Symposia of the Institute of Biology, No. 10

THE BIOLOGY OF SPACE TRAVEL

Edited by

N. W. PIRIE

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The effect of an acceleration of 5g on the face

Drinking under conditions of zero gravity. The water, rising from the container in spherical blobs formed by surface tension, is extremely difficult to swallow. The photograph was taken in a U.S. Airforce F-94C executing a parabolic arc to produce an acceleration equal and opposite to that of gravity.

INTRODUCTION

By

A. S. Parkes, C.B.E., F.R.S.

I cannot hope to summarise adequately the proceedings of this fascinating and exciting Symposium ; the most I can do is to refer to certain aspects which have been of a special interest to me. During the symposium our would-be astronaut suffered severely at our hands. He was torn away from his wife and family and subjected to a variety of most severe mental and physical tests. He was subjected to anything up to 10g and then, by way of a change, made weightless, so that he floated in space like a leaf in a gale. He was fed on scientifically produced bilge water, which being also weightless had to be sucked through a tube to avoid it spreading over his face like a wet cloth. Alternatively, he could rely on the memory of his last square meal. He was then irradiated and put under conditions of solitude and confinement from which apparently only the schizophreniac could emerge unscathed. Later, we dumped him in the nightmare land of a planet, already contaminated by somebody else's septic rocket. Fortunately we heard that there were no thermal problems in getting into space or staying there, but our astronaut came near to being incinerated on returning to earth. In spite of everything it seems that, according to current opinion, he would come back younger than if he had stayed on earth. After all this we may well ask, what next ?

It has been suggested that the space vehicle can be navigated better by remote control than by the astronaut himself and that it would add to his comfort to put him into a state of suspended animation until he arrived at his destination. According to present knowledge this could be done only by inducing anabiosis by extreme cold. In terms of mammals this means reducing the body temperature until the heart beat and respiration stop and then continuing the cooling until a relatively stable state is reached. It is not likely that any temperature much above $-100°C$ would be effective. This type of prolonged storage has been effected with cells and tissues and with small organisms, but we are nowhere near achieving it in the case of whole mammals. Even when body temperatures down to 0° are achieved the problem of suspended animation is only just beginning. The problem of preventing damage to the body as its water crystallizes and of getting the heat out quickly enough to avoid irreparable damage while cooling to a stable state are formidable in the extreme, especially in the range immediately below zero. The latent heat of crystallization of water of the human body would be sufficient to boil several gallons of water. When the problem of cooling the body to a stable state is solved, there still remains the challenge to finish the job by freeze-drying. It has rightly been said that whatever the advantages of suspended animation to explorers in transit and the off-duty crews of space vehicles, it would have little appeal to the space tourist who might just as well stay at home as travel in the freeze dried state.

All this of course sounds fantastic, but we have learnt to use the word impossible with caution. Ten years ago no normal mammalian cell had been frozen to temperatures compatible with prolonged storage. To-day this procedure is commonplace and mammalian spermatozoa and various types of mammalian cells and tissues are known to survive for years at −80° or −196°C under appropriate conditions. It is relevant, too, that the idea of this Symposium on the Biology of Space Travel grew out of a meeting on Space Medicine organized by the Interplanetary Society, which celebrated its twenty-fifth anniversary two years ago amid the excitement occasioned by the launching of the Sputniks. It is salutary to reflect that twenty-five years ago the organizers, the speakers, the chairman and the audience of a symposium such as this would all have been regarded by the general public and most of their fellow scientists as unrealistic visionaries, if nothing worse, as indeed were the members of the Interplanetary Society during its early days. It may well be that those so regarded to-day will similarly be justified by time.

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BIOLOGICAL EFFECTS OF PARTIAL AND OF COMPLETE WEIGHTLESSNESS

By

W.-Cdr. T. C. D. Whiteside, M.B.E.

R.A.F. Institute of Aviation Medicine, Farnborough, Hants.

The problems associated with high accelerations which are encountered first when a space vehicle is launched from the surface of the earth and lastly when it re-enters the earth's atmosphere and subjects its occupant to a prolonged deceleration are of course of considerable interest. However, when a vehicle of this description is travelling round a body which has mass and therefore exerts gravitational force, it is possible at specific heights and speeds to counteract that force by the centrifugal force resulting from the orbital track around the planet. When this happens, the satellite, for it can then be called that, becomes weightless as do objects within it. This weightlessness would persist for as long as the craft was in orbit. On the other hand, on a trajectory from earth to moon, the gravitational pull from earth will gradually decrease, the weight of a man in the vehicle becoming progressively less, and only for a very short time at one point between earth and moon would the man and his vehicle be weightless. Thereafter he would be subjected to a progressively stronger gravitational pull from the moon.

It is clearly of importance, therefore, to determine in so far as possible what biological effects may result if man is exposed to either "zero gravity" or less than one "g" for prolonged periods. The experimental difficulties of producing this physical environment need little elaboration for this does not come within the province of the human centrifuge which can subject an individual only to an increase in gravitational pull. Most people, however, have, at some time or other, been subjected to weightlessness albeit for short periods. All that is required to do this is to jump from the edge of a swimming pool into the water and during the time in the air, one is in fact weightless. Partial weightlessness has been experienced by anyone who has been in a lift. When the lift begins its descent the occupants are subjected momentarily, as the lift accelerates, to a gravitational pull of less than one "g".

We all know that these brief exposures to weightlessness give rise to no serious discomfort or permanent damage, but what of the effect of a prolonged exposure to partial or complete weightlessness? Without resorting to orbital flight it is impossible to achieve long periods of weightlessness, but one way to answer our question is to examine some of the physiological and psychological responses to even very short periods of partial or complete weightlessness, and to attempt to determine the nature of the changes taking place and the nature of any adaptive processes. Armed with this knowledge it may be possible to determine whether the subject is likely to be inconvenienced by long exposures to this environment.

One of the simplest methods which has been used to simulate weightlessness is underwater immersion, for in fresh water the human subject is virtually weightless compared with his environment. This, of course, is not true weightlessness since first, if one part of the body is deeper in the water than another it will be subject to a greater hydrostatic pressure than that which is less deeply placed and, secondly, some internal organs such as the otolith of the utricular maculae, which are the detectors of linear acceleration, will still be responding to 1 " g ".

Some 10-30 seconds of true weightlessness may be achieved by putting the subject in an aircraft which is following a parabolic trajectory (Gerathewohl *et al.*, 1957). In one part of this trajectory the aircraft speed can be so adjusted that the centrifugal force can be made to balance out the gravitational force of the earth. In that phase of the flight the subject is truly weightless and so are his utricular otoliths. However, depending on the power of the aircraft this type of experiment is preceded and followed by an increased gravitational pull of two or three " g ", whilst during it, immediately preceding it, and also immediately after it the subject is also experiencing an angular acceleration. By putting an aircraft into a steep dive, partial weightlessness may be experienced.

The simplest way, however, of producing weightlessness is to seat the subject in some chair or vehicle and then drop him. Immediately he is dropped the subject is at zero " g ", and thereafter, as his acceleration decreases, he is subjected to a force which gradually approaches one " g " as he approaches his terminal velocity. By this means it is possible to achieve what is virtually zero " g " for half a second by dropping 4 feet. Longer drops than this are complicated by the engineering problem of comfortable deceleration at the end of the drop. For experiments on partial weightlessness, one can employ high speed lifts in which the subject may experience less than one " g " for ten to fifteen seconds.

There are some aspects of the biological responses to weightlessness which can be investigated by interpolation between the results of experiments carried out under increased " g " and under negative "g", that is, with the force acting from foot to head, both of these conditions being produced experimentally either by a human centrifuge, or more simply, by an inverting table. The final answers on how well man can tolerate prolonged weightlessness, can, of course, be determined only by putting a man into space. Other experimental approaches merely provide a basis of knowledge from which one must extrapolate to human performance and behaviour in the weightless environment, for, although behavioural experiments upon animals provide considerable information, the final assessment of any differences found must await the subjective reporting of a human subject. It is true that micro-electrode studies upon the response from end organs would provide information from which much could be deduced, but the technical difficulties associated with such a project would seem to outweigh the advantages.

Physical Problems

Locomotion. The problems associated with movement inside a space vehicle in orbit, relate rather to methods of keeping stationary than to methods of locomotion, for in the weightless state the subject will be positively located in one place only if he is tied down by a seat harness or by other means such as magnets in his clothing or footwear. Locomotion, however, should present no difficulty for, dependent as it is upon Newton's 3rd law of motion, all that is required in the weightless state would be to push against one wall in order to go in the opposite direction. Whether this mode of locomotion would indeed be advisable is, however, another question, because, in the interests of maintaining the skeletal musculature active and able to withstand the extra stresses imposed by the high accelerations during re-entry, it may be preferable to provide magnetic shoes to make the task of locomotion more difficult although more controllable.

On the question of the ability to move and change position if one is floating weightless in the centre of a room, it is usually stated that divers can alter the position of the body after leaving the spring-board and before reaching the surface of the water. This, however, is a change in position comparable to that of a falling cat which rights itself so as to fall feet first (McDonald, 1955). It is an angular but not a linear change and although the subject may be facing in a different direction, yet his mass centre will not have moved spatially. (Dzendolet and Rievley, 1959).

A man being weightless may therefore be able to face different ways or to set up angular motion but he will not be able to move towards the ceiling, floor or walls unless he is prepared to jettison a boot for example and throw it in a direction opposite to that in which he wishes to go.

Movement of Air. Of the more dramatic of the physical problems posed by the weightless environment is that linked with the mixing of gases of different densities. There are two results which one has to consider in connection with the survival of men in such an environment, the first being the diffusion of expired air, richer in carbon dioxide, in water vapour, and deficient in oxygen. In the absence of any gravitational pull this expired air would tend to remain near the subject's head. Thus the dramatic picture which is sometimes painted is of a sleeping man " suffocating " in a cabin in which there is ample oxygen. Within limits it is possible that a higher concentration of expired air will build up in the immediate vicinity of the subject but, fortunately, the air movement set up by expiration should help remove this expired air to a greater distance from the subject. Whilst the subject is sleeping, however, this might be a real problem, but here again even if the force of expiration were insufficient to carry the expired air a distance from the body, there would still be currents of air movement set up by the air purifying and regenerating system.

Without air movement the effects of temperature, similarly, would cause air in immediate contact with the skin to become warm and saturated with moisture so that the subject would experience difficulty in keeping sufficiently cool since he would be closely surrounded by an envelope of warm and highly humid air. In practice, however, body movements, and again the air movement of the cabin air should satisfactorily solve this problem. It is none the less important to bear in mind and to ensure, if only on the grounds of greater comfort, that movement of cabin air is supplemented by forced draughts.

Deglutition. As regards the question of eating and drinking, little difficulty should be experienced because after all it is possible to either drink or eat while under -1 " g ", that is to say in the inverted position. (It has been known for people to consume a pint of beer whilst standing on their head, and if this can be performed at -1 " g ", it could no doubt be performed with half a pint of water at zero " g ".) The difficulty which would arise would be rather in the method in which the fluid is presented to the man, one satisfactory method being to employ a plastic container with a built-in tube through which the fluid can be sucked. Attempts to drink water from an open container usually resulted in the face, mouth and nostrils being covered with an amoeboid mass of water. (Ward *et al.*, 1959).

The accumulation of saliva during sleep should give rise to no difficulty, for people can sleep even head down without choking provided they have normal swallowing reflex and palate muscles. This swallowing reflex depends on closure of the larynx by a sphyncteric action and also partly on an upward and backward tilting of the larynx to shield the laryngeal opening by the epiglottis. From X-ray cinematography it is evident that normal swallowing is not dependent upon gravity. Only when there is paralysis of the soft palate is food and liquid regurgitated through the nose.

Biological Problems

Circulation. At any given point, arterial blood pressure is dependent in part upon the height of the column of blood supported, whilst cardiac systolic pressure is reflexly maintained constant irrespective of position of the subject. Thus in the erect position the highest arterial pressure is at the ankle since there is such a high column of blood above it, and the lowest is at the neck and head. Since at heart level the arterial pressure receives a contribution from the column of blood above it, with increasing " g " this column becomes heavier, the heart force is therefore reduced so as to maintain the same cardiac systolic pressure, and therefore arterial blood pressure in the periphery falls, and a compensatory reflex peripheral vaso-constriction takes place. The opposite happens at negative " g " and by interpolation zero " g " will be accompanied by a slight rise in cardiac blood pressure plus a slight peripheral vaso-dilatation. Furthermore, since the pressure at any point in the arterial tree will not be affected by the height of a column of blood above it, pressure throughout will be equal as though the subject were lying either supine or prone. This position can of course be maintained for long periods in consequence of which one surmises that the effects of prolonged weightlessness on the circulation will be tolerable.

Respiration. The respiratory system too is acted on by changes in gravity. Normally the weight of the abdominal viscera help to pull down the diaphragm and thus aid inspiration, hence the mode of action of the see-saw method of artificial respiration when the subject is rocked to and fro across a see-saw. When the head is above the level of the feet, the diaphragm is pulled down by the abdominal contents and inspiration takes place, whereas when the head is below the level of the feet the abdominal contents pressing against the diaphragm produce a forced expiration. Thus in the erect position gravity helps inspiration. But gravity also helps expiration for the weight of the thoracic cage itself pulls the ribs downwards, thereby aiding expiration by causing the thoracic cage to collapse. Even in the supine position the weight of the thoracic cage helps to collapse it so that in this position, gravity still helps expiration although it probably does not help inspiration very much as the downward pull of the abdominal contents will be either considerably reduced or absent. As in our consideration of the circulatory system we may conclude that prolonged exposures to weightlessness simulating as they do the supine position, should have little effect upon respiration, except for an alteration in the respiratory cycle resulting possibly in a shorter pause after expiration.

Muscle. The tonus of muscle is maintained reflexly in large measure by the activity of the muscle spindles. These virtual misalignment detectors signal changes in muscle length through the mono-synaptic pathway directly to the anterior horn cell from which the discharge through the motoneurone results in an adjustment in muscle length. In a weightless environment it is to be expected that this tonus will be greatly diminished because the muscle will not be stretched by gravitational pull and therefore spindles will not be stimulated to produce reflex mild contraction of normal tone. Of course one does not need to go to a weightless environment to see this, for confinement to bed for several days results in weakness and flaccidity of muscles.

In addition to those effects initiated at the level of the muscle spindle, one would expect that in true weightlessness, this asthenia and this atonia might be even more dramatic because part of the muscular tonus is normally maintained by activity of the utricular otoliths. We know that in labyrinthectomised man, shortly after the labyrinthectomy, muscle tone is diminished, a condition, however, from which gradual recovery, or to be precise, to which gradual adaptation takes place.

An experiment which indicates the role of the muscle spindle in weightlessness was performed by dropping a subject in a chair and whilst he was dropping, elicitating the flexor response of the ankle by tapping the Achilles tendon. It was found that within about thirty or forty milliseconds of becoming weightless it was no longer possible to elicit the ankle jerk (Matthews and Whiteside, 1960). This disappearance of the ankle jerk lasted approximately 100-200 msecs. from the start of the drop, after which interval a tap delivered to the Achilles tendon again gave rise to the normal ankle jerk. It seemed possible that this disappearance of the ankle jerk was associated with the changes in stimulation of the utricular otoliths, but in fact further studies showed that the utricle did not play any part at all in this disappearance which could be accounted for purely in terms of mechanical movement of the muscle as the man became weightless. The movement, presumably a shortening of the muscle, produced a mechanical cessation in the discharge of the muscle spindles, which therefore did not respond to a tap delivered to the tendon a short time afterwards.

Labyrinth. By far the most interesting physiological effects of weightlessness are likely to be encountered when one considers the labyrinth and in particular the utricle and its otoliths which respond primarily to linear accelerations. As was mentioned earlier, it is, of course, experimentally difficult to carry out experiments on prolonged weightlessness without at the same time giving rise to angular accelerations too. The effects of prolonged weightlessness on the otolith are therefore unknown and one can only speculate as to what may happen. Of course experiments have been carried out on ablation of the otolith (Van Eyck, 1959) and also selective destruction of the otolith by high speed centrifuging of the animal but we do not yet know whether the responses observed as a result of these procedures are indeed indicative of what would happen if the otolith was not being acted on by any accelerations whatsoever, or whether they are only indicative of what is happening when the end organ is damaged.

In man it is generally considered that otolithic function is subservient to the more important visual and proprioceptive impulses of muscles and joints. Certainly in labyrinthectomized man, the loss of function of the utricle is fairly quickly adapted to, the loss of tonus and the ataxia disappearing after a period of several weeks. But although it is subservient to vision and proprioception, the utricle of course does play an important part in the activities of normal man. In addition to maintaining muscular tone, it is associated with compensatory eye movement. Merton (1956) has shown that a compensatory rolling of the eyes takes place when a subject is swung from side to side on a pendulum. In part this rolling of course can be accounted for on the basis of angular acceleration stimulating the semicircular canals, but there is evidence too that it is associated with utricular stimulation by the changing of direction of the resultant " g ".

The close linkage between the control of eye movements and labyrinthine stimulations is indicated by the observation by Whitteridge (1956) that patients who had been labyrinthectomized, on being wheeled about in a wheelchair through hospital corridors, were unable to recognize even familiar faces. Apparently the vibration of the wheelchair produced a loss of visual acuity presumably because of the lack of compensatory movements of the eyes in response to small accelerations of the head.

What may be another manifestation of utricular stimulation is seen in the different patterns of a postural response which are adopted when semicircular canals are stimulated by angular accelerations. If the subject has been rotating with head erect then stops suddenly, he involuntarily assumes what is known as the discus position, in which he tends to swing round in the direction in which he has been rotating. However the pattern of this postural response can be altered even although we are stimulating the same set of canals. For example, if the subject rotates to the right with the head erect, then stops, then bends the head forward through 90°, the postural reflex will tend to throw him down not as before twisting to the right but this time downwards and to the left. Thus even if it serves only to tell the subject which direction is vertical with respect to the plane of the stimulated semicircular canal, the utricle appears to be involved in the determination of these postural responses to angular acceleration.

In an attempt to determine the effect of weightlessness on voluntary muscle activity, a test similar to the past pointing test employed by the clinician was devised. This test of hand eye co-ordination is usually carried out with eyes open and with eyes closed to differentiate between the ataxias of sensory and of cerebellar origin. If the ataxia is associated with sensory loss, the inaccuracies of pointing may be manifest when the eyes are closed. With adequate visual information, however, the patient may correct his performance so well that no abnormality may be evident. On the other hand in cerebellar ataxia the performance of a test of hand eye co-ordination is little better with eyes open than it is with the eyes closed because it is the co-ordination of muscular activity which is affected.

An aiming test of this nature was set up in which the subject had no knowledge of his performance (Whiteside, in press). The subject pointed to a target but, by means of mirrors, was prevented from seeing his hand reaching it. When this test was performed under normal conditions in the laboratory it was found that a fairly good co-ordination of the hand and eye existed. The subject could point consistently and fairly accurately to his target, but when a test was done in simulated 0 " g " by immersing the subject in water, he pointed consistently too high. When the experiment was repeated under true weightlessness in an aircraft performing a parabolic flight manoeuvre, the subject surprisingly pointed too low. The principal difference between the underwater experiment and the airborne experiment was that in the first the utricle was at 1 " g " whereas in the second the utricle as well as the rest of the subject was at 0 " g ". To this difference therefore one must attribute the difference in performance of the task in these two conditions. When the experiment was repeated in the centrifuge at 2 " g " it was found that the subject pointed too high.

The conclusion from these experiments was that the utricular changes probably acted not directly on muscle control but rather on vision, producing an apparent displacement upwards or downwards in the visual field—downwards in the case of zero " g " and upward in the case of increased " g ". This illusion is experienced whenever one ascends or descends in a fast lift.

That there is undoubtedly a part played by the labyrinth in neuromuscular co-ordination is shown by experiments with the water turtle which feeds by darting its head forward and thus catching its prey (Von Beckh, 1954). It was shown that in the weightless state the accuracy of its aim was greatly disturbed. The labyrinthectomized turtle also aimed inaccurately but soon learned to adapt to its lost utricular function, after which it performed better in the weightless state than the intact animal.

The dependence of the cats righting reflex upon utricle stimulation has also been demonstrated by releasing a cat while weightless in an aircraft (Gerathewohl and Stallings, 1957).

In addition to these effects which are attributable to stimulation of the utricle, it is probable that this end organ also plays a part in the production of motion sickness.

It has been known for many years that the labyrinth was the end organ responsible for motion sickness and it has been shown more recently that angular acceleration is the stimulus responsible. In spite of this one is faced with the fact that, when a subject is exposed to purely linear acceleration, he can still be made motion sick. Johnson has shown that much of this effect is associated with involuntary head movement as the subject accelerates or decelerates and that if this head movement is prevented the subject is prevented from being motion sick (Johnson *et al.*, 1951). Although as explanation Johnson points out that the angular accelerations imparted by this head movement can be quite large, since the radius about which the head is moving is relatively small, one must face the fact that if the same head movements were taking place at 1 " g " the subject would experience no ill effects. It appears that only when these head movements take place in either increased " g " or reduced " g " does nausea result and one wonders even whether it is the alternation of direction and magnitude of force which is the responsible factor because the motion to which the subjects are exposed is usually one in which the increased and reduced gravity components are imposed successively.

Since head movement can play such an important part in the production of the motion sickness syndrome by transforming low angular velocities into marked angular accelerations, it is evident that the production of an artificial gravitational field by rotating a satellite is going to present difficulties unless the angular velocity of the rotation is extremely low. The threshold for stimulation of the semicircular canals is of the order of one or two degrees per second but even if the satellite were rotating more slowly it would still be possible to produce stimulation of the canals by sufficiently rapid head movements.

This problem is of course made much easier if one does not require to reproduce a centripetal acceleration of 32 feet per second per second. One would imagine indeed that the adoption of even 0·1 " g " rather than 1 " g " would assist greatly the elimination of this difficulty and yet still provide the man with sufficient gravitational pull to overcome the many mechanical and orientational problems associated with 0 " g ".

Perception of Vertical. It is usually accepted that in the perception of the vertical, man makes use of either visual or proprioceptive stimuli. Where he can see, he usually bases his judgment of the vertical with reference to the vertical and horizontal components of his immediate visual environment such as the corners of a room and the window sills, and it is when this frame of visual reference is absent that he makes most use of his proprioceptive sense. However, another factor comes into the perception of the vertical. If the man is weightless and is therefore deprived of his proprioceptive information and if his visual environment is one which has no strong link with the vertical, for example an aircraft cabin, the judgment of the vertical tends to be based upon the orientation of the man himself. Thus in a parabolic flight, subjects who wore magnetic shoes and were able to walk on the ceiling of the aircraft cabin under weightless conditions formed the impression that the aircraft was flying inverted and the entire environment was upside down, only the subjects themselves being orientated in the normal way.

Reduced sensory environment. The last aspect upon which one might comment in connection with this environment of weightlessness pertains rather to the realm of pure psychology. The monotony of this environment, the reduction of proprioceptive stimuli, the circulatory and respiratory changes analogous to those occurring in the decubitus position, and in general the absence of change, provides a psychological environment which is regarded as monotonous and from which people seem to wish to withdraw into their own minds in search of experience of fantasy.

When the lack of change is prolonged, the subject goes through stages of irritability and finally of hallucination. The subject in the type of environment one would expect to go through a stage of a high degree of suggestibility (Wheaton, 1959).

In this condition the monitoring of controls would be impaired for the subject would be withdrawn and would attend insufficiently to the primary task which he had to perform. This condition, if prolonged, would be associated in due course with frequent periods of somnolence rather than of sleep of the pattern usually associated with the diurnal rhythm. To combat this one requires change and the physical changes in the environment produced even by changes in temperature, changes in air flow, the carrying out of muscular exercise would be necessary. The avoidance of sleep, except at specified times, and mental exercise as a result of audible and visual information are especially required if the astronaut is to maintain " mens sana in corpore sano " over long periods in this environment.

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