | × | × | × | 0.3 | × | 1.1 | 0.1 | × |
| | Mean | 0.7 | × | × | × | × | 0.1 | 0.5 | 0.25 | 0.65 | 0.6 | 0.1 |
| Noradrenalin (Micrograms per liter of serum) | LI | - | 6.2 | 4.3 | 8.7 | 5.7 | 4.0 | 7.3 | 5.1 | 5.7 | 7.1 | 3.5 |
| | MO | 6.5 | 5.0 | 5.2 | 6.4 | 5.6 | 3.8 | 3.6 | 3.0 | 4.2 | 6.4 | 3.7 |
| | SH | 2.7 | 2.8 | 2.3 | 2.4 | 2.9 | 3.4 | 4.2 | 2.6 | 4.5 | 4.3 | 3.5 |
| | WI | 3.1 | 3.9 | 2.9 | 3.3 | 4.9 | 5.3 | 3.5 | 2.9 | 5.4 | 3.5 | 2.9 |
| | Mean | 4.1 | 4.5 | 3.9 | 5.2 | 4.8 | 4.1 | 4.65 | 3.4 | 4.95 | 5.3 | 3.4 |

× — Non detectable
* — Run Began 0900
** — Run stopped 0900

Normal Range: Adrenalin 0.2 - 0.6 μg/L
Noradrenalin 2 - 6 μg/L

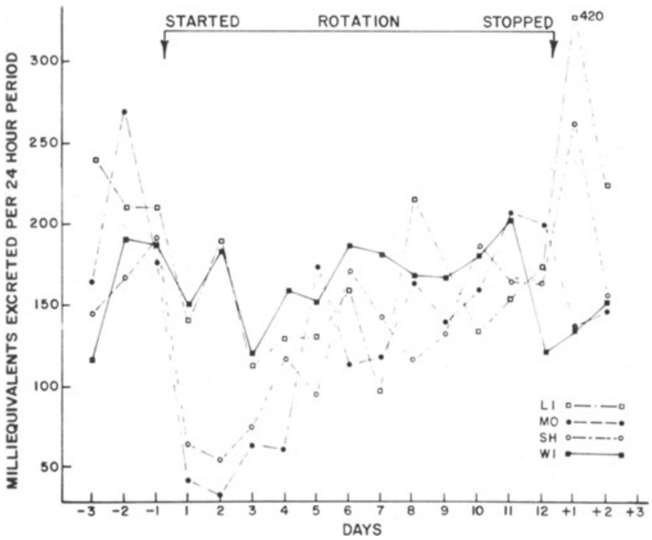


Fig. 6. Urinary excretion of sodium of four subjects.

lithium internal standard; chloride was determined using an ultramicro-modification of the method of Schales and Schales.[15] The values obtained (Table XI) were within the normal range and did not change significantly throughout the experimental period. Serum calcium was measured using an ultramicro-modification of the method of Diehl and Ellingboe[16] and phosphorus (inorg.) by the method of Fisk and Subbarow.[17] The results are included in Table XI. The values for calcium tended toward the lower end of the normal range (4.5-5.7) during Days 2, 3, and 8. Some of the values for inorganic phosphorus were above the normal range (2.4-3.8). There were slight tendencies toward lower values perrotation and on Day +2.

*Catechol Amines in Blood and Urine*—Measurements of catechol amines in the blood were done by the method of Weil-Malherbe and Bone,[18] and the results are shown in Table XII. With regard to adrenalin the single highest value was obtained on MO three days prior to rotation; this probably represents a response to drawing blood. There is a pattern evident with the lowest value between Days —2 and 3 and the highest values between Days 8 and +2. There were only minor variations in levels of noradrenalin.

Crout's method[19] was used to measure the urine catechol amines for each of the four collection periods and all of the results were graphed. There were no significant changes in release of noradrenalin; the graphs (not reproduced) show much the same saw-tooth curves for each subject. Although the release of adrenalin was probably within normal limits, the individual variance was so characteristic for each that the curves are depicted in Figure 7. Note that the values for the "night" samples are similar for all and that the variance in values for "day" samples reflects difference in lability of response.

*Urine Corticosteroids* (mostly cortisone, hydrocortisone, and tetra derivatives)—These were determined on each of the four collection samples by the method of Kornel,[20] and the results graphed. It should be pointed out that there is a "lag" of two to three hours in excretion of the products of 17-hydroxycorticosteroids

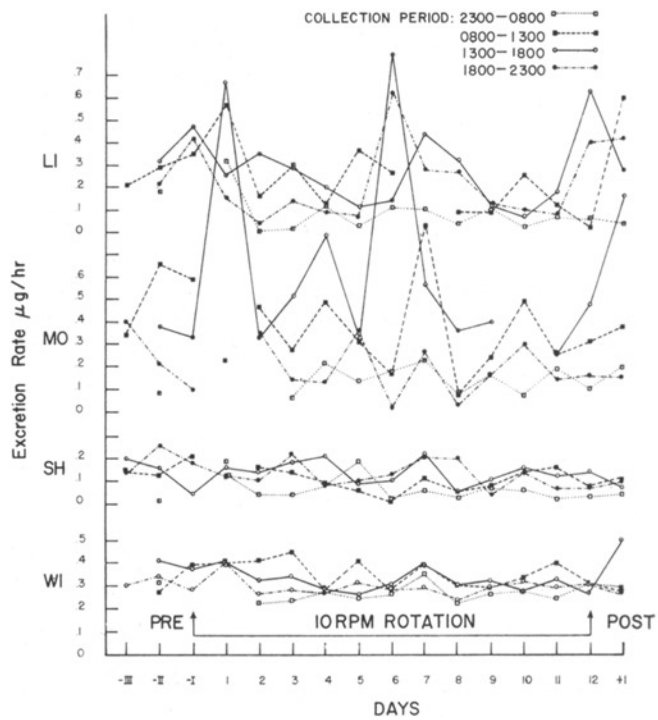


Fig. 7. Catechol amine (urine) excretion of four subjects.

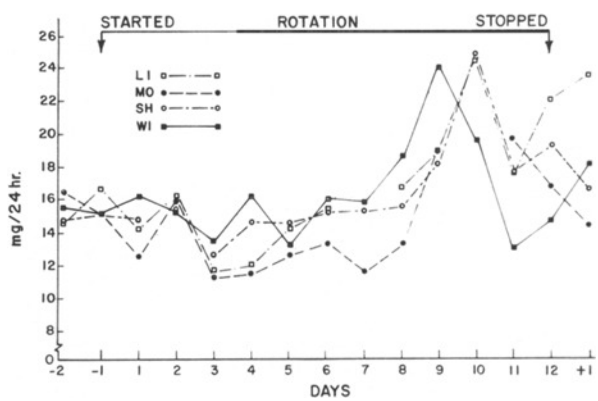


Fig. 8. Urine corticosteroid excretion of four subjects.

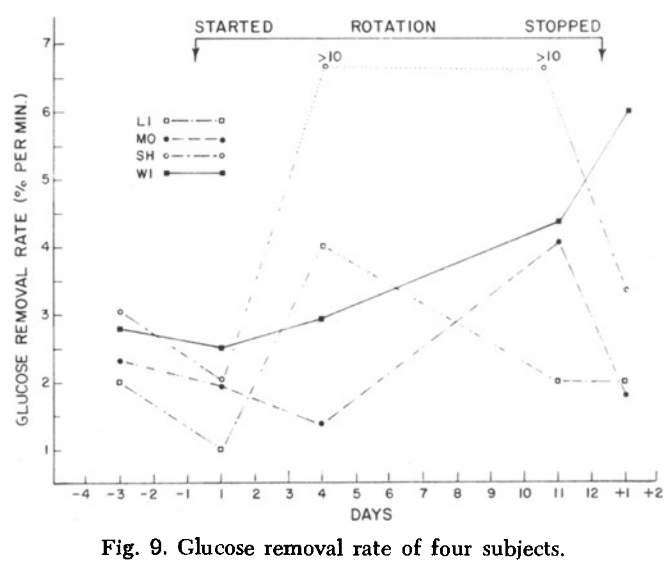


Fig. 9. Glucose removal rate of four subjects.

TABLE XIII. INTRAVENOUS GLUCOSE TOLERANCE TESTS

| Subject | Day of Expt. | Blood Fasting | Sugar 15 min | Concentration in mg 30 min | 45 min | 60 min | Glucose Rem. Rate (% min) |
|---|---|---|---|---|---|---|---|
| | 2 | 82 | 204 | 174 | 144 | 139 | 1.78 |
| | 5 | 79 | 201 | 180 | 160 | 153 | 1.14 |
| LI | 8 | 73 | 190 | 109 | 83 | 90 | 4.7 |
| | 15 | 67 | 188 | 142 | 131 | 105 | 2.41 |
| | 17 | 73 | 196 | 154 | 138 | 118 | 2.15 |
| | 2 | 88 | 214 | 161 | 155 | 129 | 2.30 |
| | 5 | 81 | 208 | 167 | 150 | 128 | 2.13 |
| MO | 8 | 76 | 222 | 189 | 175 | 153 | 1.37 |
| | 15 | 85 | 225 | 140 | 130 | 105 | 4.03 |
| | 17 | 70 | 207 | 181 | 146 | 131 | 1.86 |
| | 2 | 75 | 194 | 160 | 122 | 104 | 3.2 |
| | 5 | 74 | 201 | 176 | 151 | 120 | 2.3 |
| SH | 8 | 78 | 118 | 109 | 76 | 40 | high |
| | 15 | 81 | 184 | 114 | 71 | 60 | high |
| | 17 | 78 | 186 | 146 | 123 | 100 | 3.45 |
| | 2 | 67 | 205 | 164 | 122 | 104 | 3.01 |
| | 5 | 71 | 200 | 169 | 130 | 110 | 2.74 |
| WI | 8 | 76 | 177 | 132 | 100 | 102 | 3.27 |
| | 15 | 62 | 198 | 134 | 99 | 78 | 4.72 |
| | 17 | 75 | 178 | 123 | 87 | 80 | 6.97 |
| | 2 | 78 | 294 | 164 | 135 | 119 | 2.51 |
| Average | 5 | 76 | 202 | 173 | 147 | 127 | 2.00 |
| N = 4 | 8 | 75 | 176 | 134 | 108 | 96 | 3.52 |
| | 15 | 73 | 198 | 132 | 107 | 87 | 5.19 |
| | 17 | 74 | 191 | 151 | 123 | 107 | 2.82 |

released. Figure 8 represents the mean values for each day and shows two trends. The first trend downward in the early perrotation period is not significant but the second upward trend during the late period is highly significant.

*Glucose Utilization*—Thirty grams of dextrose were injected intravenously after an overnight fast and the subsequent decline of excess blood sugar values was determined for one hour on Days –3, 1, 4, 11 and +1. The qualitative response of the group was quite uniform. There was a decreased rate of glucose removal after one day of rotation (Figure 9 and Table XIII). On Day 4 the average removal rate increased significantly from 2.0 per cent to more than 3.5 per cent excess glucose per minute and to more than 5.2 per cent per minute on Day 12. On Day +1 the average rate was returning toward the initial value.

There was a significant degree of intraindividual variance. Subject LI showed the initial reaction of a decreased rate, after Day 1. After Day 5 his rate of removal was 4 per cent per minute, a four-fold increase over his Day 2 value. On Day +1 a return to normal was found; after the end of rotation, his rate was almost identical to its initial value. In MO the initial decline of removal rates continued through entire Day 3 but on Day 11 a significant increase to 4 per cent per minute was observed. After the end of the experiment the rate returned to below its control value. SH demonstrated the greatest reaction. After the initial decline on Day 2 unusually rapid removal rates (7-10 per cent) were observed throughout the experiment. On Day 5 blood glucose levels fell nearly to hypoglycemic levels one hour after the glucose load. On Day +1 blood sugar also declined to a point moderately below the fasting level. On Day +2 the utilization rate was again quite close to the initial normal value. In WI the

TABLE XIV. BLOOD ENZYME RESPONSES

| Enzyme | Subject | Day of Experiment –3 | 1* | 2 | 3 | 5 | 8 | 12 | End of Run** | +1 | +2 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| LDH | LI | 60 | 30 | 40 | 20 | 120 | 440 | 1040 | 260 | 460 | 160 |
| | MO | 240 | 720 | 80 | 40 | 100 | 360 | 660 | 360 | 520 | 350 |
| | SH | 260 | 220 | 60 | 60 | 100 | 440 | 480 | 260 | 560 | 180 |
| | WI | 140 | 720 | 100 | 100 | 120 | 160 | 800 | 280 | 620 | 200 |
| SGOT | LI | 26 | 30 | 34 | 28 | 24 | 32 | 44 | 25 | 26 | 26 |
| | MO | 28 | 36 | 32 | 28 | 26 | 28 | 32 | 30 | 28 | 22 |
| | SH | 64 | 28 | 28 | 30 | 26 | 26 | 38 | 28 | 26 | 32 |
| | WI | 44 | 30 | 42 | 28 | 24 | 40 | 38 | 18 | 24 | 24 |
| Alkaline Phosphatase | LI | 1.45 | 1.45 | 1.15 | 1.25 | 1.7 | 1.15 | 1.6 | 1.4 | 1.4 | 0.80 |
| | MO | 1.05 | 1.20 | 1.75 | 0.6 | 0.9 | 0.9 | 1.0 | 0.9 | 0.85 | 0.70 |
| | SH | 1.5 | 1.35 | 1.80 | 0.7 | 1.0 | 0.9 | 0.8 | 0.8 | 1.1 | 0.78 |
| | WI | 0.87 | 0.85 | 0.65 | 0.7 | 0.9 | 0.85 | 0.65 | 1.6 | 0.72 | 0.70 |

*Run began 0900.
**Run stopped 0900.

Normal values: Lactic dehydrogenase 100-350 units.
SGOT 8-40 units.
Alkaline phosphatase 0.8-2.3 Sigma units per ml.

typical initial decrease of utilization was observed. However, a significant increase occurred only toward the end of the experimental period and was followed by a further increase in the postrotation period.

*Blood Enzymes*—Glutamic-oxaloacetic acid transaminase (SGOT) and alkaline phosphatase and lactic dehydrogenase (LDH) were determined (Table XIV). The only significant changes were in LDH which are summarized in Figure 10. Two of the four aviators showed a considerable increase in LDH on Day 1 and all of them showed reduced activity during the following four days. On Day 5 and again on Day 11 there were significant additional increases. After cessation of rotation the high values on Day +2 were preceded and followed by values near the control level.

*Food Absorption*—Intestinal absorption of food, as reflected by the oral zylose absorption, did not show any significant change during any phase of the experiment. Any variations were considered to be within the experimental error.

*Discussion of Biochemical Findings*—In general the significant changes in the biochemical and other labora-

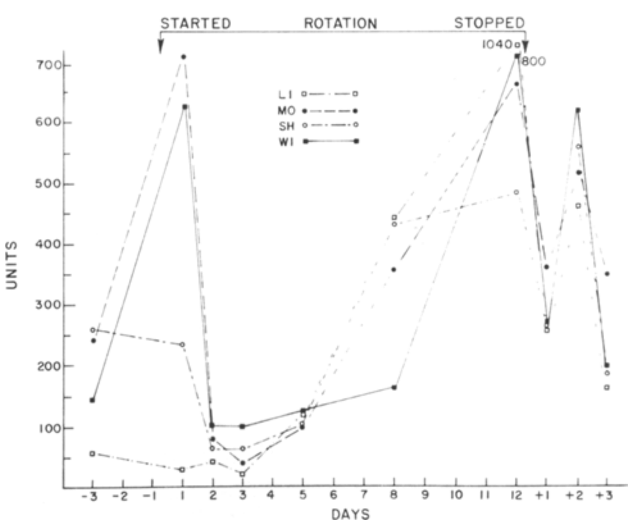


Fig. 10. Lactic dehydrogenase response of four men.

tory findings paralleled the changing symptomatology described in the previous section. In attempting to interpret these changes in terms of the effects of stimulation by the accelerative forces it is important to emphasize that they might reflect not only specific effects of such stimulation but also nonspecific complicating effects. Moreover, one is handicapped by the limited quantification both of the stimulus and its effects and by the lack of previous experimentation to provide background information.

In the early perrotation period the subjects learned by experience that it was necessary to restrict their head movements, although prior to this they were, in varying degrees, less cautious and, as a result, MO vomited on eight occasions and SH once. Moreover, in varying degrees, they reduced their physical activity and limited their intake of fluid and food. As they adapted to the nausea syndrome they increased their head movements and eventually imposed no restriction. Consequently, in the late perrotation period the level of accelerative stimulus was increased, the food and water intake was guided by hunger and thirst and physical activity was increased compared with the early period. The time-course of these trends differed in different subjects but in general their overt behavior became more uniform in the late perrotation period. One other factor deserves mention: the possible role of "anticipation" as the end of rotation drew near. This is difficult to estimate; in all likelihood it was not a significant factor except possibly on the morning of Day 12. These subjects not only were conditioned to stressful experience but also the end of rotation was not the end of the experiment.

With regard to changes in urine output the release of the antidiuretic hormone, previously shown to be associated with unusual vestibular stimulation,[21] was the probable primary factor; variations in fluid intake and, in the case of MO and SH, vomiting, were complicating factors. In the early perrotation period when the nausea syndrome was prominent, WI was the only subject who gained weight and this occurred while his urine output was falling, suggesting water retention. It is possible that LI and MO had a greater tendency to release the antidiuretic hormone than SH and WI inasmuch as they manifested the greater decreases in urinary output both in the early and late perrotation periods. In the early period LI, who did not vomit, had nearly as great a decrease in output as MO, who vomited, and in the late period, not characterized by nausea, the decrease in output may have been associated with increase in head movements (stimulus). If this last assumption is allowed it demonstrates that they adapted more readily to the nausea syndrome than to the factor responsible for the antidiuretic effect. Especially interesting are the similar variations in urine output for SH and WI who nevertheless varied in their susceptibility to nausea.

The changes in urine volume and electrolytes were not reflected in the blood hematocrit, total protein and serum electrolytes, at least to any significant degree. In other words, the excretory mechanisms constituting our first line of defense in adjustments to stresses imposed were adequate to preserve homeostasis with respect to serum electrolytes. The determinations of serum pH may not have been reliable but the $pCO_2$ determinations indicated slight variations from normal, the most significant a tendency toward alkalosis in the subject who vomited eight times.

There was no significant change in release of noradrenalin as indicated from measurements on blood and urine. Similar measurements on release of adrenalin showed only minor fluctuations and these in LI and MO. These negative findings are nevertheless significant in that they tend to minimize the possibility that emotional stress was an important variable in the experiment.

With regard to the release of catechols and corticoids the increase in urinary corticoids in the late perrotation period alone was significant. If it is assumed that this increase was in response to increasing the head movements, two interesting facts emerge. First, it was not related in time to manifestations of the nausea syndrome and second, all subjects were affected almost equally but not at the same time. Previously we had assumed that there was a relation between occurrence of nausea and the release of adrenal corticoids but the present findings suggest that even an association between the two may be absent. Of all the significant positive findings the increases in release of corticoids showed the least individual variance.

The most striking findings requiring explanation were the changes in rate of glucose utilization and in LDH level in the plasma. The group trends showed some similarity, i.e., an initial decrease followed by an increase above prerotation values, but there were exceptions to the group trends and there was often a lack of parallelism between the glucose and LDH responses for a given subject. An attempt was made to relate both findings to an increase in muscle metabolism and consideration was given to the difficulty in maintaining equilibrium while standing and walking and the possibility that there was an increase in muscle tonus[22] due to bizarre stimulation of the semicircular canals. There was a closer relationship between physical activity and LDH than existed with glucose utilization levels.

The increase of glucose removal rates is highly significant. The qualitative similarity of response in all four men indicates that the exposure to stress had a pronounced effect on carbohydrate metabolism and that the only difference among individuals is the time at which the reaction set in. Two mechanisms could explain the findings. First, there is the possibility of increased levels of circulating insulin in the blood caused by rotation. No measurements of plasma insulin were made but the finding that fasting blood glucose levels were little affected by rotation would make the existence of significant hyperinsulinism unlikely. Secondly, there was an increased permeability of peripheral tissue to glucose. It is known that muscular activity causes a great increase of cell permeability to sugars and consequently of glucose metabolism and that this effect is independent of insulin. This increased activity is normally compensated by increased hepatic glucose pro-

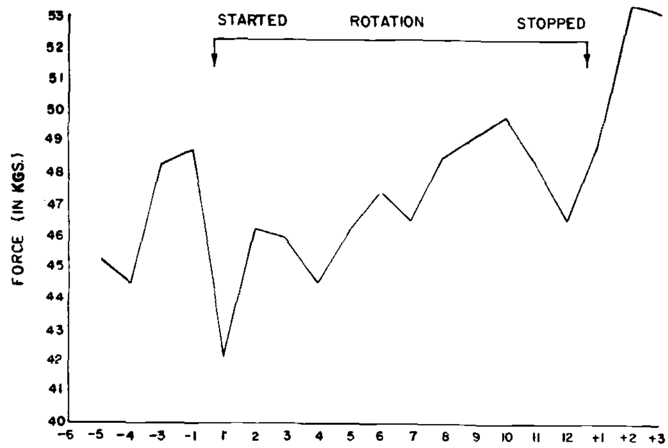


Fig. 11. Hand dynamometer scores for four men.

duction and thus the blood glucose level remains unchanged. The additional increase of permeability caused by the release of insulin during the glucose tolerance test might well lead to greatly increased glucose removal rates and even to hypoglycemia.

The initial decrease of glucose removal rates could then be explained by a diminished physical activity during the first day of rotation, very pronounced in LI and SH, less in MO and WI. It is more difficult to explain the subsequent striking increase inasmuch as none of the subjects became very active.

## RESULTS OF PSYCHOPHYSIOLOGICAL TESTS

*Hand Dynamometry*—The dynamometer used in this experiment was a standard model Stoelting hand dynamometer. The subject's daily score was the arithmetic mean for five trials. From the group data in Figure 11 it can be seen that on Day 1 there was a sharp drop in performance which by Day 2 returned to the average for the four prerotation days. From this point until Day 10 there was a gradual increase in performance where the best prerotation score was equaled. The last two days of rotation performance showed a pronounced drop and postrotation there was a sharp rise to values greater than the initial control level.

*Spoke Test*—This is a simple test of eye-hand coordination which requires that the subject point to different compass coordinates and then to the center. In test A the coordinates are randomly numbered, and the subject must point progressively (e.g., 1, 2, 3, . . .). The task is similar in test B; however, the subject must alternate numbers and letters progressively (1,a,2,b, etc.). The score is in seconds to completion of the task.

The data appear to indicate an over-all practice effect. However, the learning curve for the complex task (test B) is interrupted at the onset and cessation of rotation, although the change is small. The decrease in performance at the cessation of rotation on test A appears smaller than the expected day-to-day variability.

*Simplified Electronic Tracking Apparatus* (SETA)—The *tracking test* used in this experiment was similar to the one devised by Fitts,[23] but a knurled knob was substituted for the lever. In this test an irregular motorized cam drives a pointer on a dial off zero and the subject's task is to keep the pointer at zero. A computer element monitored the pointer and compiled the subject's total error (in microvolts). Each trial lasted one minute and there were five trials in a session. The first data point in Figure 12 is a mean of 100+ trials and may be considered stable. The over-all impression is of a learning function and the interruption of this trend on the first day of rotation is therefore probably meaningful. By Day 2 the prerotational level was obtained and improvement continued.

*Speed of Tapping*—This required that the subject alternately depress buttons on two cumulative counters with the index and second finger of his preferred hand. Each trial lasted 30 seconds and there were 10 trials per session. The scores were read directly from the counters and error was the difference between two totals. Two subjects improved in performance and two remained about the same. The onset and cessation of rotation did not appear to have any effect upon performance. The variability did not change with time nor did the error score vary in any consistent fashion.

*Reaction Time*—This consisted of a simple reaction time to a visual stimulus. There were 50 trials per day for each subject. The data are plotted in Figure 13, with the first (practice) session included. The group

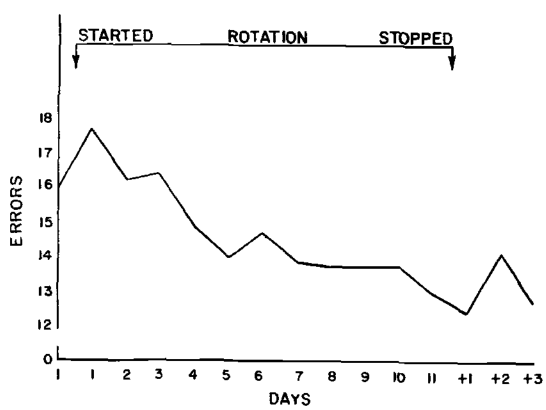


Fig. 12. Simplified electronic tracking apparatus: mean score for four men.

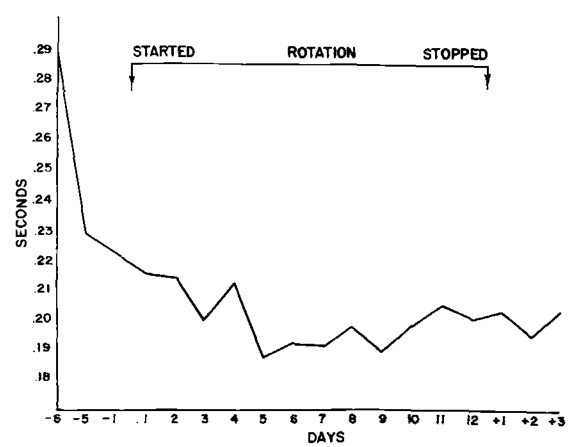


Fig. 13. Reaction time: mean for four men.

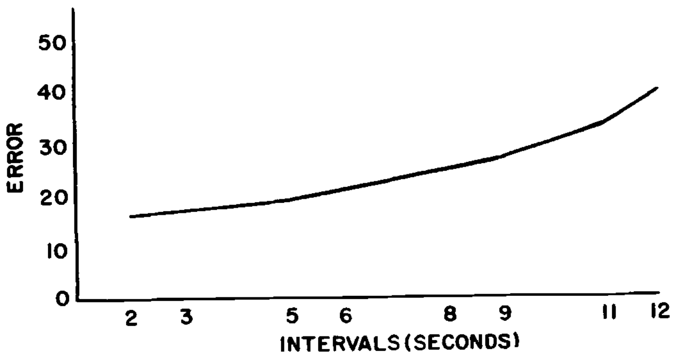


Fig. 14. Time estimation: average error per day for four men. (see text.)

performance appears to indicate a simple learning function which flattens slightly at the onset of rotation. However, the individual data show that WI (least affected overall) continued to improve until Day 10 and then did less well. Subject SH continued to improve slightly throughout. The other two subjects also continued to improve but their learning appeared to be interrupted the first few days of rotation. Subject WI obtained one of his poorest scores on Day +1.

*Time Estimation*—This was tested by the "production" method and required the subject to depress a key for a given number of seconds. Ten judgments were made at each of eight intervals (2, 3, 5, 6, 8, 9, 11, 12 secs) on each day of the experimental period. Because these data showed no consistent over- or underestimation within a session or from one session to the next they were plotted in terms of total absolute error. Average deviations for each interval also were obtained. Figure 14 shows the average deviation for the four men at each interval. The magnitude of the error appears to be directly related to the length of the interval to be estimated and is as expected. Figure 15 shows the mean absolute error for all intervals for the four subjects for the entire experimental period. It may be seen that the greatest errors occur at the onset and cessation of rotation.

*Digit Span*—This was administered in a way similar to that devised by Wechsler[24] but the numbers were presented visually once per second. The results of this test appear to show a learning effect, which may in part be explained by the fact that only 260 number sequences were used and the subjects saw them more than once. The learning curve is interrupted at the onset of rotation and midway through the run, indicating a decrement in performance.

*Complex Counting Task*—In this test[25] the subject is presented with a panel containing three lights (A, B, C) with a button below each light. The lights were programmed to flash at different frequencies (viz., A-5.4 times per minute; B-8.9 t.p.m.; C-4.6 t.p.m.). The test lasted five minutes and the subject's task was to depress the button below the light after it had flashed four times. Stimuli and responses were recorded on an Easterline Angus event recorder.

Group means indicate a small decrease in performance at the onset and at cessation of rotation. This was, however, within the range of day-to-day variability; on Day 8 there was a pronounced drop in performances. The individual data show WI (the subject least affected by rotation) with an over-all increase in performance as the experiment continued. Subject SH remained about the same and the other two subjects began to make more errors as the run progressed. Subject WI obtained one of his poorest scores on the first day after rotation.

*Reading Test*—This consisted of assignments selected from two workbooks routinely used in the reading course at the U. S. Naval School, Pre-Flight. A range of difficulty level was assigned according to the "Flesh Scores."[26] The results of the reading test are inconclusive. Inter- and intrasubject variabilities of speed and comprehension are enormous. The subjects suggested that interest value should have been included in the score for difficulty level.

*Mathematics Test*—This was a simple five-minute test of addition, subtraction and multiplication. For the most part there was a gradual increase in performance which was probably a function of learning (Figure 16). Although many vigilance and fatigue studies indicate a spurt or upsurge in performance just prior to completion of the experiment, here on Day 11 there was a decrease in performance. Motivation was believed not to be a factor.

*Vigilance Tests*—Each subject stood a night watch for 90 minutes at the same time every evening after the crew had secured. The subject was required to monitor

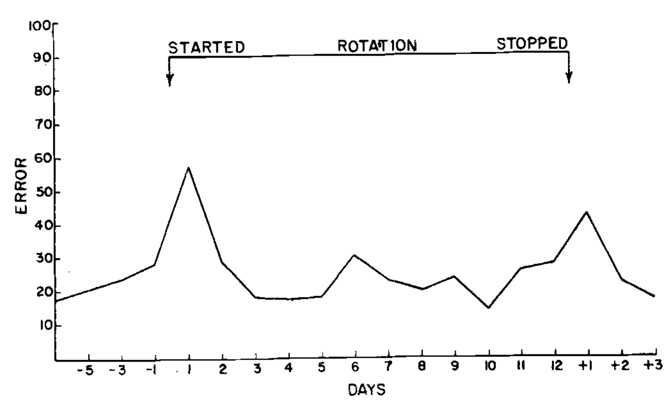


Fig. 15. Time estimation: mean average error per day for four men.

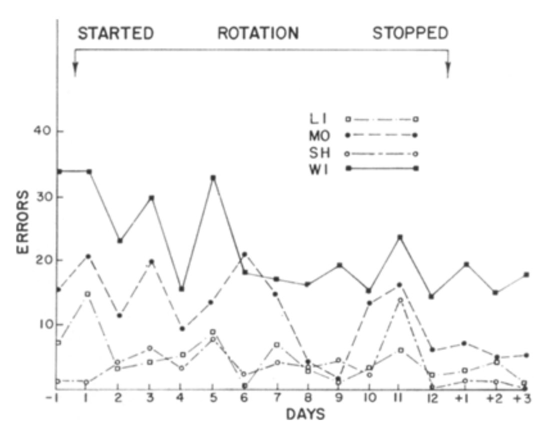


Fig. 16. Math test scores for four men.

flashing lights, an auditory signal and several gauges; however, only four of the tasks were scored:

*Alternating Lights*—In the center of the console two lights flashed alternately (30 cycles per minute each) to produce one flash per second. At irregular intervals (and less than 10 times in 90 minutes) one light stopped flashing and the other doubled in frequency. The subject was to depress a button when this occurred. Both stimulus and response were read out on an event recorder. Score was delay of response in seconds. A step relay which caused the light to stop flashing produced an auditory cue. However, the light did not change every time the relay advanced. It is felt that if sensory summation made the task less difficult it did so by a small amount.

In the main there was a very small increase in performance which for these men did not appear to be interrupted by the onset or cessation of rotation. The individual data showed one very long response and this by subject LI on Day 1. Actually, the subject fell asleep and this is particularly meaningful since of the four men LI appeared to be most competitive and least likely to fall asleep on watch.

*Three-Digit Test*—In the center of the console and below the alternating lights was a nixie tube. The tube

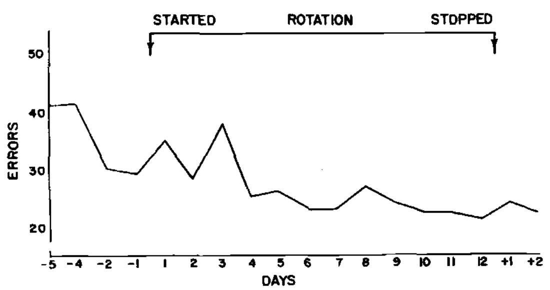


Fig. 17. Three-digit test (night watch) for four men.

lit once a minute for 10 seconds and numbers were programmed randomly. The subject was assigned a code number for the evening and it was his task to record when his number came up (vigilance). He was also obliged to remember the number which appeared previously (memory) and the number which occurred next (attention). There were more attention errors than vigilance errors and more memory errors than attention errors. The performance of these men appeared to decrease at the onset of rotation but for WI (least affected) it did not. All scores dropped at the cessation of rotation but the change was small (Figure 17).

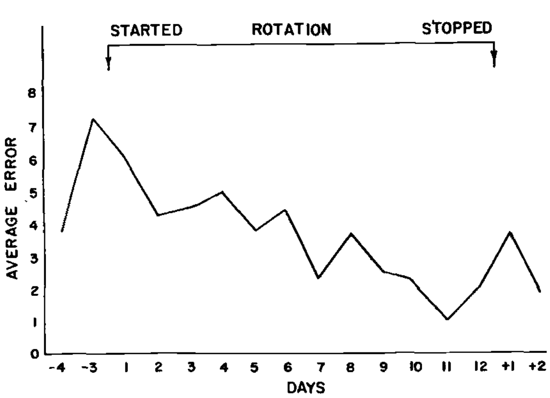


Fig. 18. Audio vigilance test (night watch) for four men.

*Audio Vigilance*—Along with 84 db broad band noise, an 87 db tone (1175 cps) of 0.25 second duration was presented every 0.95 second, for ninety minutes. Sporadically (but less than 12 times in a session) the interval was stretched from 0.95 to 1.40 seconds. It was the subject's task to note the time at which this occurred. Score was number of intervals missed. From the group data, Figure 18, there appeared to be a learning effect which did not seem to be interrupted by the onset of rotation. However, there was a decrease in performance at cessation.

*Fifteen-Minute Test*—In this test the subject was required to read a continuously varying gauge every fifteen minutes. The score was the absolute error in time. The data seem to indicate that subjects were able to perform this task quite well and with very few gross errors. There were only two errors of more than one minute (3 min. and 6 min.) in a total of 56 trials (i.e., 14 for four subjects). Most errors were less than 10 seconds.

*Discussion of Psychophysiological Tests*—All of the subjects carried out all of the tests except on one occasion when LI fell asleep during his watch. After making allowance for practice effects and time-to-time variance, it is obvious that significant changes in performance were either absent or small except in the case of the hand dynamometer test. It is interesting that these changes in performance, aside from those in close relation to the onset or cessation of rotation, were manifested more frequently in the late than in the early per-rotation period. Hand dynamometry deserves particular notice inasmuch as the scores seemed to reflect the general fitness of the subjects throughout the entire experimental period. Moreover, the sharp rise in values after cessation of rotation suggests that disturbances in neuromuscular coordination were not a factor in carrying out the test.

## GENERAL DISCUSSION AND SUMMARY

Prolonged exposure in a rotating environment is a unique experience and differs in important respects from exposure to turbulent seas or to turbulent air. One striking difference has its origin in the fact that in the rotating environment the subject's movements are essential to the generation of the bizarre accelerations whereas at sea or in the air, fixation of the head and body might influence the effects but would not abolish the unusual inertial forces to which the traveler is passively subjected. Thus, during rotation in the SRR when the subject is seated with head fixed or asleep the conditions are not far different from those with the room stationary. Movements of the subject resulting in functional disturbance fall mainly into two categories, namely, rotation of the head out of the plane of rotation of the room and whole body movements. The former generate very small inertial forces and their effect, at least when the subject is near the center of the SRR, would be negligible were it not for the semicircular canals. They are so structured that the sensory elements are stimulated by the gyroscopic forces and the bizarre pattern of the stimulus is the essential factor causing the symptomatology of canal sickness, although other etiologic factors are also involved.

Whole body movements, insofar as they generate Coriolis forces and affect, through change in distance from the center of the SRR, the level of centripetal force, result in a change in the gravitoinertial force vector and, consequently, in the direction of the force upright with respect to the room. Neuromuscular coordination is affected, which increases the difficulty in maintaining postural equilibrium, for example, and the amount of work involved in walking. A distinction is made between these neuromuscular effects and canal sickness, inasmuch as the semicircular canals are not directly implicated unless the head is rotated out of the horizontal plane of the SRR. Such rotations of the head may be unavoidable and then the bizarre stimulus to the canals contributes to the neuromuscular disturbances.

Past experience has shown that there is a good correlation between the velocity of rotation of the room and the severity of the symptoms manifested by the subjects. The reason is simply that the movements required in meeting essential needs and carrying out prescribed tasks are similar at all velocities, thus making velocity of the room the dependent variable. The subject can, however, by omitting tasks and remaining inactive in his free time reduce his activities. Hence, not only the velocity of rotation but also the movements of the subject must be taken into account if any attempt is made to estimate the changing levels of exposure to the unusual inertial forces at any given velocity. In this experiment a precise measure of bodily movements was not obtained; the estimates are in terms of "restriction of head movements" and "level of physical activity." In the SRR the subject could anticipate every stressful stimulus, perfectly with respect to occurrence, although imperfectly with respect to disturbing effects characterized by summation and perseveration. With training and experience, however, the subject became adept at avoiding disturbances by regulating the stimulus both quantitatively and qualitatively. Thus, in terms of the stressful inertial forces each subject, consciously at first, then automatically to an increasing extent, exerted a modulating influence on the level of stimulation.

A second important difference refers to the stability of the SRR compared with ship or aircraft. With full illumination of the room while he is engaged in ordinary activities the subject regards the platform as being not only stable but also level and the walls upright. Under special circumstances the room may appear tilted (the oculogravic illusion[27]) and, seated in the dark, the subject may regard the chair on which he is seated as being tilted but always with respect to a level stable platform. Under most conditions, however, the visual environment appears the same as when the room is not rotating.

The effects of rotation already have been discussed under three headings: the clinical symptoms, clinical laboratory findings and psychophysiological performance. They will now be discussed briefly in terms of the significant changes along the time axis of the experiment, and some of the practical and theoretical implications will be summarized.

The unexpected finding of two quite distinct perrotation periods is explained in this way. In the early perrotation period the subjects restricted their head movements and consequently their physical activity to prevent the nausea syndrome. This subject-paced stimulus level was well below the unpaced level and was individually adjusted to the time-course of adaptation to this unpleasant syndrome. With the disappearance of nausea this restriction on head movements was lifted, thus increasing the bizarre stimulus to the semicircular canals. This paved the way for the appearance of effects which either (1) necessitated a longer time-course of adaptation than did nausea, (2) required a stronger stimulus for their exhibition or (3) had different transfer-patterns in terms of levels of stimulation. The restriction on physical activity, however, was partially maintained inasmuch as it was now paced by such symptoms as drowsiness and fatigue. Thus the late perrotation period, while initiated by the lifting of restrictions on head movements, was characterized by a rising level of physical activity which, although never reaching the prerotation level, may nevertheless have exceeded it in terms of muscular work. The symptomatology of the two distinct perrotation periods revealed many interdigitations both for the individual and for the group and in all likelihood was complicated by symptoms referable to confinement and level of physical work.

The first day of rotation made the greatest over-all impact on the subjects. The sudden onset, marking the rather dramatic beginning of a long exposure to unfamiliar stresses, was, after the days spent in carrying out preliminary arrangements and baseline studies, keenly anticipated. Such immediate effects as difficulty in walking and the strange feeling associated with head movements were not unpleasant and all except LI were lulled into making a false estimate of their susceptibility to the nausea syndrome. Within an hour MO experienced the first of eight vomiting episodes and SH complained of nausea. Before long quiet fell over a previously noisy group and all except WI attached the head brace to minimize movement between head and thorax. Thus the findings on the first day reflected not only differences in susceptibility to a given level of stress but also differences in self-appraisal of the susceptibility, which influenced the subjects' self-paced exposure to stress. This accounted in part for the severity of symptoms the first day and for certain differences in pattern of response between Day 1 and Day 2.

Adaptation to the nausea syndrome was the main guide in defining the early perrotation period, a period characterized not only by typical symptoms of canal sickness but also, except on Day 1, by a low level of physical activity. Individual differences in severity of symptoms and rate of adaptation were revealed. Moreover, there were significant alterations in the clinical laboratory findings reflecting in part the low level of physical activity and in part the stress of the force environment. All of the subjects carried out the performance tests on the first day, although MO and SH did not participate in all of the clinical tests. Slight decreases in performance were recorded in several tests especially on Day 1 and notably in hand dynamometry.

The late perrotation period was characterized by the fatigue syndrome, a changing pattern in the laboratory findings and slight decrements in certain performance tests. It was necessary to take into account three etiological factors, namely, vestibular stimulation, increasing physical work and confinement.

Such symptoms as drowsiness and fatigue were complaints even in the early perrotation period but were overshadowed by nausea. With the disappearance of nausea, however, they became the presenting symptoms. The subjects reported a gradual decrease in drowsiness but continued to complain of fatigue. It is difficult to distinguish between boredom and fatigue and the increase in physical work may have been a factor.

The unexpected biochemical findings were the appearance of stress hormones in the urine during the late but not the early perrotation period, which were almost surely attributable to stimulation of the canals. Moreover, striking increases in glucose utilization and in the serum enzyme LDH were also observed in the late perrotation period.

All of the tasks were carried out in the late perrotation period. With regard to the performance tests there was a drop in score in hand dynamometry on Days 11 and 12 which was probably significant and a slight drop in scores in digit span on Days 7 and 8, in the Complex Counting Test on Day 8, and in the Math Test on Day 11.

Cessation of rotation had less effect than anticipated on the symptomatology. Only SH experienced a mild return of nausea (stomach awareness) lasting a short time and, while the subjects were surprised over their difficulty in walking, especially when rotating the head, this soon disappeared. None of the changes in the clinical laboratory findings were unexpected. There were slight decrements in some of the performance scores but an increase in score in hand dynamometry.

The onboard observer KE presented no history of motion sickness and had amassed >500 hours at different velocities in the Slow Rotation Room. In his first few exposures dizziness and slight discomfort were his only complaints. In subsequent experiments he remained symptom free. Audiometric examination, caloric response and postural equilibrium were within normal limits and there was no history of disease of the sensory organs of the inner ear.

During the present experiment KE reported slight dizziness only during the first hour. This rapidly subsided and with the exception of drowsiness was the only characteristic symptom reported throughout the rotation period. The first day KE had only slight difficulty walking and (unlike all the subjects) did not restrict his movements at all. From all indications adaptation was accomplished quickly. Although KE's log was sprinkled with comments on "sleepiness" his fatigue was probably not so great as that of the other four men. This freedom from difficulties may be the result of this individual's initial insusceptibility but is more probably the result of his conditioning from previous experiments.

KE remained on board for the duration of the experiment and his exposure was equivalent at least to that of the subjects, with the exception that during the short daily stops KE left the SRR (and consequently moved his head). This was done, as a probe, to discover the feasibility of maintaining adaptation to 10 RPM and to zero simultaneously. This proved quite successful (at least with respect to postural equilibrium) since KE did not experience ataxia problems when rotation finally ceased. On the other hand the additional stress of adaptation to both environments may have contributed to the fatigue he reported. Verification of these findings awaits future experimentation.

All of the aviators were asked whether, in their opinions, they were unfit at times during the run to carry out tasks which might be expected of astronauts in orbital flights. All agreed that this was the case; even WI, who was quite fit in the early period, considered he was less fit later due to prolonged fatigue. This opinion is fairly well supported by the objective findings. The most severe symptoms were experienced by the two subjects who were nauseated and their performance was adversely affected. Even this did not seriously affect vital homeostatic mechanisms and at no time were the subjects in need of medical care. Such countermeasures as selection, adaptation and drugs would have greatly minimized the nausea syndrome but fatigue might present a more difficult problem.

In attempting to apply the findings obtained in the SSR to a rotating orbiting spacecraft it is necessary first to consider important differences between the two with regard to the force environment.[28,29] A spacecraft with a radius of 30 feet and rotating at a velocity of 10 RPM would generate a centripetal force of about 1.0 G unit at the periphery. The disturbances in neuromuscular coordination resulting from changes in the linear gravitoinertial vector associated with "body movements" would be comparable to those in the SRR. The disturbances resulting from "head movements" might be worse due to the fact that the "upright" position of the astronaut would be at right angles to the axis of rotation rather than parallel to it as when in the SRR. At least this would be true to the extent that swivelling rotations of the head, which can be made with impunity in the SRR, would prove to be more stressful than nodding motions.

If the radius of the spacecraft were 15 instead of 30 feet, thus generating only 0.56 G unit at the periphery, the smaller magnitude of the linear force vector and the greater changes in direction associated with body movements would adversely affect equilibrium. Although the gyroscopic accelerations stimulating the semicircular canals would be the same the possible decrease in the (modulating) influence of the otolith organs might be significant.

It should be pointed out that in the SRR the subject's head, when he is bending over, reclining or recumbent, is nearly at right angles to the axis of rotation and that he adapts to whatever rotations of the head are made in these positions. Although plans have been made for a systematic study comparing the effects parallel and at right angles to the axis of rotation it is safe to predict that the differences will not be great and that adaptation in one circumstance will provide a large measure of "protection" in the other.

The fact that the onboard observer did not experience nausea and was never more than moderately fatigued suggests that much can be accomplished in the areas of selection, training and habituation with regard to the prevention of canal sickness. It would be worthwhile to explore the effect of slowly increasing the angular velocity of the SRR in order to minimize or even prevent unwanted effects. Moreover, adaptation at a higher angular velocity than that planned for a space flight might be advantageous.

Additional countermeasures might include such practical measures as the location of hand rails for support, the arrangement of instrument panels to take advantage of the fact that head movements in the plane of rotation are not stressful and the identification of the most effective drugs to prevent nausea and possibly other symptoms.

It is also of more than passing interest that the onboard observer who left the SRR for short periods was not seriously disturbed by such transitions, suggesting that simultaneous adaptation to rotating and stationary environments is feasible.

In the present experiment, especially in the late perrotation period, it was difficult or impossible properly to evaluate the etiological roles of confinement, muscular work and vestibular stimulation responsible for the symptomatology. The significance of factors other than the force environment could be determined, in part at least, by comparing the responses once with the SRR stationary and again with the room rotating. The role of the vestibular organs could be determined by a comparison of the effects between normal subjects and persons with loss of vestibular function.

From a more theoretical standpoint several findings deserve mention. The changes observed in the fusion frequency of flicker (CFF) are of interest whether they represent specific or nonspecific effects of stimulation of the semicircular canals. In either case the value of such a delicate indicator is emphasized and it points up the need to investigate not only its advantages and limitations but also its implications in terms of central nervous system mechanisms. If the changes in CFF were specific, the findings indicate that decrements in performance were associated with manifestations of the nausea syndrome but not with drowsiness and fatigue in the late perrotation period when, in fact, mean performance was above the prerotation level. It is possible that changes in CFF and the time-course of adaptation to these changes may have practical application. It would be interesting to compare these with nystagmographic findings.

The present experiment did not permit a distinction between the etiological roles of the semicircular canals, otolith organs and nonotolith gravireceptor mechanisms in the causation of ataxia and its disappearance. It did provide, however, a forceful reminder of the dominance of the visual upright over the gravitoinertial force upright under the experimental conditions, i.e., relatively weak inertial force and strongly structured visual field.

An attempt might have been made to explain the changes in serum level of the enzyme LDH by the changing level of muscular work were it not for the finding that on Day 1 two subjects had low and two had high values. The fact that on Days 2 and 3 all subjects had low values suggested that restraint in making either head or body movements or both were responsible. The relatively high values manifested by two subjects (MO and WI) on Day 1 are best explained if it is assumed that two factors were operating, namely, restriction in physical activity tending toward a decrease and vestibular stimulation tending toward an increase in serum LDH. MO, who restricted his activities considerably, was most susceptible to typical symptoms of canal sickness. WI, who restricted his activities least, necessarily stimulated the labyrinth most among the four subjects. Whatever the etiological factors involved, it is worthwhile to investigate the underlying mechanisms. Although it has been shown that serum level of LDH is related to muscular work, clearcut changes are manifested only with large changes in work load.[30] With regard to stimulation of the labyrinth it has been shown that it is an important factor modulating muscle tonus.[22]

One of the most striking and unexpected findings observed was the increase in rate of glucose utilization, which, directly or indirectly, must have had its genesis in exposure to the unusual force environment. The most likely etiologic factors and underlying mechanisms involved have been discussed above in some detail. Here it is important only to emphasize that the elucidation of this phenomenon might represent a significant scientific contribution.

It may be concluded that the present experiment, although it constituted only an initial probe into the problems incidental to adaptation at a velocity of 10 RPM, has advanced our knowledge in two main respects. First, it has shown that countermeasures in addition to adaptation are needed if rotational velocities of 10 RPM are required. Secondly, it has demonstrated the usefulness of the rotating room for the further exploration of vestibular and central nervous system mechanisms.

## ACKNOWLEDGMENTS

The success of the experiment was due in no small part to many persons of good will who are not listed as authors.

The two Marine Corps subjects were 2nd Lt Charles Moran and 2nd Lt Richard Wiseman; the two Navy subjects were Ensigns Edward Shaw and Carl Lind. Ensign Ben Vincent acted as back-up subject and helped with compilation of the data.

The expert technical assistance for laboratory determinations was provided by Edward A. Roginski and Sgt (E-7) Joseph Kelly, Walter Reed Army Institute of Research, and Mrs. Delores Beaver, Naval School of Aviation Medicine.

The entire crew of the Slow Rotation Room aided the investigators immeasurably. Robert Upchurch successfully carried out many and varying tasks which were essential to the experiment.

The excellent art work in the completed manuscript was done by Mrs. Wilma Bredt, medical illustrator, and the text edited by Mrs. Catherine Kasparek, publications editor.

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