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The Function of the Semicircular Canals During Weightlessness

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KNOWLEDGE OF the functioning of the vestibular organs in weightlessness is of practical and theoretical importance. From the practical standpoint interest centers around their role in causing illusions and space sickness. From the theoretical standpoint weightlessness offers a unique opportunity to investigate individual functions of the otolith organs and semicircular canals.

The most obvious and probably the most important effect of weightlessness on the vestibular organs is to cause deafferentation of the otolith apparatus. This contributes directly to postural[1, 4; 6-8; 11, 12] and visual[2, 3, 9, 10, 13] illusions which have been the objects of recent investigations. Weightlessness also provides an opportunity to carry out investigations on the canals in the absence of any stimulation of the otoliths, unless, in the course of the experiment, significant inertial forces are generated. The basic question whether the two vestibular organs function independently has not been answered satisfactorily, and the purpose of the following experiment was to compare the effects of stimulation of the semicircular canals under conditions of 1 G and near-weightlessness, using the oculogyral illusion[5] as the indicator mechanism. Any significant difference in response under the two conditions would have to take into account the functional interrelationship of canals and otolith as well as other factors. Insofar as we are aware, the only comparable experiment was conducted by Astronaut John Glenn,[4] who compared the illusion observed during rotation in the laboratory and in the Mercury spacecraft during the course of his orbital flight. He reported that the illusory effects as the result of very similar angular accelerations were "essentially the same."

METHOD

Subjects:—The subjects were the same three medical officers who had participated in previous studies[9, 10] in an F-100 aircraft at the USAF School of Aerospace Medicine. All had extensive experience as experimental subjects and two, RO and WA, age 34, were thoroughly practiced in the observation of visual illusions on the human centrifuge at the Naval School of Aviation Medicine and in flight. The third subject, KA, age 29, had had considerably less experience in flight and had received no familiarization on the centrifuge. Moreover, KA was the only subject who experienced airsickness; this was experienced in all maneuvers including weightlessness.

Experimental Apparatus:—The visual target and method of operation have been described previously.[9]

In order to obtain a history of angular acceleration with respect to time, the experimental subject wore an instrumented helmet (Figure 1) provided with three linear accelerometers and three rate gyros, each gyro reading out in a plane orthogonal to that of the other two gyros.* Rate information was transmitted by a cable to an instrumented seat pack under the subject. Within the seat pack, this rate information was differen-

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* This equipment was designed and built to USAF School of Aerospace Medicine requirements by the Instrumentation Branch, Air Force Flight Test Center, Edwards Air Force Base, California.

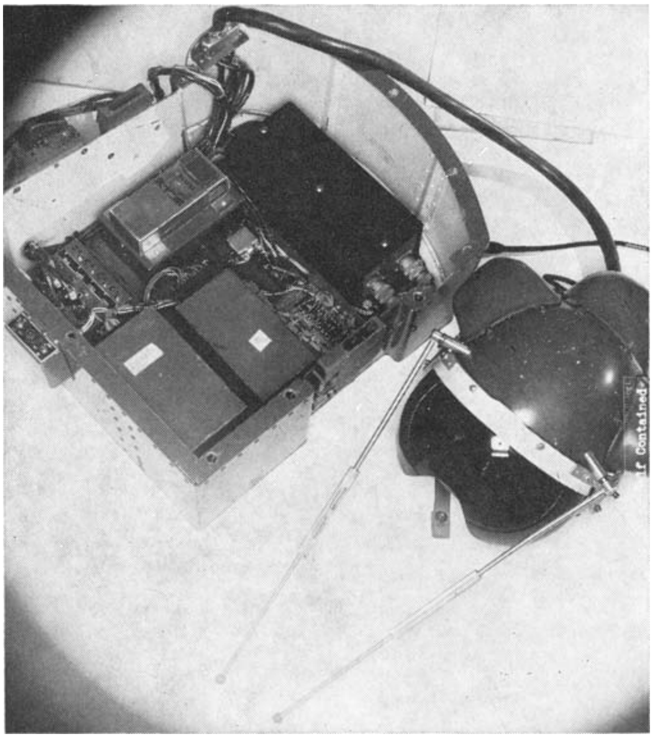

Fig. 1. The instrumented helmet is shown on the right, the seat pack on the left. The bulges on the helmet house the rate gyros and accelerometers.

tiated with respect to time so that either angular velocity or angular acceleration was alternately available for readout. Although the helmet was provided with linear accelerometers, these were not used in this study. Time history of aircraft linear acceleration was recorded, however. Angular velocity, timing information, and linear acceleration in the vertical axis were recorded on a CEC 119-5 recording oscillograph in the forward electronics compartment of the aircraft. The sensitivity of the angular velocity recording was set at approximately 50 degrees/second/inch while linear acceleration was recorded at 2 G/inch. Paper speed was 25 mm./second.

The instrumented helmet was provided with rods which were attached both to the helmet and to the illuminated box and functioned so as to keep the subject-to-target distance constant.

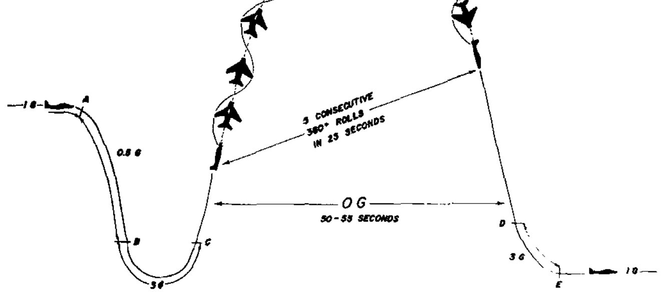

Fig. 2. Maneuver used to obtain large angular accelerations during zero G. In this maneuver the center of rotation of the aircraft moved along a Keplerian trajectory. The control maneuvers were roughly similar as regards flight path except that 1G instead of zero G was maintained for 50 seconds.

The aircraft used were two F-100F aircraft modified at the Air Force Flight Test Center for on-board recording and telemetry of physiological information. The F-100F is a supersonic single engine jet aircraft featuring two tandem cockpits.

Procedures:—After takeoff, when passing through 5,000 feet, the experimental subject positioned the metal box on the instrument panel and locked it in place. He attached the rods to the visual target housing and to the instrumented helmet and draped the various thicknesses of cloth over himself and over the apparatus.

The maneuver flown is shown in Figure 2. The parabolic maneuver used in previous experiments[9, 10, 15] was modified so that the aircraft was first dived to attain the necessary airspeed, then after 3 G pullup lasting approximately 20 seconds, the aircraft was pushed over into zero G. Once the zero G state had been approximated, at a pitch angle of approximately 53 degrees, a roll to the left was started by coordinated use of aileron and rudder at an angular acceleration of approximately 35 degrees/second[3] for approximately two seconds, thus establishing an angular velocity of approximately 70 degrees/second. This angular velocity was maintained to the best of the pilot's ability for five complete rolls. As the aircraft lost airspeed, rudder was used almost exclusively in order to maintain rotation, and the time required to complete five rolls averaged 28 seconds. After five rolls had been completed, rotation was stopped by coordinated use of rudder and aileron by establishing an angular acceleration approximating 80 degrees/second[3] for less than one second. Approximately 20 seconds of near zero G remained between the time the rotation was stopped and pullup was begun. Following a 3 G pullup, the aircraft was oriented for the next maneuver. Approximately four minutes elapsed between maneuvers.

Each experimental maneuver was alternated with a control maneuver. The control maneuver consisted of a pushover into a dive, a 3 G pullup, then a pushover into the 1 G state with five consecutive rolls to the left as performed during the subgravity maneuver. After rotation had been stopped, 20 seconds elapsed before a 3 G pullup was initiated. An average of 10 maneuvers per flight was obtained. Starting with the first pushover (Point A Figure 2), the subject continuously recorded his observation of the apparent rotation of the target and on the same recording the pilot signified the progress of the maneuver by calling off Points A, B, C, D, and E.

Because of the very low tolerance of Subject KA to rolling maneuvers either at zero G or 1 G, he participated in only three flights and on each of these flights was able to complete only one experimental maneuver and one control maneuver. The results he obtained were used only to qualitatively confirm the results of the other subjects. The other two subjects were given three flights each, totaling 58 maneuvers for both subjects.

Perfect zero G was not obtained. During a representative maneuver, linear acceleration varied between ± 0.05 G for 40 per cent of this subgravity period and

TABLE I. DATA (ARITHMETIC MEAN) OBTAINED ON TWO SUBJECTS DURING FIFTY-EIGHT MANEUVERS IN SIX FLIGHTS

	Duration of 3-G Pullup into Maneuver (sec.)	Average Angular Velocity in Roll	Angular Acceleration to Start Roll	Duration of Visual Illusion (sec.)	Angular Acceleration to Stop Roll	Duration of Visual Illusion (sec.)	Time Remaining at Zero-Gravity or at 1 G after Stopping Roll (sec.)
Parabola	22.2	70.6°/sec.	34.1°/sec.^{2}	10.50 ± 3.95 *	80°/sec.^{2}	10.32 ± 2.52 *	19.5
1-G (control	19.8	66.6°/sec.	31.6°/sec.^{2}	9.88 ± 3.42 *	91°/sec.^{2}	10.65 ± 4.68 *	17.7

* Standard deviation.

between ± 0.15 G for the remainder of the maneuver. The linear acceleration acting on the subject's head due to centrifugal force secondary to rolling of the aircraft was negligible as compared to the tolerances just mentioned. If the subject's head is assumed to be 5 feet from the center of rotation, this centripetal acceleration would amount to less than 1/100th of a G at the rotational speeds encountered. All evidence suggests that distance of the subject's head from the center of rotation was actually less than 5 feet.

RESULTS

Visual and Postural Illusions:—Once the subgravity state had been established and a roll to the left was begun, the experimental subject noted a definite perception of rotation to the left while at the same time the target appeared to rotate counterclockwise. Once rotation was established, the perception of rotation as well as the illusion of counterclockwise rotation of the target gradually decreased and finally vanished entirely after approximately 15 seconds. The cessation of the perception of subject rotation was synchronous with the cessation of apparent rotation of the visual target. For the remainder of the rolling maneuver, no clues could be perceived which would indicate to the subject that he was still in a continuous roll to the left. Upon the fairly abrupt cessation of the roll, a very strong aftersensation, rolling to the right, was perceived, and at the same time the visual target appeared to rotate clockwise. Again, after approximately 15 seconds both sensations disappeared. The subject reported the onset and offset of all illusions and sensations verbally and these were recorded. In the course of the control maneuver which was performed at 1 G, the same phenomena were noted by the subjects.

The results as regards angular velocities, angular accelerations, duration of the visual illusion of rotation of the target and the duration of the subject's perception of rotation are all tabulated in Table I.

The displacements of the target due to the elevator illusion, and previously observed and described in the course of weightlessness,[9] were also noted in this study but will not be commented upon here.

Motion Sickness:—These maneuvers were somewhat uncomfortable at first even for experienced experimental subjects. Very mild nausea was noted on occasion in two subjects while the third became airsick on each flight. While the experimental findings do not bear out any quantitative differences between happenings in the course of our control maneuvers as compared to the experimental maneuvers it was, nevertheless, the opinion of two of the subjects that the 1 G control maneuvers were more likely to produce nausea than were the experimental maneuvers at zero G. The third subject noted no difference. In comparing the subjective effects of these maneuvers in darkness to the subjective effects of the maneuvers while looking outside the cockpit, it was felt that total darkness tended to be less conducive to nausea or disorientation than did the maneuvers in which an outside frame of reference was provided. Upon abrupt cessation of the roll, an outside frame of reference created a conflict between visual clues and a strong illusory perception of rotation of the experimental subject. Abrupt cessation of rotation in darkness while viewing a visual target which was fixed to the airplane created no such conflict inasmuch as the illusory nature of the strong sensation of rolling to the right could not be determined in the absence of an outside visual reference.

DISCUSSION

The perception of rotation by experimental subjects upon stimulation of the semicircular canals by angular acceleration or by other means is a common phenomenon. The apparent rotation of the visual target has been experienced by all those who have been on ships, or have traveled in airliners, especially under turbulent conditions. When the airliner banks, the passenger perceives a sensation of rotation in one direction and at the same time his frame of reference within the airliner appears to turn with him. This same phenomenon was noted in observing the real target in our experiment. While a strong perception of rotation of the visual target occurred, it did not at any time appear to rotate with respect to the subject. Thus, the visual frame of reference never gave the subject clues which were contradictory to his subjective sensations of rotation. This in part explains why the maneuvers were more comfortable to subjects when performed under the hood.

When the subgravity state had been established and a roll to the left begun, the perception of rotation agreed with the actual rotation of the aircraft. As rotation became established and the perception of rotation of the subject and of the visual target diminished and disappeared, the clues perceived by the experimental subject were illusory with respect to the behavior of the target and remained so until the end of the maneuver. When the aircraft stopped rolling, for example, and remained wings-level in the dive, the subject felt a strong sensation of rolling to the right; a sensation which was "confirmed" by the apparent rotation of the visual target clockwise.

As is seen from Table I, no quantitative difference

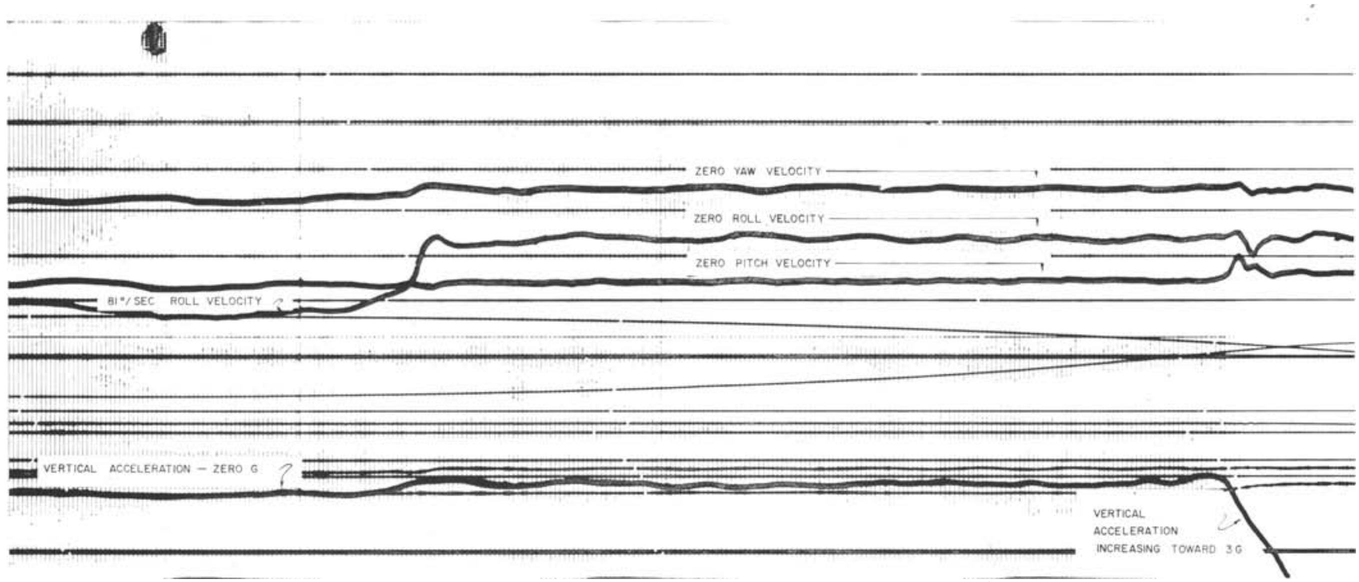

Fig. 3. A typical on-board recording, showing the output of three rate gyros and one accelerometer. On the left the start of the record shows rolling to the left at zero G. The stop of rotation is seen in the middle of the record. The pullup is shown on the right as the vertical acceleration tracing goes off the paper. The photographic recording has been traced over for purposes of reproduction.

can be established between the subgravity maneuver and the 1 G control maneuver as regards response of the semicircular canals to stimulation. While the angular velocities and angular accelerations are not identical at 1 G as compared to those produced in the course of our zero G maneuver, they are, nevertheless, very similar. The duration of the perception of subject rotation (which was precisely the same as the duration of apparent rotation of the visual target) both on onset and cessation of the roll was so similar at 1 G to that seen at zero G that the difference between them is obviously not significant.

In evaluationg these results, several limitations to the experiment should be kept in mind both as regards experimental design and sources of error. With respect to experimental design, it is clear that the subjective perception of rotation of the subject himself or of a visual target does not qualify as an exact measurement. An attempt was made to record nystagmus electrically in the course of two flights on one subject. The sensitivity of the apparatus allowed for recording of only coarse nystagmus, and no evidence of such nystagmus was seen in the tracings.

Among the sources of error, it was observed that the planimetric methods used to obtain angular velocity and angular acceleration data from our records were accurate to only within 5 per cent. Pilot technique caused substantial departures from pure zero G as noted under "Procedures." In addition, while rotation of the aircraft was by and large smooth and angular velocity constant, some variations from the ideal may be seen in the reproduction of one of our tracings (Figure 3) which is representative of the deviation from the ideal seen on our flights. Head position of the subject was not absolutely constant from one maneuver to another and neither was the position of the helmet. Our values for angular velocity and angular acceleration were computed from the output of only one rate gyro (the one oriented to the plane of rotation we were using), and the output of the other two gyros was assumed to be negligible. Inspection of our records (Figure 3) shows this to be a good assumption in most cases; however, occasional errors in our figures for angular velocity and angular acceleration did arise in those cases in which the assumption proved less than perfect.

Our findings, supported by those of Glenn who observed the oculogyral illusion in association with much smaller angular accelerations, indicate that the canals functioned similarly in 1 G, subgravity, and weightlessness. This would imply that the cupula-endolymph system is not significantly affected by weightlessness and that central nervous system mechanisms responsible for the oculogyral illusion are not significantly affected by deafferentation of the otoliths. Caution should be exercised in attempting to extrapolate these results to more prolonged exposure under weightless conditions.

SUMMARY

The sensitivity of the semicircular canals to stimulation during periods of weightlessness averaging 46 seconds was estimated by timing the duration of apparent rotation of a visual target (oculogyral illusion) and of the subject's perception of rotation after stimulation. Stimulation was accomplished by rolling the aircraft during periods of subgravity as well as during 1 G control maneuvers. Time-intensity relationships of the stimulus were obtained by means of specialized instrumentation incorporated into the experimental subject's crash helmet.

For three subjects under the conditions of our experiment, no significant difference between the sensitivity of the semicircular canals to stimulation at zero G was noted as compared to sensitivity determined by similar means at 1 G.

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