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Human Reactions During Flight to Acceleration Preceded by or Followed by Weightlessness

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DURING the past quarter of a century, aeromedical investigators have succeeded with great ingenuity in simulating on the ground nearly all the conditions and stresses to which the pilot of an aircraft or of a space vehicle could be exposed. Gigantic human centrifuges and rocket sleds have been created to produce high accelerations at controlled rates of onset and decay. Elaborate low pressure chambers now simulate any desired condition of temperature, humidity, and altitude, including even explosive decompression. This makes possible a thorough and more comfortable observation of the subject's physiologic reactions than has been possible in actual flight. However for studying weightlessness, one of the most challenging problems of space flight, no laboratory has been available which could produce this condition on the ground.

Investigators resorted back to a device which they had nearly forgotten as a research tool: the aircraft. The recent "renaissance" of the aeromedical experimental aircraft, which represents the oldest aeromedical laboratory, has been the result. Here weightlessness has been experienced and observed in the tradition of the first acceleration studies done more than twenty-five years ago before centrifuges for human use were available.

REVIEW OF LITERATURE

In 1950 Haber and Haber[7] described theoretically the possibility of producing the weightless state for medical research by flying segments of a Keplerian ballistic trajectory. Extensive studies of the behavior of humans and animals during the weightless state began at this time. Figure 1 contains a chronological review of the

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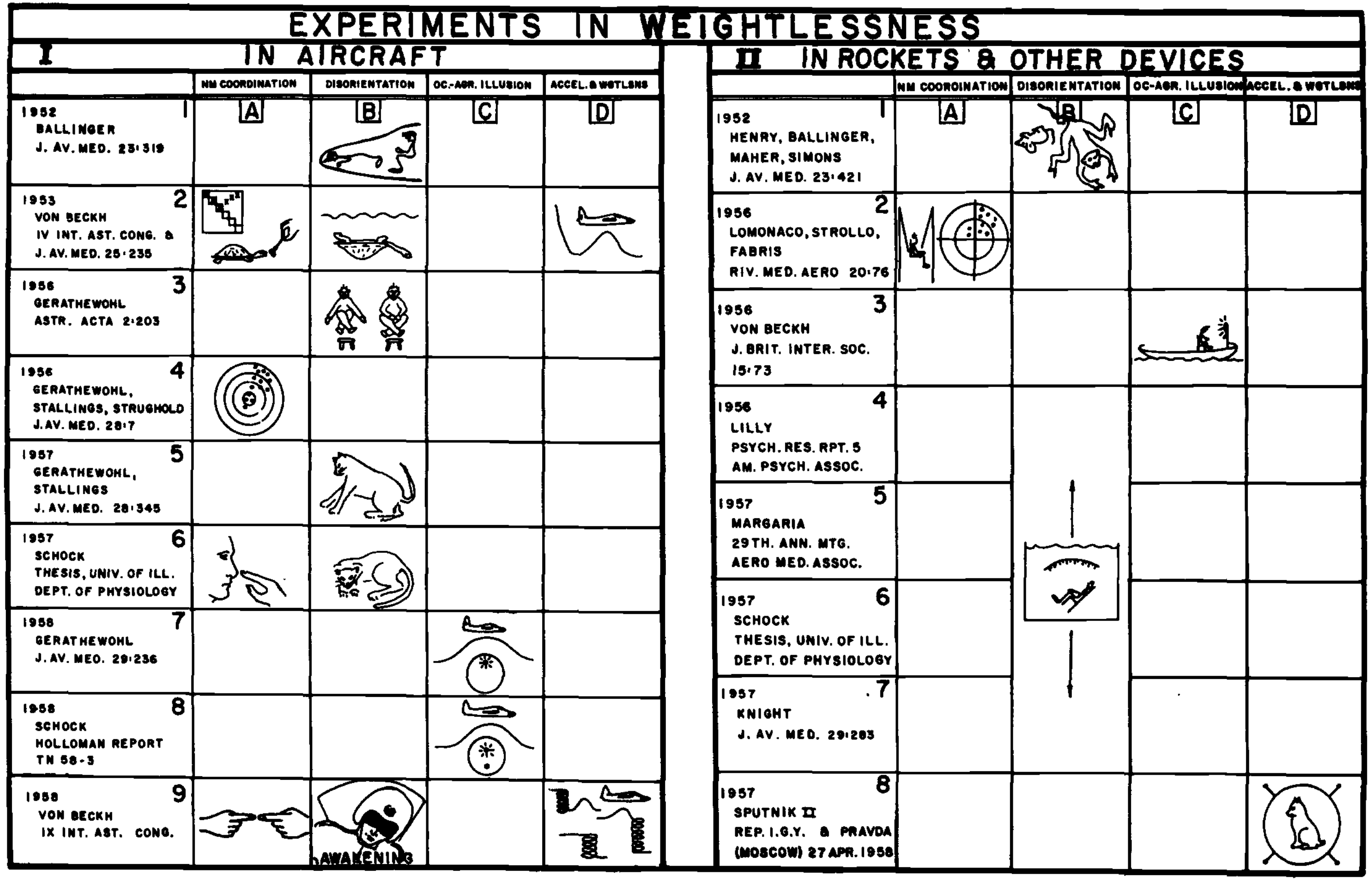


Fig. 1. Chronological chart of weightlessness experiments (I) in aircraft and (II) in rockets and other experimental devices. The vertical columns A, B, C, D, represent the different areas of research: neuromuscular co-ordination, disorientation, oculoagravic illusions, alternation of acceleration and weightlessness.

different areas of research in weightlessness. Divided into two parts, it indicates (I) experiments in aircraft and, (II) those conducted in rockets and by other methods such as "subgravity towers," on ships or by immersion in swimming pools. The vertical columns A, B, C, D correspond to the different areas of weightlessness research such as neuromuscular coordination, disorientation, optical illusions and effects of the alternation of weightlessness and accelerations. In this report the numbers in parentheses refer to Figure 1.

In 1953 this author described an eye-hand coordination test,[20] (I-A-2) termed "cross drawing test," which consisted of drawing crosses in small squares arranged diagonally across a sheet of paper attached to the instrument panel of the experimental airplane.

Each subject took the test during non-accelerated horizontal flight, during radial acceleration and during the weightless state. The tests were made both with eyes open and with eyes closed. It was shown that during the weightless state, especially when blindfolded, the diagonal direction of the crosses could not be maintained and the line of the drawn crosses showed an upward deflection ("overshoot") because of the changed input-output ratio of the elevating arm muscles. Later it was shown that after several attempts the performance of the subjects improved.

These findings were confirmed by Gerathewohl[4] (I-A-4) who employed similar tests, consisting of aiming and hitting, with a stylus, a bullseye attached at arms length at the instrument panel, and by Lomonaco, Strollo and Fabris[12] (II-A-2) who used the short duration of weightlessness produced in their ingenious device, termed "Subgravity tower," for performing a similar test. These investigators described an identical "overshoot" upwards and concluded that the subjects learn noticeably on subsequent trials.

Ballinger[1] (I-A-1) formerly had conducted acceleration studies in a modified F-80E fighter. The subject was tied down on a prone bed in the nose of the aircraft. His subjects did not report disorientation or co-ordination troubles. However, he predicted that disorientation or lack of co-ordination could have been extreme if the subjects had been deprived of visual control and of adequate restraint.

Henry and his associates[8] (II-B-1) carried out most outstanding investigations during rocket flights with the V-2 and Aerobee rockets. Heart rate, blood pressure, and respiration rate were telemetered to a ground station and a motion picture camera photographed the behavior of the test animals.

It was shown that a normal mouse during weightlessness was confused when floating freely in the compartment. Another mouse, whose inner ear was previously destroyed, was less disturbed because it did not receive any labyrinthine cues either true or false. Besides that, the mouse had learned after the labyrinthectomy to replace the missing information from its inner ear by the sense of vision.

This author[20] (I-A-2) reported similar findings which were obtained in subgravity flights with water turtles *(Hydromedusa tectifera and Chrysemis ornata).* These animals were especially suitable for studies of orientational behavior and neuromuscular co-ordination because of their ability to move under water with extraordinary speed and skill in all directions during their quest for food. They strike like snakes at their food, projecting their S-shaped necks with pin-point accuracy at the bait. It was shown that during the weightless state these animals were incapable of striking accurately at the bait. When striking, their heads passed over, under, or to one side of the bait. Only one turtle, without labyrinthine functions, but already visually adapted, behaved with complete normality during the experiments.

Gerathewohl[3] (I-B-3) analyzed the subjective impressions of numerous persons during the weightless state: one-fourth of the subjects suffered severe discomfort and nausea; half of them were comfortable and reported even feelings of exhilaration and pleasantness; another fourth had intermediate reactions as slightly disagreeable motion impressions such as tumbling, falling, or being suspended in an inverted position, but only moderate nausea. Gerathewohl and Stallings[6] (I-C-7) and Schock[16] (I-C-8) contributed valuable studies of optical illusions, termed oculo-agravic illusion. A luminous target as well as a visual after-image, observed in the dark, seemed to be displaced upwards during the weightless state. In consideration of the importance of visual information in the weightless state these illusions could possibly present inconveniences in space flight.[16] A further contribution was made by Gerathewohl and Stallings[5] (I-B-5) and by Schock[15] (I-B-6) studying the labyrinthine posture reflex (righting reflex) in cats, showing that after a certain duration of weightlessness this reflex ceased to function.

Lilly,[11] Margaria,[13] Schock,[15] and Knight[10] (II-B-4 to 7) succeeded in simulating the weightless state to a certain extent by immersion in water. Applying Archimedes' principle, a subject immersed in a fluid of about the same specific weight is in a kind of weightlessness relative to the surrounding medium. Tilting the person back into an approximate horizontal position, the so-called "blind spot" of the otoliths could be reached and only a minimum of labyrinthine cues would be emitted.

Considering the last column of Figure 1, Alternation of Acceleration and Weightlessness, we see that this area, when compared with the others, was the least investigated.

In 1953 this author included in his early series of experiments certain flights in which the pull-out before entering the weightlessness parabola, which normally does not exceed the 2-G value, was made at high speed and so abruptly that G values of up to 6.5 G resulted.[20] (I-D-2). Control runs were made with the same high G pull-out, but without subsequent weightlessness, and instead were followed by unaccelerated horizontal flight. It was found that blackout lasted longer and discomfort and disorientation were stronger when the recovery from the G-stress took place in the weightless state. After this early observation no more airborne experiments on alternation of weightlessness and accelerations were reported, until the Soviet IGY release[19] about *Sputnik II's* passenger, Laika (II-D-8) stated that "the accelerated heart rate of the animal, produced by the acceleration of the thrust, returned gradually to the normal rate after the entry into the weightless state. It took, however, about three times as long for the number of heart beats to reach their initial values, as it did in laboratory experiments, when the animal was subjected to accelerations similar to the launching accelerations."

The aspects of alternation of acceleration and weightlessness have today a special importance because this condition will occur during the ascent and the re-entry of a rocket vehicle. In biosatellite experiments the subject will have to endure an accelerative phase from the launching until the burnout of the engine. The transition from this powered ascent to weightlessness will be very abrupt because the designers prefer an abrupt burn-out to a gradual one. On the other hand, during orbital and space flights the subject would stay for hours, days, or weeks in the weightless state, and during the re-entry would again be exposed to considerable G loads.[2,9,24]

The author in his early experiments termed the pattern flown as "post-acceleration weightlessness." However, under these new circumstances, inasmuch as the reactions to accelerations with preceding or following weightlessness are to be studied, an inversion of the nomenclature seems more convenient: pre-weightlessness accelerations for the ascent patterns and post-weightless accelerations for the re-entry patterns. Because of the importance of the problems in consideration of space flight, fifty-one subgravity flying missions of the overall weightlessness program of ninety-eight missions were performed in the study of pre-weightlessness and post-weightlessness accelerations.

METHODS

Aircraft.—The test vehicle was a Lockheed F-94C two-place jet propelled interceptor aircraft, powered by a Pratt-Whitney J-48-P-7 engine, developing with after-burner a maximum of 8,750 pounds of thrust. Preliminary experiments showed that in the two-place, supersonic fighter-bomber F-100F, much longer durations of weightlessness could be obtained. However, the different behavior of fluids in the weightlessness state causes functional difficulties in the fuel, lubrication and hydraulic reservoirs, and in its sensitive engine, which are more pronounced than in the less sensitive F-94C engine. The author participated in one F-100F mission in which subgravity parabolas of limited duration were authorized. During these maneuvers, oil and hydraulic pressure dropped critically, and further attempts to fly ballistic trajectories in this aircraft were discontinued. At the same time the indicated values of the liquid oxygen gauge and the oxygen-pressure gauge gave reason to believe that conventional liquid oxygen converters would not function satisfactorily in zero G conditions of longer duration.

Flight Patterns.—In the earlier series of experiments[20] (I-D-2) high radial accelerations of up to 6.5 G were produced only by a sharp pullout for

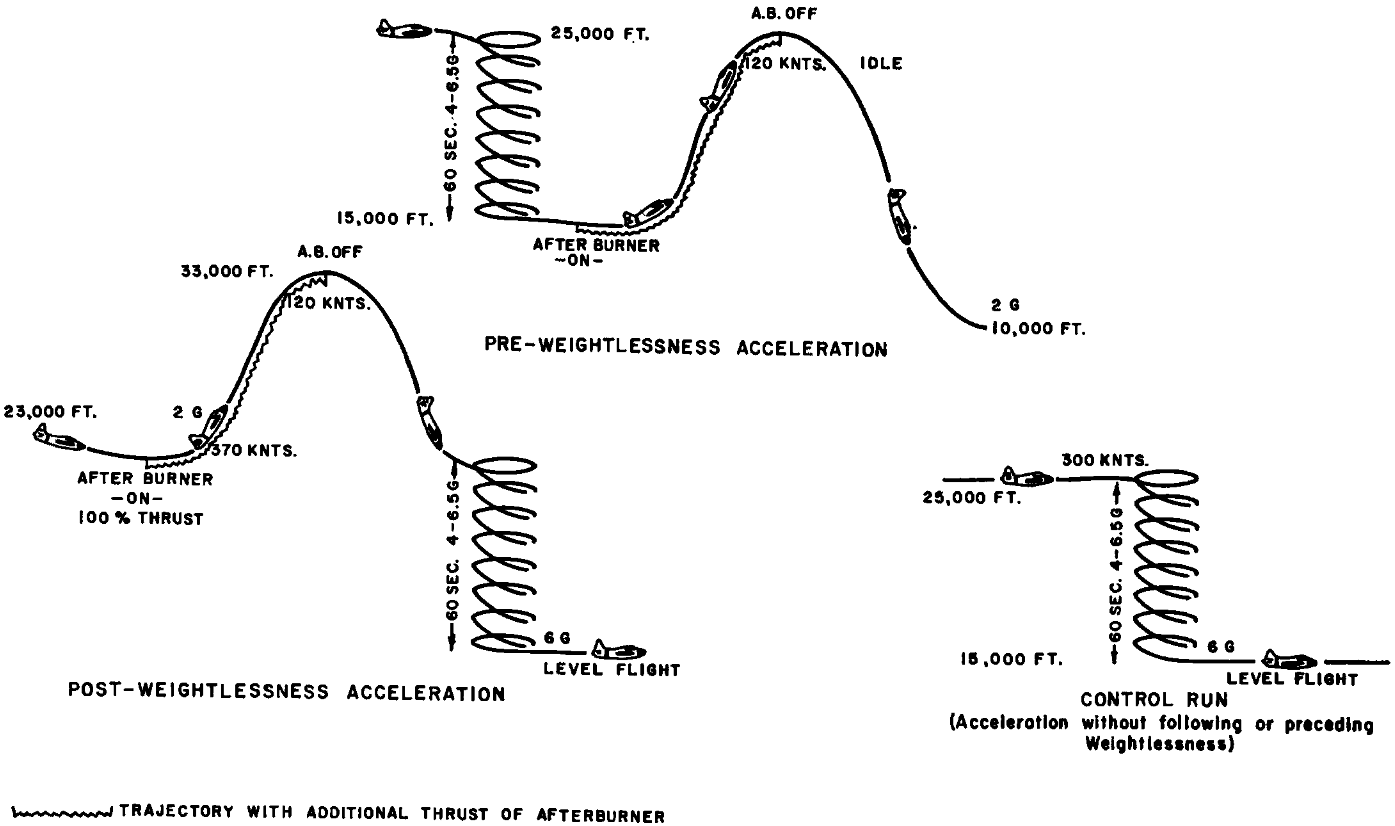


Fig. 2. Flight patterns used for simulating the accelerations of thrust and reentry followed or preceded by weightlessness.

a duration of from 5 to 8 seconds. In these experiments, however, it was desirable to simulate as nearly as possible, the conditions of rocket take off and re-entry. Therefore another high centrifugal G load-producing pattern was adopted in which periods of from 4 to 6.5 G accelerations were obtained by flying continuous steep turns. Giving up altitude during these turns helps in dosifying and maintaining the desired G values. These maneuvers were termed "diving spirals," (Fig. 2).

The weightless state was obtained for periods of from 35 to 45 seconds by flying Keplerian ballistic trajectories. These patterns were combined in the following flight program: the pattern of pre-weightlessness acceleration, simulating the thrust of a rocket vehicle, and the weightlessness following burnout, was produced in the aircraft by a diving spiral of 40 to 60 seconds duration, which was initiated at an altitude of 25,000 feet and followed by a subgravity trajectory. These diving spirals are completely controlled maneuvers producing centrifugal forces and, because of the apparent similarity of the graphs, should not be confused with spins. The loss of altitude during the spirals was approximately 10,000 feet.

Post - weightlessness accelerations, simulating conditions which would occur during re-entry into the atmosphere after orbit or true space flight, were produced by a Keplerian trajectory initiated at 23,000 feet, reaching the apogee at 33,000 feet, and a subsequent diving spiral. A control pattern was flown, consisting of the diving spiral followed after the pullout by unaccelerated horizontal flight. This pattern established the G tolerance and subject's reactions to accelerations, when weightlessness was not involved. All spirals during a given mission were flown at the same number of G and the same duration. The sequence of these three patterns was changed adequately from mission to mission, to make sure that fatigue in the patterns flown later in the same mission could not jeopardize the correct evaluation of the observed reactions and symptoms.

The subject was instructed to sit upright and to avoid straining or "fighting the G," while the pilot was protected by an anti-G suit, and was allowed to increase his G-tolerance by crouching forward. In this way it is possible to black out the subject, while leaving the pilot in full possession of his senses and in control of the aircraft.

INSTRUMENTATION

G Registration.—In the pilot's cockpit close to the instrument panel was a visual display, designed by Schock and Simons,[14] consisting of two microammeters with a range of 25-0-25 microamperes connected to a set of sensitive Statham accelerometers with a range of ± 0.5 G, which were fixed to the airframe. Each division on the microammeters is equivalent to ± 0.014 G. If the needles of both microammeters were on the zero mark, the pilot knew that his trajectory was exact.

Another set of sensitive accelerometers was fixed to the subject with a chest band, to provide recording of accelerations actually experienced by the subject. The output of these accelerometers was fed, together with the other data, into a sensitive galvanometer-type oscillograph recorder (Midwestern 560). In several flights a second conventional accelerometer and a stop watch were added in the subject's cockpit, and both were photographed by the motion picture camera. Their function will be mentioned later.

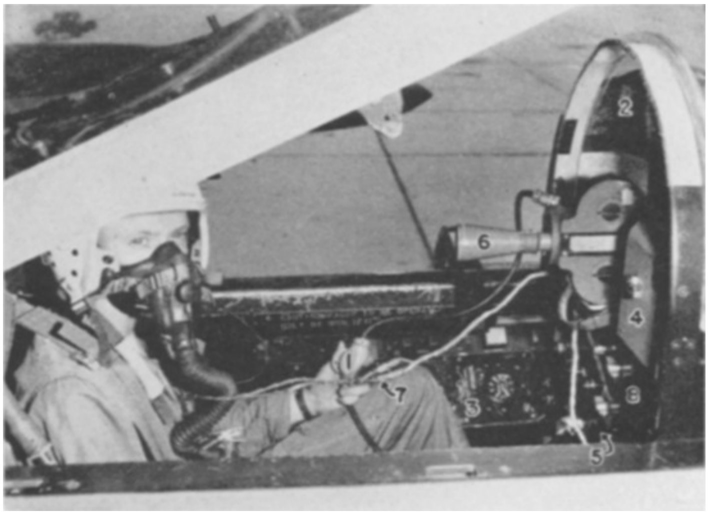


Fig. 3. Subject before takeoff with recording switch (1) in left hand. Shown also are (2) aluminum foil with high reflective qualities to reduce changing light conditions during diving spiral and aid photography; (3) oxygen regulator; (4) oscillograph; (5) electrocardiogram; (6) camera with wide angle lens; (7) quick-release plugs for leads of electrodes; and (8) GSR dermo-ohmmeter.

Electrocardiography and Galvanic Skin Resistance Recording (GSR).—The instrument rack in the subject's (rear) cockpit (Fig. 3) contained an ECG amplifier (Grass, P-5), a dermo-ohmmeter (Yellowspring-Fels, 22-A, airborne), the recording oscillograph, and battery power supplies. Two ECG electrodes were placed the chest; the other on the right ankle. The GSR electrodes were applied to the sole of each foot. All five electrode on leads were united to one cable. A quick release plug was provided between the subject and the amplifier, to avoid hazard or delay in case of emergency ejection.

Cinematographic Observation.—The subject was photographed continuously during the maneuvers by a motion picture camera (Bell & Howell, B-1A) with a wide-angle lens (Wollensack, F: 1.5, 89 degree). At the same time the camera photographed the accelerometer and stop watch (Fig. 4). The subject indicated with his fingers the G values, as transmitted from the pilot through the aircraft communication system. Greyout was shown by waving hand movements. All this helped in the chronological reconstruction and evaluation of the physiologic reactions of the subject and to co-ordinate this data with the information of the recorded voice.

Fig. 4. Subject in cockpit, showing mounting of clock (at left upper arm) and accelerometer (right) for use in analysis of motion pictures.

Voice Recording.—Pilot, subject and experimenter were in continuous radio communication. The subject was indoctrinated to describe his impressions and his symptoms into the microphone. He carried a miniaturized tape recorder (Mohawk, BR-1) on his left leg (Fig. 5) and the aircraft was in constant communication with a ground station from which the experimenter could speak to the pilot and subject. The entire conversation was recorded both on the ground and on the subject's tape recorder. This assured preservation of a verbal record even in case of radio failure.

The two way radio installation gave the opportunity to initiate also some psychologic studies. From the ground station, a research psychologist asked test questions concerning word associations, inverted number repeating, syllable completions, and drawing tests. The responses were compared to others which had been recorded on the ground before and after the flight.

Fig. 5. Pre-flight preparation of subject. On the chest belt (1) is a sensitive accelerometer for recording G values near the zero mark, and (2) on left leg is miniaturized tape recorder to assure preservation of verbal data in case of radio or ground-station recording failure.

RESULTS

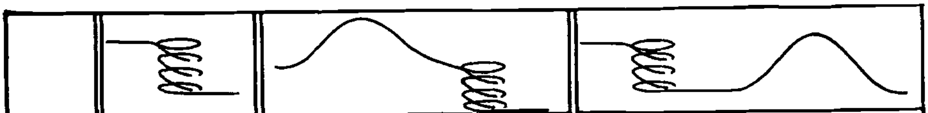
In fifty-one missions of more than 200 weightlessness and acceleration patterns, eleven different subjects experienced pre-weightlessness and post-weightlessness accelerations. The subjects included two experienced jet pilots, two persons who had never flown previously, and seven others of intermediate flying background as pilots or observers. Figure 6 is a summary of these missions.

Post-Weightlessness Acceleration.—The subjects experienced higher strain when they were exposed to a G load immediately after the weightless state. Two subjects, who did not blackout during the control run at 5 G, blacked out during the post-weightlessness acceleration pattern at 3.5 and 4 G, respectively. Three subjects who blacked out at 5 G during the control run blacked out at lower G values and at shorter G duration in the post-weightlessness acceleration pattern.

One subject who tolerated 5 G in the control run without visual impairment, blacked out in post-weightlessness acceleration pattern at 3.5 G and lost consciousness at 5 G. Subjects who did not black out either in the control run or in post-weightlessness acceleration, nevertheless reported stronger discomfort during the latter.

This was also observed in the cinematographic records.

Pre-Weightlessness Acceleration.—It requires a special technique to re-



		Control Run				Post-Weightlessness Acceleration								Pre-Weightlessness Acceleration								
						Weightless Phase				Accelerative Phase				Accelerative Phase					Weightless Phase			
Subject	Number of Missions	Discomfort	Visual Impairment	Substernal Pains	Loss of Consciousness	Discomfort	Disorientation	Substernal Pains	Nausea	Discomfort	Visual Impairment	Substernal Pains	Loss of Consciousness	Discomfort	Visual Impairment	Substernal Pains	Loss of Consciousness	Recovery from Blackout Delayed	Discomfort	Disorientation	Substernal Pains	Nausea
J.F.	12	+								++	+			+					+		+	
C.L.	8	+							+	++	+			++	++			+++		++	++	+
H.v.B	6	+								++	+			+								
C.McC.	6	+								++	+			+	+							
J.B.	5	+	+							++	+++		++	+	+			+++	+	++		+
E.D.	4	+	+							++	++			++	+			++	+	++		+
H.C.	4	+								++				+						+	++	
L.B.	2	+	+							++	+++			+	+							
T.S.	2	+								++	+++	+++		+								
R.H.	1	+								+				+								
E.S.	1	+								++				+					+			+

Fig. 6. Summary of 51 missions.

strict the transition phase, from the G-producing spiral to the weightlessness trajectory, to a duration of less than five seconds. This was not always possible. In the missions in which this transition period was short enough, however, subjects reported unusual symptoms of longer duration of blackout (three subjects), generalized discomfort (four subjects), chest pains (three subjects), and pronounced disorientation (four subjects).

Galvanic Skin Resistance Recording.—The data showed a drop in resistance 25 seconds before the G load was initiated when the pilot indicated that the altitude to initiate the spiral had been reached by saying "ready to go." (Fig. 7). During the acceleration the GSR returned to its initial value. In the transition phase to weightlessness a sharp drop appeared, but with the onset of weightlessness an increase took place again. After the final pull-out, i.e., during unaccelerated horizontal flight, the resistance rose steadily to its initial value.

It is too early to draw conclusions about specific responses to weightlessness and its transition phases. In the run illustrated in Figure 7, marked decrease in GSR occurred with anti-

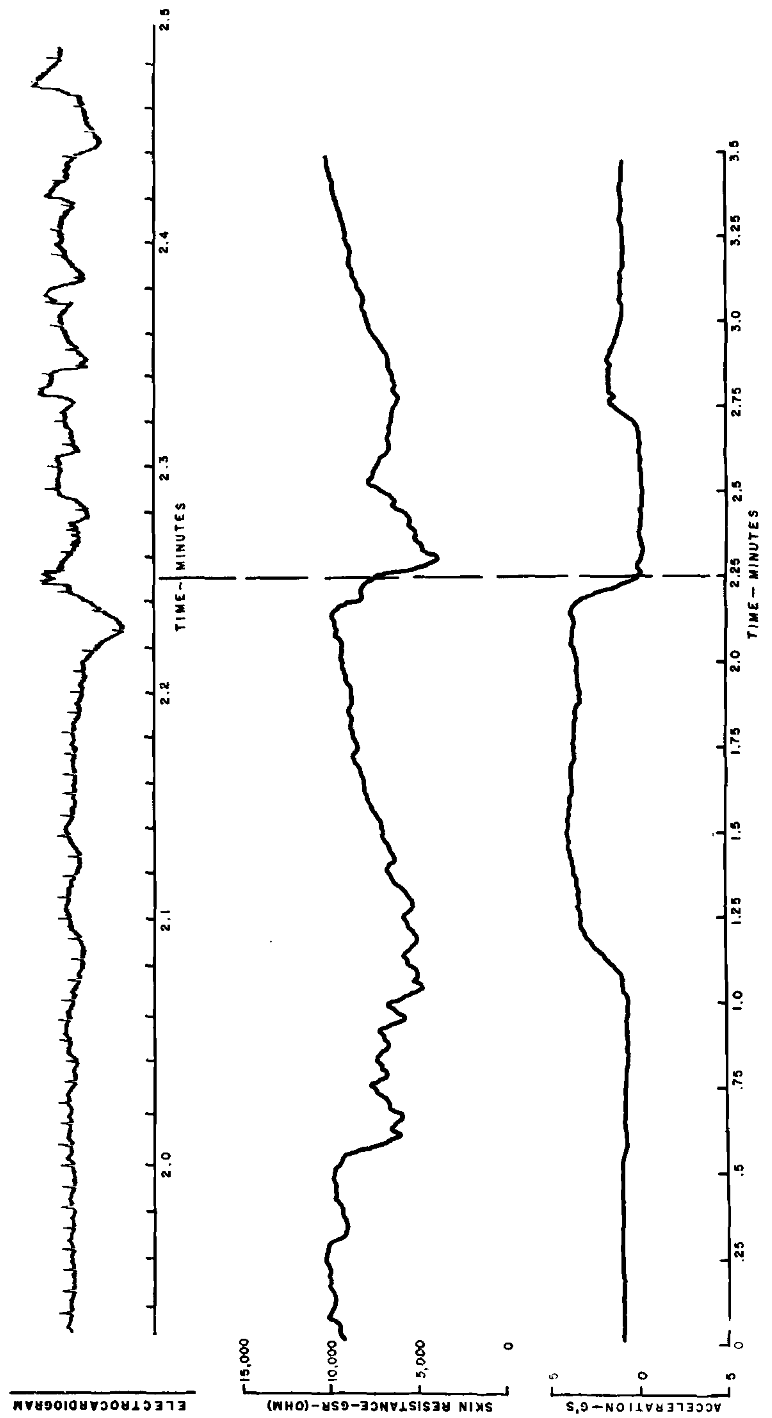


Fig. 7. Electrocardiogram, galvanic skin response (GSR) and acceleration, vs. time.

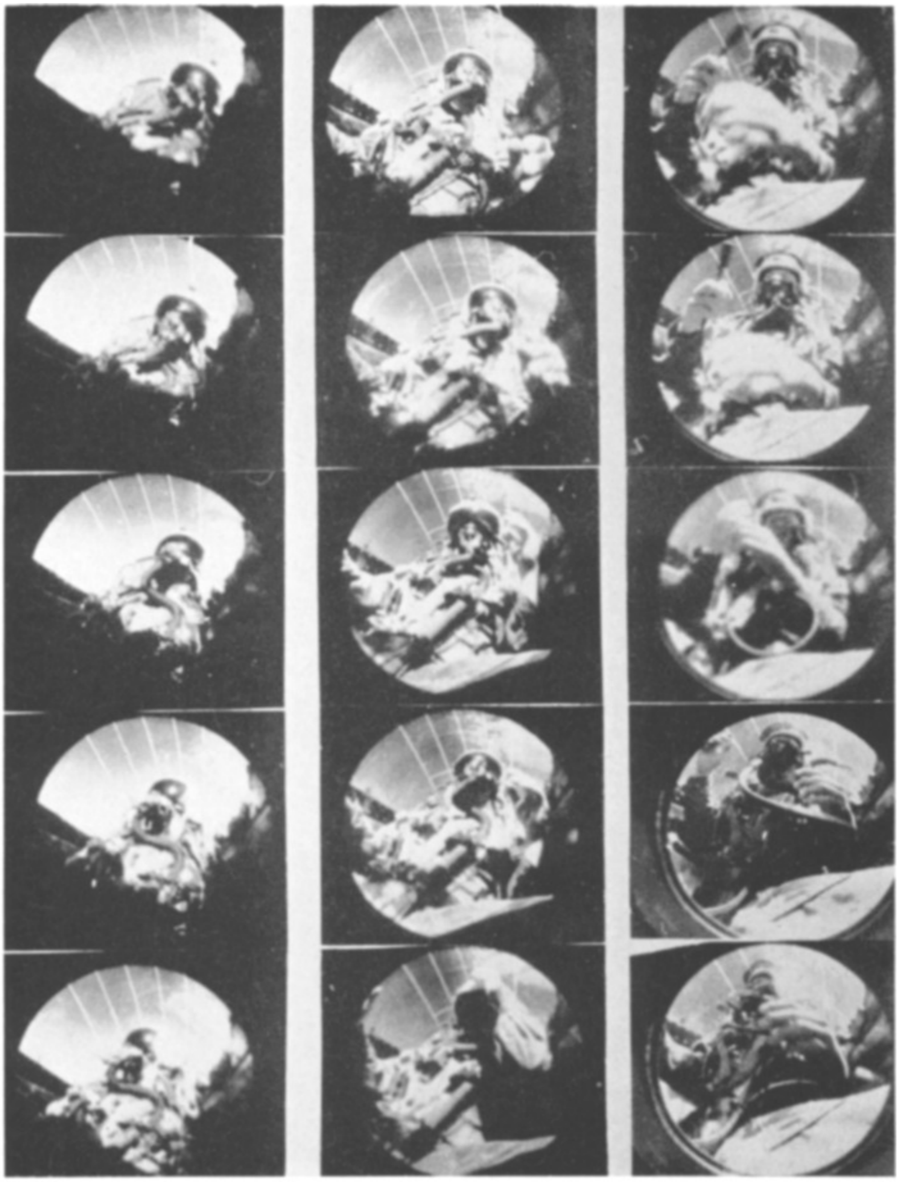


Fig. 8. Motion pictures taken in flight awakening in weightlessness. Column A: Frame 1: subject is asleep, leaning against the cockpit wall. Frames 2-5: awakening. Column B: Frames 1-5: lifting hand to raise dark visor of helmet; and Column C: Frames 1-3: reconnects with difficulty the plugs of helmet earphones; and frames 4-5: disorientated, tries to hold on to the cockpit to maintain some sort of normal posture.

cipation of maneuvers and change of intensity of gravitational cues which also can be considered as warning messengers of a new gravitational situation. Such decreases are generally associated with increased levels of alertness. Specific responses to the weightless state "per se" could not be observed.

Disorientation.—A supplementary problem occurred in our test series and should be reported here, though it is not directly associated with alternation of weightlessness and accelerations. Simons,[18] during his balloon flight *Manhigh II* experienced marked disorientation on awakening from one of his short periods of sleep, and required several seconds before he was aware of his situation. This observation suggested an investigation of the impressions of a subject who is awakened during the weightless state. A prospective *Manhigh III* subject was selected for this experiment. He went without sleep for 48 hours. After a full breakfast, which increased his sleepiness, he entered the rear cockpit of our experimental F94C aircraft. He unhooked his headset at 11,000 feet, so as not to be disturbed by the conversation of the pilot, tower, and experimenter. Twenty-five minutes after takeoff the subject fell asleep, leaning against the right side of the cockpit (Fig. 8). A string was fixed on his left wrist, which the pilot could pull to awaken him. The pilot avoided any rough maneuvers. The aircraft was then flown in a zero G trajectory and the subject was awakened. His first impressions upon awakening were that his arms and legs "were floating away from him" so that he felt a desperate need to pull them back toward his body to maintain some sort of normal posture. He tried to hold on to the canopy and some part of the cockpit. He could not orient himself. He is a pilot of over 500 jet hours and had not experienced such pronounced disorientation previously.

DISCUSSION

Delayed recovery from black-out and increased discomfort caused by pre-weightlessness acceleration was first observed by this author in 1953.[20] Similar data concerning delayed return to normality of phenomena induced by the previous accelerative phase was reported[19] in the tachycardia of Laika in *Sputnik II* which lasted three times longer than in previous centrifuge runs when weightlessness was not involved.

Three interpretations of these observations come to mind. First, it could be assumed that the complicated synergism of the autonomic cardiovascular pressoreceptors and pressoregulators is "calibrated" for function in a normal one G field. In zero G conditions some disorder or "confusion" of these complicated reflex mechanisms could be expected. This speculation seems to be supported by our finding that the heart rate, after the accelerative phase of the control run, returns to the initial value and remains at this value. When the acceleration is followed by the weightless state, however, the return to the initial value takes place more or less after the same length of time, but the heart rate continues fluctuating up and downwards for a certain period (Fig. 9). This possibly could correspond to the time necessary for the cardiovascular reflex mechanisms to adjust to the unaccustomed zero G conditions. The native, contradictory to the former one. After the accelerative phase a large quantity of blood returns to the

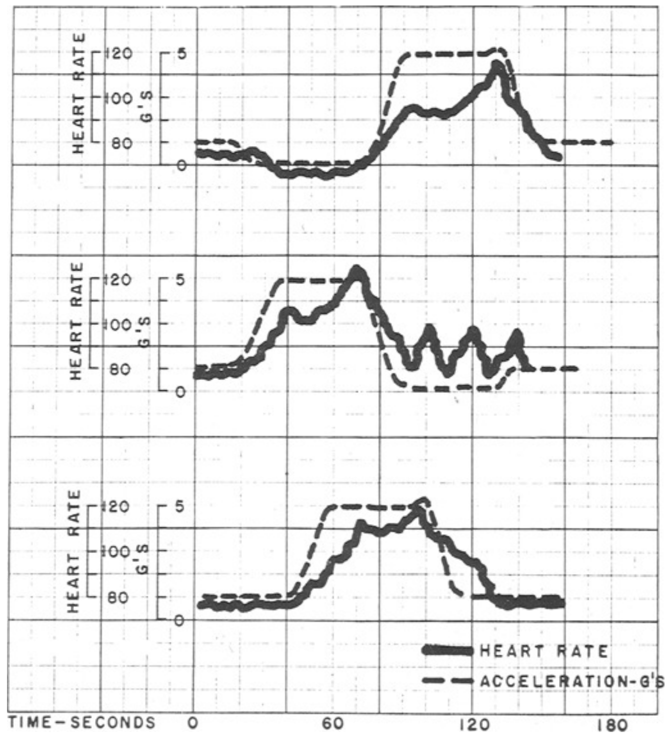


Fig. 9. Acceleration and heart rate vs. time during post-weightlessness acceleration (above), and pre-weightlessness acceleration (center), and control run (below).

difference in the heart rate patterns between data from *Sputnik II* and our experiments may be explained by the higher accelerative load and the additional stress of noise and vibration in the *Sputnik* flight.

Second, delayed recovery and generalized discomfort might be caused by the general relaxation of the muscles during the weightless state. This would cause delay in the return of venous blood to the right ventricle.

Third, we could assume an alter- right heart producing the phenomena of overfilling, which would explain the cardiac disfunction and substernal pains experienced by three subjects.

A series of roentgenograms, made during the transition phase, might explain these observations, but the installation of radiographic equipment in a modern fighter aircraft, equipped with ejection seats, is not so simple as it was twenty years ago in the experimental Heinkel He-70.[28]

Referring to the post-weightlessness

acceleration findings, it seems rather logical that a subject who has been in the weightless state, even for a short period should evidence greater strain when G loads are imposed. In the evaluation of both groups of experiments we must consider that in our experiments the subject was exposed to head-foot accelerations. In manned space flight, however, the location of the subject would be such that the main acceleration of thrust and reentry would act in a transverse direction. For technical reasons it was not possible to locate our subjects in supine position. Also, the G values obtainable in our experimental aircraft would not have been high enough to cause major discomfort in the less "vulnerable" supine position, and we would not have had at our disposal such adequate parameters as blackout for comparing the reactions of the different conditions. We can assume also that in supine position discomfort and impairment thresholds would be lowered and orientation and blood pressure regulation would be equally affected (Figs. 10 and 11).

Because there is a decreased acceleration tolerance every effort must be made to reduce G loads to a minimum. Despite the fact that a subject is positioned transversely to the longer axis of the vehicle and, therefore, protected against the acceleration of the thrust, there exists the possibility that by imperfections of the automatic guidance systems, especially in the gliding reentry patterns and in emergency separations of the capsule from the vehicle, high G loads could be produced. This G force would act in the vulnerable longitudinal axis of the subject. One may recall the formerly described principle of multi-directional G protection[22] which would protect the subject against severe accelerations with continuously varying direction, rate of onset and intensity.

CONCLUSIONS

Alternation of weightlessness and acceleration results in a decrease of acceleration tolerance and of the efficiency of physiologic recovery mechanisms. This indicates that acceleration thresholds of reversible and irreversible injury will be lower in space flight conditions than in the one G field of man's earthly environment. Defects of circulation, muscular effectiveness, vision, and of conscious judgment will occur at lower acceleration values and will probably continue for longer times than they do under present normal flight conditions. In an astronautical venture depending upon the skill of a human pilot, a blackout, lapse of judgment or even the slightest reduction in efficiency at a crucial time, could undoubtedly cause the failure of the mission.

The implications for planning of manned space flight are, first, that thrust values and reentry profiles must take the lower acceleration tolerance into consideration and, second, that adequate G protection must be designed for the pilot to prevent dangerous effects of high acceleration.

ACKNOWLEDGMENT

These experimental flights were possible only by the thorough co-operation of numerous services of the Air Force Missile Development Center, Holloman Air Force Base, New Mexico. The author is especially

celeration showed more severe effects than in other runs producing the same G load without preceding weightlessness. Column A: frames 1-2: weightless state; and frames 3-6: under increasing acceleration. Column B: frame 1: weightless state; and frames 2-6: under increasing acceleration.

A B

Fig. 11. Subject during post-weightlessness acceleration and pre-weightlessness acceleration. Column A: Subject in post-weightlessness acceleration increasing to 5.5 G. Column B: Subject in the transition phase from an acceleration peak of 6.5 G to weightlessness. Frames 1-2: 6.5 G; frames 3-5: recovering from G stress during weightlessness.

indebted to the Fighter Test Group, Maintenance Services, Photo Lab Services, and Messrs. C. M. McClure, H. Castillo, A. Brown, and J. C. Bunn for their efficient help in developing and monitoring the instrumentation and recording devices. Last, but not least, I want to recall the co-operation of the subjects of these missions, who volunteered for this task, which was for them not always very comfortable.

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