Human Factors: Aspects of Weightlessness*

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I. Introduction

The phenomenon of weightlessness associated with orbital flight, presents many problems in many areas of space science and technology. Fluids, biologic systems, plant systems, mechanical systems, materials, etc., in many instances behave much differently in a zero "g" field than in the common environment of 1 g. Often their behaviors are not completely predictable and as a consequence pose intriguing problems for new areas of study.

The material in this chapter is devoted primarily to considerations of

* *Note:* The contents of this chapter reflect the personal views of the author and are not to be construed as a statement of official United States Air Force policy.

weightlessness insofar as it affects human factors and life-support systems. However, it is not intended to detract from the importance of the phenomenon from the viewpoint of many other disciplines and technologies. Problems of direct interest to engineers undoubtedly are equally important as those of the physician, the psychologist, and the biologist, but are not discussed herein.

A. Definition

The terms *weightlessness, zero gravity, zero "g," the gravity-free state,* and the *agravic state,* are synonymous, and all apply to that condition which prevails when a body is allowed to move freely under the influence of gravitation and of its own inertia. Thus, a body without support (lift or drag) in a gravity field free-falls and is weightless. And, a space vehicle in which the gravitational pull of the Earth or other body is exactly neutralized by the centrifugal inertial or fly-away tendency, during periods free of thrust or drag, is weightless, and except for very minor considerations to be discussed later, everything on board is weightless.

There remains considerable confusion among the lay followers of the space sciences relative to weightlessness. The confusion is a natural one, as they often consider the phenomena to be due to distance from the Earth rather than to be a function of centrifugal force and counteracting pull. That is, they confuse the gravity-free state used in the static sense with that of the dynamic sense [1]. There are points between celestial bodies at which their respective mass attractions are equal, thus producing gravity-null. From the standpoint of space travel this situation, for the most part, is negligible as compared with the dynamic situation.

For the centrifugal force exerted by a space vehicle to be neutralized by the gravitational pull of Earth, and thus for an orbit about Earth to be achieved, a speed of approximately 5 miles/sec, is required, while the vehicle is closely paralleling the surface. When the two counteracting forces are equalized, the vehicle is in the weightless state. At approximately 7 miles/sec, escape velocity is achieved, but the inertial forces are still equalized by the gravitational forces, and weightlessness is still the result.

B. Analogies

As weightlessness is one of the more important conditions which is coincident with space flight, a fundamental understanding is necessary. Consequently, it is useful to consider some analogies. The weight indicated on an ordinary bath-type scale, placed in a stationary elevator would be an individual's true weight, the result of 1 g. Suppose the individual weighed 150 lb; the scale would then indicate 150 lb. Suppose the elevator began to move downward; the scale would now indicate less than 150 lb—a condition of subgravity or fractional gravity. If it registered 75 lb it would represent $\frac{1}{2}$ g. Suppose the elevator were thrust downward so rapidly that the individual became suspended above the scale in mid-air; the scale would then indicate zero. The situation would represent zero g so long as the floor of the elevator were accelerated at such a rate as to keep the individual just above the scale in a state of free-fall. The rate of acceleration in this case would be 32.17 ft/sec/sec.

If, however, the acceleration were in the opposite direction, i.e., the elevator moved upward, the effect would be positive g, and if the scale were to read 300 lb the amount would represent 2 g, and so forth.

As a second analogy one may consider the act, commonly performed by children, of swinging a bucket of water through a vertical arc above one's head, without spilling the contents. In this case the water does not leave the bucket because the centrifugal force (or "fly-away" tendency) due to the velocity of the bucket about the arc is greater than the "fall-to-earth" tendency produced by gravity. As movement through the arc is slowed, the water will begin to leak just below the zero g point.

From the biological point of view weightlessness is extremely important. During the time a vehicle is coasting above the drag of the atmosphere, it and everything aboard, including man, his organs, and all of the materials of (or in) his body will be weightless. This condition may prevail for long periods of time, possibly weeks, months, or years, depending, of course, on the state of the art of space flight technology.

All the organs of the body, body fluids, and genes, in sum, man and his remote ancestors have evolved in an Earth environment of 1 g [2]. Through various tricks, amusement devices, athletic games, and the like, most humans have been in the weightless state for periods measurable in fractions of seconds [3, 4]. A few have undergone free-falls or have flown parabolic flight patterns resulting in periods of weightlessness up to several seconds. The author is not aware of any individual who has been constantly weightless for more than a few minutes. Thus, extrapolation of conditions and reactions which would prevail for long periods can only be conjectures. Final solution [5] must await either the attainment of a gravity-free laboratory on Earth (improbable) or actual manned orbital flight for long periods (realizable in the relatively near future).

II. History

A. Concept

The concept of weightlessness had numerous roots which are difficult to disentwine and actually represent concept built upon concept. Some of the tendrils seem even to dip into the nutrients of science fiction. The 16th century concepts of Copernicus (1473-1543) were placed in a new light by Kepler (1571-1630) a century later. Galileo (1564-1642), through his experiments, discovered the laws of free-fall. Their combined work, in turn, was placed in a solid framework by Newton (1642-1727) author of the law of universal gravitation. In 1742 d'Alembert pointed out that Newton's third law holds for bodies entirely free to move, as well as for fixed bodies in stationary equilibrium. Thus, the physical laws concerning the phenomenon were established.

Jules Verne [6], in his predictive novel "Tour of the Moon," written almost a century ago, described static weightlessness as his lunar voyagers reached the null-gravity point of the spheres of equal attraction between Earth and the Moon. He described flotation of the cabin occupants and objects in a realistic manner. Verne made surprisingly few mistakes or omissions. He did, however, fail to realize, or at least to describe, the dynamic state of weightlessness which would have prevailed during almost the entirety of the voyage to and around the Moon.

K. E. Tsiolkovsky, the father of Russian astronautics, is accredited by Shternfel'd [7] as having identified some of the problems and solutions concerning the weightless state before the turn of the century.

Herman Oberth [8], one of the great pioneers of space flight, in his revolutionary book "Wege zur Raumschiffahrt," alluded to the phenomena of dynamic weightlessness.[1] He went into rather great detail in an attempt to predict psychological and physiological effects, and even described rotation of a space vehicle to simulate gravity. His suggested solution was for two vehicles which should be separated by a long cable and made to rotate slowly about the cable's midpoint, thereby producing radial acceleration as a substitute for gravity.

The relatively unknown "Bulletin of the American Interplanetary Society" [9] published, in 1931, an abstract of an essay submitted in December, 1928, in the Rep-Hirsch Competition by one Noel Deisch. Entitled "The Navigation of Space," it was an almost clairvoyant article describing many of the problems of space flight:

[1] Oberth used the term "Andrucklosigkeit," which is best translated as lack of *appression,* more freely translated as lack of support or lack of sustentation.

"Apart from embarrassments of a pathological nature, the personnel would, as has been elaborated on at length in fiction and essay, be seriously hampered in a merely physical way, due to an apparent change in the mechanical properties of objects."

Here he alluded to an interesting paradox when he pointed to the fact that principles of space flight in the era to which he referred were being elaborated on "at length in fiction and essay." Weightlessness as a principle and as a problem was recurring in science fiction, possibly to a greater extent than in scientific publications.

Otto Gauer and Heinz Haber [10], in the two-volume work entitled "German Aviation Medicine, World War II" presented a learned discussion under the title "Man Under Gravity-Free Conditions" in which they described the weightless situation itself and speculated on some of its sensory aspects. In a symposium held at the University of Illinois in 1950, Campbell [11] discussed orientation in the gravity-free state. At this same symposium von Braun [12] discussed his concept of rotation of a space vehicle for the purpose of producing "synthetic gravity" and demonstrated a drawing of the concept. This was the era of speculation. The serious problem at the time was how one could simulate the gravity-free state on Earth for extrapolation into the situation which would occur during space flight.

B. Concept of Simulation

The Haber brothers, Heinz and Fritz [13], in an historic paper presented at the Aeromedical Association Meeting in May 1950, pointed out at least a partial solution which has since been utilized to gain almost all man's knowledge concerning human reactions in the gravity-free state. Their solution was flight by airplanes along Keplerian parabolas.

During World War II pilots of the major belligerent air powers gained knowledge to some extent, at least, about gravity-free flight. For example, in 1941 the author was asleep in the rear seat of a training aircraft. A bad dream of falling awakened him to find his key chain and keys floating in front of him. A look into the pilot's rear-view mirror presented a set of grinning eyes, as the pilot was about to collect a bet he had made with the author the night before. The bet was that the pilot could get him into inverted flight without him being aware of it. He stated later that by careful coordination he had rolled the airplane onto its back and was then losing altitude at free-fall rate, producing the floating keys and a short spell in the gravity-free state.

C. Early Studies

During combat it was learned that a pushover maneuver, properly timed and executed, could be used for evasive purposes. Some aircraft could not follow such a profile without engine difficulties. Caviation of fuel in the tanks would prevent proper flow to the engine and proper function was disrupted. As it was an interesting maneuver and produced unusual reactions of various sorts it was apparently performed by many as an aerobatic trick; however, so far as the author can determine, it was not performed according to the pattern described by Haber and Haber [13] in their profile along a Keplerian parabola. Following the Haber Brothers' description of the maneuver, several pilots performed short gravity-free flights. In 1951 Scott Crossfield flew about 30 parabolas in a YF-84 airplane. Major (now Colonel) Charles Yeager who, incidentally, was the first pilot to fly faster than the speed of sound, flew a series of parabolas about the same time and produced the weightless situation for periods in excess of 10 sec. Shortly thereafter E. R. Ballinger [14], Henry, Maher, and Simons of the Aero Medical Laboratory, Wright-Patterson Air Force Base, Ohio, performed a series of studies in the weightless state using a modified F-80. A little later H. von Beckh [15] commenced flying parabolic flight patterns in Argentina, and a team organized by S. J. Gerathewohl [16] at the USAF School of Aviation Medicine, Randolph Air Force Base, Texas, began their controlled study, first with Lockheed T-33's and later with F-94C airplanes.

D. Lengthening the Time Period

As studies progressed, limitations were imposed by lack of sufficient speed of available aircraft for manned studies in the gravity-free state. To undertake many of the studies required at about the time the former USAF School of Aviation Medicine was expanded into the USAF Aerospace Medical Center, an F-100 was procured to perform periods of weightlessness longer than 50 sec. A larger C-131 aircraft, at about the same period, gave the group at the newly designated Aerospace Medical Laboratory at Wright-Patterson Air Force Base a larger platform for their studies, although the time element was less than 25 sec.

Lengthening the periods of gravity-free flight to more usable parameters will now have to await flights in faster jet airplanes, or flights of the type planned for the X-15 rocket airplane and the Redstone ballistic missile with its manned Mercury capsule. The Mercury Redstone flight of astronaut Alan B. Shepard, Jr. on May 5, 1961, resulted in more than four minutes of weightlessness [17]. Future Atlas-boosted Mercury orbital flights will give much longer periods of weightlessness, producing more basic information.

E. Other Studies

To turn to studies of weightlessness outside the United States, T. Lomonaco and associates [18, 19] have reported on studies utilizing a tower about 40 ft in height, within which there was a platform suspended by elastic cables. Upon release, the platform moved up and down producing acclerations varying from 3 to zero *g*.

F. Historic Animal Studies

As early as 1951 animals were studied during the subgravity state by Henry *et al.* [20]. Through the medium of telemetering, they conducted studies of electrocardiograms, pulse rates, and other parameters, using anesthetized animals flown in V-2 and Aerobee high-altitude sounding rockets. The V-2 produced approximately 3 min of gravity-free flight, while the Aerobee flights approximated zero *g*, but there was some variation reaching magnitudes of 1/10 *g* during part of the time. Recently, small animals have been flown by a number of investigators including van de Wal and Young who, in 1958, conducted the "Mouse-in-Able" project [21]; an Army-Navy group responsible for Jupiter missile-borne monkey flights [22]; and the Soviet scientist who conducted the orbital flight of Laika in Sputnik II [23]. Details of these flights will be described later.

III. Basic Physics

Two excellent expositions of the basic physics of the weightlessness phenomenon are those by Fritz and Heinz Haber, published in 1950 [13], and by S. J. Gerathewohl *et al.*, published in 1957 [24]. Their articles alluded to the following:

Newton's universal law of gravitation states that all bodies exert mutual forces of attraction upon one another. In accelerated motion, "gravity" is the vectoral sum of the forces of gravitation and inertia acting upon a body. According to this established law, Force equals the product of Mass and Acceleration. At the Earth's surface the accelerative force *g* has the value of 32.17 ft/sec/sec.

When an object is at rest and the forces of inertia are absent, the object is in the normal state of gravity and the value is represented as one gravitation unit, or 1 *g*.

When a body is in the state of free-fall the forces of inertia equalize the forces of gravity, resulting in zero g, or weightlessness. Similarly, a body is weightless if it moves freely under the influence of gravity and its inertia, only. This is true during movement along a Keplerian trajectory and continues to be true until a situational change is encountered. According to the law of d'Alembert, a body, whether accelerated or not, finds itself in a state of dynamic equilibrium resulting from a combination of effects of all the forces exerted upon it. Thus, not only the forces of gravity and the forces of inertia are in effect, but also the forces of propulsion (drive) or resistance (as produced by the atmosphere) may enter the combination. The sum of all forces is always zero.

Thus the equation

$$F = m \cdot a \tag{1}$$

can be written

$$F - m \cdot a = 0. \tag{2}$$

Since F represents the gravitational forces and $m \cdot a$ the reactive effects [24], the formula can be written

$$F_{\text{gravity}} - F_{\text{inertia}} = 0. \tag{3}$$

During free-fall without resistance, F_i is a quantity equal in magnitude and opposite in direction to F_g and is thus the sole effect of inertia [24].

Thus, zero g can be achieved through free-fall, until resistance of the atmosphere becomes a factor, reacting because of the increasing velocity of the free-falling body. It should be pointed out here, however, that free-fall does not mean absence of gravity but rather lack of resistance, hence, lack of weight. Weight is experienced on Earth because something is always resisting the pull of gravity whether it be the Earth's surface, or the floor of a building, or something supported by the Earth's surface, or the atmosphere. During free-fall in the atmosphere the resistance afforded by the air produces support, and therefore weight. As soon as the resistance becomes effective the falling body is no longer weightless. A body, whether it be a satellite, a rocket, or a spacecraft operating in an orbit above the resistance (drag) of the atmosphere, and without propulsive power, is in the state of free-fall and is weightless. Its centrifugal "fly-away" tendency, produced by an imparted orbital or escape velocity, is exactly neutralized by the "fall-to-Earth" tendency resulting from the pull of gravity.

As long as a body is not in rotation about one or more of its own axes, everything on board will be weightless except for the forces of mutual attraction within the body itself [25]. These effects, of course, would be negligible in a vehicle of the size and proportions which can be visualized for space travel in the foreseeable future.

The problem of simulating zero g within the earth's environment, then, can be tackled by assuming two possible practical solutions: (1) controlled free-fall from altitude, which would be difficult and would be limited to very short periods by the build-up of atmospheric resistance, and (2) carefully controlled flight along a Keplerian trajectory.

The Haber brothers, with whom the author has had the privilege of working, explored the possibilities of the use of free-fall employing very long elevator shafts, but selected as most practical, simulation through flight along the Keplerian profile [13].

During flight along a Keplerian trajectory in the atmosphere, the symbol F inertia (F_i) of the formula $F_g - F_i = 0$, is replaced by the sum of the inertial and external forces (drag and thrust) superimposed upon F gravity (F_g). Thus, an airplane can simulate the motion of a rocket or other space vehicle coasting in a vacuum. To attain the state of weightlessness during flight through the atmosphere the craft must be controlled in attitude and speed in a manner such that thrust forces are exactly counterbalanced by drag.

To perform such a maneuver [24] the pilot must eliminate all accelerations other than that produced by the downward pull of the gravitational force of the Earth (1 g). This requires a so-called pushover until the accelerometer of the aircraft indicates exactly zero g, then held there by careful coordination of the throttle and stick; that is, speed and attitude.

According to the description of the maneuver as set forth by Gerathewohl *et al.* [24], the air speed decreases uniformly from an initial entrance velocity to a minimum at the top of the parabolic flight curve, and thence reverts uniformly back to the initial value before the pull-out recovery from the maneuver. The horizontal component of the velocity remains constant during the entire weightless portion of the parabola.

The factors limiting the time in the weightless state, which can be predicted for any given aircraft, depend upon the initial velocity with which it can enter the parabola, as well as the near stalling speed at which the aircraft can remain in complete control. The number of g's which the plane can safely tolerate, or the pilot or experimental subject wishes to tolerate during the initial pull-up and final pull-out, are still important limitations. In some types of human study, the physiological effect of the initial pull-up can carry over into the weightless state and mask the true situation in the physiological or psychological parameters under study.

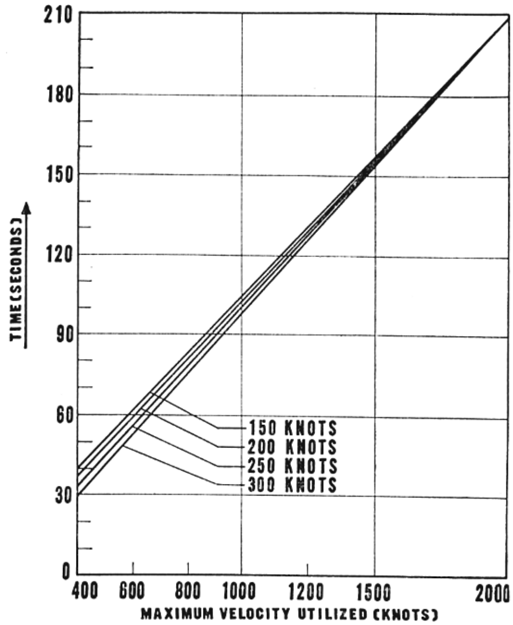

FIG. 1. A graph showing duration in the weightless state as a function of maximum utilizable aircraft speed, plotted for varying minimum controllability speeds [24].

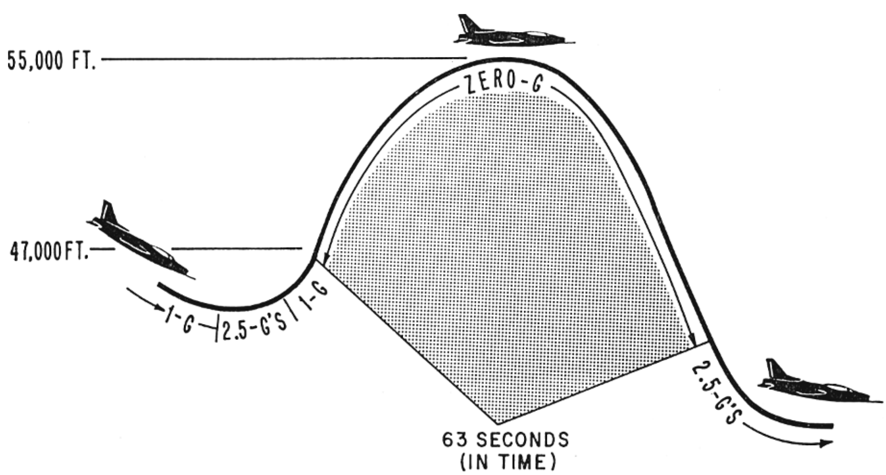

FIG. 2. A flight profile of one of the flight patterns used by F-100 aircraft to get a theoretical maximum of 63 sec in the near weightless state.

A graph showing duration in the weightless state as a function of maximum utilizable aircraft speed, plotted for four varying minimum controllability speeds, is shown in Fig. 1.

A flight profile of one of the flight patterns used by F-100 equipment to get a theoretical maximum of 63 sec in the weightless state is shown in Fig. 2.

Characteristics of optimal flight parabola for three types of aircraft are shown in Table I.

TABLE I. CHARACTERISTICS OF OPTIMAL FLIGHT PARABOLA FOR THREE TYPES OF AIRCRAFT

Aircraft	Minimum controllability speed: True air speed (knots)	Entry speed: True air speed (knots)	Starting altitude (ft)	Maximum altitude of ground (ft)	Angle of climb (deg)	Duration of virtual weightlessness (sec)
T-33A[a]	180	320	18,000	20,600	55	28
F-94C[a]	195	425	18,000	24,400	63.5	40
F-100F	200	535	47,000	54,500	50	63

[a] Figures by Gerathewohl, Ritter, and Stallings.

IV. Physiological and Psychological Effects of Zero *g*

A. Orientation

It is generally accepted that human spatial orientation is the result of precise central nervous system integration of stimuli emanating, for the most part, from three-body systems representing the so-called orientation triad. The components of the system are considered to be:

1. The visual apparatus, consisting of the eyes and their central nervous system connections.
2. The labyrinthian system of the inner ear, consisting of the semicircular canals and the otolithic organs.
3. The so-called kinesthetic system, consisting of sensory receptors situated in the muscles, skin, viscera, etc., with their nervous connections.

Originally, it was felt that two of these systems had to be functioning normally for proper orientation. It was known, however, that the visual apparatus played the dominant role. As the otolithic portion of the labyrinthian system and the sensory receptors of the so-called kinesthetic systems are considered to be gravity-orientated, it was thought by many that weightlessness would be associated with disorientation. It was felt this would especially be true if confused stimuli came from the gravity-vectored systems, as would be the situation in the weightless state.

The short periods of near zero *g* flights (up to 60 sec), however, have indicated that the eyes *are* dominant and so long as a horizon or a horizon-indicating instrument can be seen, and is believed, no serious disorientation occurs. Thus, proper instrumentation and proper indoctrination seem to be the answer. What happens when time in the weightless state is measured in hours, days, or months is still conjectural, as is the situation occurring with the eyes closed (e.g., sleep).

A number of animal studies have been performed to determine if activities in the weightless state could cast any light upon the subject. As early as 1951 Dr. James P. Henry [20] and a group of co-workers of the Air Research and Development Command's Aero Medical Laboratory flew a series of small anesthetized animals in the instrumented capsule of V-2 and Aerobee nosecones. Some reached altitudes of 200,000 to 400,000 ft. At times, near-weightlessness was achieved for periods as long as 2 min. From those flights came the classic film of mice reacting to the gravity-free state (Fig. 3).

In one series of experiments a mouse with its gravity-sensing labyrinthian and otolithic system removed seemed less disturbed, and possibly better orientated, than a normal mouse exposed at the same time to an identical situation. The explanation proposed is that the central nervous system, in the case of the mouse with its labyrinthian system removed, was not receiving false information from the absent system. In 1954 H. J. von Beckh [15] reported a series of parabolic flights during which he studied orientation and coordination in both animals and humans. In the course of his studies he determined the ability of water turtles, carried in a small aquarium, to stretch their necks and grab food in their mouths. He found that those with normal labyrinthian systems hesitated to grab the food during the weightless period. Those with their labyrinths destroyed some time before, and who had become adapted to living without the system, grabbed the food in precise, well coordinated movements.

According to Shternfel'd [7], mice and dogs have been studied in the weightless state in the USSR for periods of time up to 3-4 min. Under the direction of A. V. Pokrovsky, dogs were carried to altitudes of 68 miles and later to 125 miles by rockets. During the descent of the rockets, the animals were ejected and allowed to free-fall in pressure suits. From altitudes of 13,000 ft downward the descent was by parachute. Nine experimental dogs were used, three of which went through the experience on two different occasions. Motion pictures, electrocardiograms, temperature, and pulse measurements were made during the flights. The investigators demonstrated that the animals were able to adapt well to weightlessness. However, according to the authors, each reacted, to some extent, according to its own individual peculiarities.

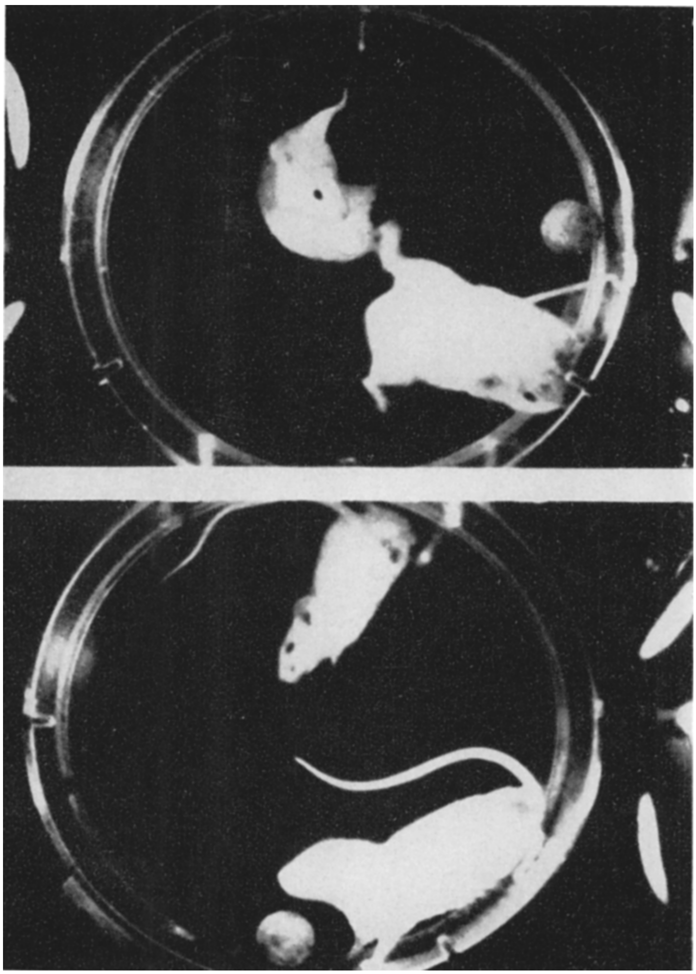

FIG. 3. Mice in gravity-free state during Aerobee rocket flight [20].

In the United States a very detailed study of American-born monkeys, launched in the nosecone of Jupiter missiles, has been reported by A. G. Graybiel and associates [26]. The study seems to show no evidence of disorientation after the animal had returned to a steady state following acceleration; so long as there was no rotation, and so long as a visual frame of reference existed. A study of the work of Chernov and Yakolev [23] in the Soviet Union resulted in the same conclusion.

These conclusions would be expected from almost all of the background studies on orientation relative to aviation [11].

B. Coordination and Body Movements

Before zero *g* parabolic flights were a part of the modus operandi for weightless studies, there was considerable discussion and controversy concerning the effects of weightlessness on body movements. It was the opinion of some well-grounded physiologists that if the gravity vector

FIG. 4. Flotation of subjects during parabolic flight in C-131 aircraft [27].

were removed there would be a tendency to "overshoot" during purposeful movements, such as reaching for, or grasping, an object. As soon as weightlessness could be simulated it was determined that after a little practice, fine movements, such as those required by a pilot, could be performed. The pilots could even carry out emergency procedures during zero *g* [27].

The requirement for a larger platform for zero *g* flights led a group under Major Edward L. Brown [27] at the Aero Medical Laboratory

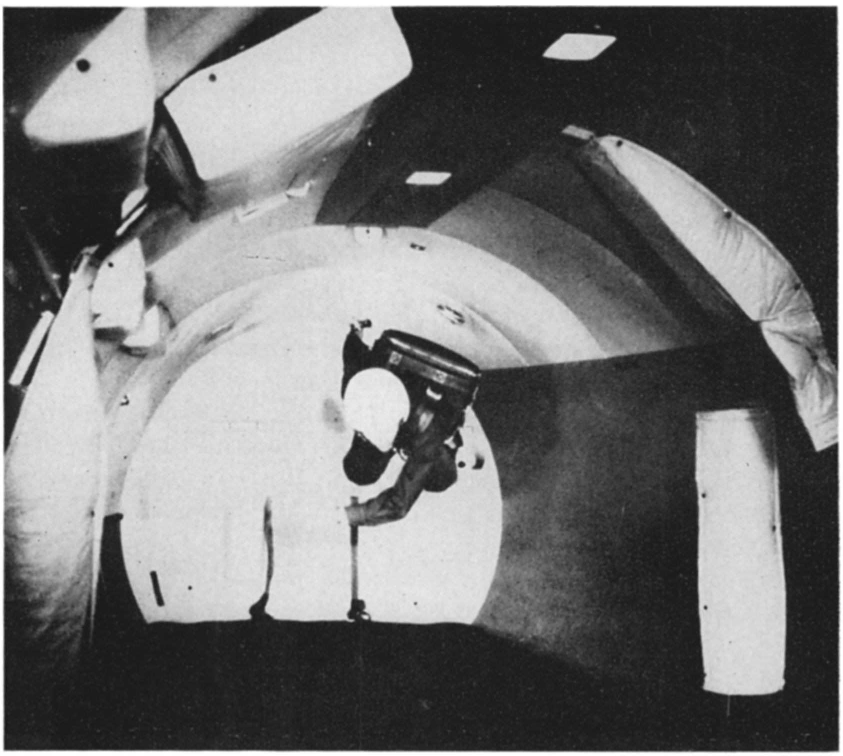

FIG. 5. Swimming movements during flotation in gravity-free flight [27].

of the Wright Air Development Center to modify a C-131B transport airplane for the flights. With the larger amount of space available, and in spite of the relatively short period of weightlessness (12-15 sec), they were able to conduct a number of interesting experiments, including the flotation of subjects in the cabin (Figs. 4 and 5), and development of methods of maneuvering by swimming-like motions and by pressure against the cabin walls. Manipulative tasks of various sorts were also performed. It is interesting to record that the subjects were able to do quite complicated manipulative tasks after short periods of practice. For locomotion they adopted magnetic-soled slippers and were able to walk, fairly effectively, even along the ceiling of the aircraft.

C. Heart and Circulatory Changes

Extensive human and animal experiments of heart circulatory and respiratory functions, during periods of weightlessness up to a few minutes, have been carried out and are well documented by observers both in the United States and the Soviet Union. Some of the investigators who have made extensive reports are: J. P. Henry [20], Graybiel *et al.* [26], van der Wal and Young [21], Chernov and Yakolev [23], and von Beckh [15, 28].

The accumulated work has been well summarized by Burch and Gerathewohl [22]. As can be surmised, it is quite difficult to separate the carry-over effects of acceleration, surprise, and other new environmental situations, from the effects of weightlessness itself. However, within the framework of the relatively narrow time limits in the weightless state, one can state the opinion that no changes in the cardiocirculatory system have been noted, which are not within the range of human and animal tolerance and physiological adaptation.

The same conclusion can probably be drawn concerning respiratory function. For long periods of weightlessness, however, some method of moving the air in the environmental cabin may be required in order that the expired gases may be removed from the proximity of the subject, as they probably will have a tendency to accumulate in that area. Simple circulation of the gases by means of a fan, or similar arrangement, will probably suffice to meet the situation.

D. Eating, Drinking, and Nutrition

In the weightless state liquid collects in spherical globules due to surface tension, and the fluid becomes difficult to control. This led to an early prediction that drinking and food-taking during space flight might be a serious problem. A series of studies by Ward *et al.* [29] at the USAF School of Aviation Medicine placed some 25 subjects in weightless parabolas from 35 to 40 sec. Some 165 parabolas were flown in all. Their results indicated that open containers could not be used, as any movement of the container would result in the liquid leaving the vessel in a globular, amoeboid mass, enveloping the face or the eyes (Fig. 6). At times the material got into the nose and even the nasal sinuses. Choking was a rather common occurrence. The use of drinking

FIG. 6. Example of an attempt to drink water from an open container during gravity-free flight. Note fluid leaving container in globular, amoeboid masses.

straws did not answer the problem; however, a squeeze bottle served admirably. According to the study, it made little difference if the subject squirted the material into his mouth or sucked it in from the tip of the squeeze bottle (Fig. 7). After fluids or solids enter the mouth, the swallowing act forces them into the esophagus by means of a complex, well-coordinated series of muscular movements. According to the detailed studies of Hoelzel [30], passage through the esophagus, stomach, and the intestinal tract is not correlated with the specific gravity of food. He also determined that the specific gravity of food is not of prime importance in the speed with which food moves through the intestinal tract. Thus, the evidence at hand leads one to the opinion that food and fluid taking will present a problem, but the problem is solvable.

Passage of the food through the gastrointestinal tract and the derivation of nutrition from the food will probably represent no problem unless very long periods in the weightless state are involved. Whether or not some form of nausea or lack of appetite will accompany long-term

FIG. 7. Use of the squeeze bottle for fluid and soft food taking during gravity-free flight in F-100 aircraft.

weightlessness will remain controversial until studies involving days or weeks can be conducted.

E. Muscular Tone, General Body Tone, and Physical Conditioning

General body tone and physical conditioning will probably be affected by long periods of weightlessness, as illustrated by an interesting experiment of Graveline *et al.* [31], at the USAF School of Aviation Medicine. Graveline used the phenomenon of buoyancy to simulate, as near as possible, some of the aspects of weightlessness. He was immersed on a couchlike structure, in a semireclining position, in a large tank of water for a period of 7 days. The water temperature was held at 33.5°C. His protection against the prolonged effects of water was achieved by using a conventional SCUBA suit. Feeding, fluid taking, etc., were carefully controlled. His head remained out of the water at all times, and the remainder of his body was supported in accordance with the Archimedes principle. As the resultant specific gravity of the subject was close to 1, movements of his trunk and extremities were very nearly effortless.

After seven days in the buoyant state muscular tone was definitely diminished, cardiovascular reflexes were disturbed, and his ability to perform complex psychomotor tasks had deteriorated. Of interest is the fact that Dr. Graveline's need for sleep seemed markedly reduced during the 7-day period.

F. Elimination of Body Waste

The effects of loss of weight of the contents of the urinary bladder and the lower intestinal tract formerly were considered as possible problems. Experience at the USAF School of Aviation Medicine and the Holloman Aeromedical Field Laboratory, reported by Ward and Simons [32], leads to the conclusion that elimination is not adversely affected, and that other than from the standpoint of convenience, no serious problem is anticipated.

V. Areas for Further Study

Investigators closely associated with studies of weightlessness from the human factor point of view generally agree that studies to date do not seem to indicate that serious biologic stresses and other biologic problems associated with human travel in the weightless state will prevail so long as the weightless periods are limited to a few minutes. By extrapolation, one would be led to conclude that a few hours of zero g flight will not lead to serious problems. The bases for further extrapolation, however, are nonexistent, since other situations begin to complicate the picture as the time parameters are extended. Some of the questions that arise concern:

1. *Fatigue,* with resulting inattention to visual frames of reference, such as would be afforded the astronaut by natural or artificial horizons.
2. *Sleep,* with its detachment from all gravity cues.
3. *The reaction of the autonomic nervous system,* possibly similar to that resulting from long periods of subjection to motion.
4. *Muscular deterioration* from long periods of muscular inactivity.
5. *Circulatory changes* from alterations in fluid dynamics of the heart and vascular system.
6. *Neuropsychiatric adjustment,* to detachment from earthly ties afforded by gravity vector.

These and many other potential problem areas can be investigated only after man has spent days and weeks in the weightless state.

VI. Gravity Simulation or Substitution

As the problems associated with weightlessness become more and more apparent, gravity simulation and/or substitution will create increased interest. According to Shternfel'd [7], K. E. Tsiolkovsky described the production of artificial gravity through radial acceleration, the separation of the space vehicle into two portions being effected by a long connecting cable. Rotation about a common center would produce the sensation of gravity. Oberth [8] credits O. W. Gail in "The Stone from the Moon" with a description of a rotating observer's chamber connected to a space vehicle by means of a cable. von Braun [12] described a space station, assembled in the orbit of operation, in the form of a huge doughnut, 200 ft in diameter, rotating about a hub, and thus generating centrifugal "synthetic gravity" at its rim. This, according to calculations, would require one revolution each 11.1 sec for the production of 1 g at the periphery, or one revolution each 35.1 sec to produce 1/10 g.

Constant linear acceleration of 1 g, as well as constant slight radial acceleration changes produced by slowly swerving to the right and to the left of the course, have been suggested for gravity substitution. The characteristics of propulsion systems presently employed, together with their propulsive fuel requirements, would seem to obviate such methods in the near future.

Lap belt or shoulder and arm harness restraints, or magnetic restraints [11, 27], would produce a certain degree of gravity substitution permitting the astronaut to be made one with his machine, so to speak. He would be on a more or less stable platform, oriented by its orbit to some stable focus (such as the Earth) or foci. As the author of this chapter suggested more than 10 years ago [11], a rather tightly fitting suit, similar to underwear, may be helpful, especially during sleep. It would contain interwoven threads of iron or magnetically oriented material, and should be used in proper relation to flooring or bedding of proper magnetic orientation.

A real breakthrough will occur as soon as a small group of human subjects can be placed in the weightless state for periods as long as two, or more, weeks. With a satellite laboratory [5] capable of orbital flight for a sufficient period time, many interesting studies can be performed and definitive answers reached. From the point of view of weightless studies, two men could observe one another and through simple recording and telemetered data-gathering processes, answer an important series of questions concerning the effects of relatively long periods in the weightless state. When the periods in orbit become significantly extended, or when the state of the art permits crew replacement and resupply flights to occur, then geotropism of various other forms of life, such as plants, vegetables, etc., could be studied to improve our basic knowledge. Knowledge of the effect of weightlessness on photosynthesis and the elements of photosynthetic systems, especially the fluid elements, could then be studied.

In concluding this chapter it is important to point out that although our understanding of weightlessness may seem to progress slowly, one need only compare the situation today with that of ten years ago to quickly refute that statement. It is easily recognized that our capabilities for study and accumulating knowledge have increased along an exponential curve.

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