Comparative Studies on Animals and Human Subjects in the Gravity-free State

By Siegfried J. Gerathewohl, Ph.D.
School of Aviation Medicine, Randolph Field, Texas

In 1947 Gauer and H. Haber were stimulated by the fabulous advent of rocketry to make speculations about human behavior in the gravity-free state. The outlook at that time seemed to them rather dim. Since then, a lot of work has been done to clarify both the physiological and the psychological aspects of this problem. The literature has been scanned for data on previous experiences, animals have been photographed during rocket ascents and in airplanes, and experiments have been made with human subjects under sub- and zero-gravity conditions during dives and in parabolic flight. We now have much more information, both theoretical and experimental, on which to base some tentative conclusions about the behavior of man under gravity-free conditions. Nevertheless we do not believe that the problem has yet been solved entirely.

In this paper, we will limit the discussion to the psychophysiological aspects of the problem. These concern mainly the question whether the powers of orientation and sensorimotor co-ordination are disturbed under subgravitational conditions, as has been previously suggested. If this is so, flying safety would necessarily be endangered whenever subgravity states occur.

While this question is of direct application to rocket and space flight in the future, investigation of it also will yield results of a more basic nature. It is in the light of these considerations that the following presentation must be understood. Let me start with the theoretical and historical background of the subject.

In his book, "Physiology of Man in the Aircraft," Schubert[18] briefly touches the problem of subgravity. He refers to Ferry, who reported in his book, "L'aptitude à l'aviation," a weakening of the lower extremities and insecure control movements, during the gravity-free state.

According to von Beckh, Dr. von Diringshofen observed zero-gravity during flight maneuvers before World War II. He experienced about the same symptoms that Ferry did. After he became accustomed to them, von Diringshofen and his pilots enjoyed the gravity-free state as a very pleasant situation in flight.

In 1949, this author made two theoretical studies of the "Physics and Psychophysics of Weightlessness," in the first of which Dr. H. Haber participated. We suggested that during the transition from a normal gravitational state to one of subgravity, a sensation of falling may occur from

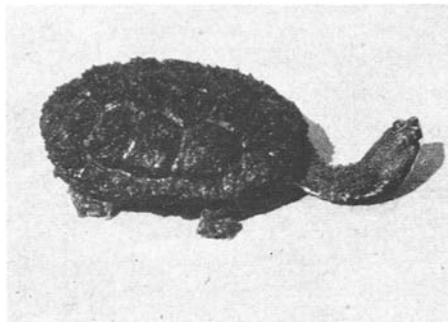
Presented at the 25th Annual Meeting of the Aero Medical Association, Washington, D. C., March 29-31, 1954.

the effect of weightlessness on the otoliths. In recent years, the functional characteristics of the otolith organs of animals have been studied by several physiologists, and the impulses travelling from these organs to the brain have also been recorded. In the absence of weight it seems plausible to expect that the messages sent to the nerve center would be contradictory and confusing, particularly since there are several otolith organs with macular layers facing in different directions. If the otoliths are weightless, will this condition produce sensory and motor disturbances? Will these disturbances be enhanced by a change in stimulation of the other mechanoreceptors under abnormal states of gravity?

Speculation about the consequences of weightlessness has been far from equivocal. While Gauer and Haber predicted impairment of muscular coordination and effects on the vegetative system including a "very severe sensation of succumbence associated with an absolute incapacity to act," Slater [19] vigorously maintained that we can do very well in space without proper stimulation of the mechanoreceptors.

We had reached this systematic juncture of the problem when the first experimental results of investigation in the gravity-free state were reported.

First, let me discuss some experiments with animals in rockets and in aircraft. Using a V-2 and two "Aerobees," Henry, Ballinger, Maher, and Simons[13] studied the behavior of several mice in sub-and zero-gravity states. They also contrasted the activity of a normal animal with that of a labyrinthectomized one. The results were reported two years ago to the Aero Medical Association. By and large, Henry and his group found that the normal mice showed violent movements and symptoms of disorientation.



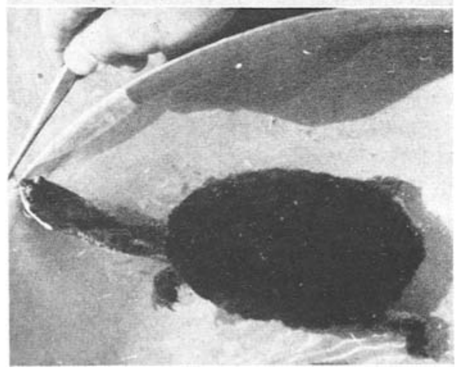


Fig. 1. *(above)*—Hydromedusa tectifera used by von Beckh in his experiments on weightlessness. The animal is on the ground searching for food.

Fig. 2 *(below)*—The test animal striking at the food which is offered by means of pincers. Under normal conditions the turtle never misses his bait.

whereas the operated animal was less susceptible to gravity-free conditions.

These findings were confirmed recently by the experiments of von Beckh[4] on water turtles (Fig. 1). Under normal gravitational conditions these animals strike like snakes at their food, projecting their S-shaped necks with pin-point accuracy toward the bait (Fig. 2). Like Henry and his coworkers, von Beckh used several normal animals and also a turtle with a permanent injury of the labyrinth. At first, this animal was severely disoriented. In striking for food, he passed over, under, or to one side of the bait. After a period of three weeks, however, the animal learned to compensate for the loss of labyrinthine cues by visual orientation. Some of von Beckh's test animals can be seen in the following slides.

Dr. von Beckh took these turtles on sub-gravity and zero-gravity dives in his airplane. Sometimes, during the transition from straight and level flight into the dive, short negative accelerations caused the water of the aquarium to rise and float freely in the air. In spite of this minor complication, von Beckh observed that only the animal with the defective vestibular organ was able to maintain his orientation. The normal animals, instead, moved very little, quite slowly, and out of balance. Since the turtles were not able to aim properly, the bait could not be caught. But in horizontal flight, all the animals acted normally. This disturbance of orientation and motor co-ordination diminished after twenty to thirty zero-gravity flights.

Experiments on human subjects were also done at that time. During the summer 1951, Scott Crossfield, NACA test pilot at Edwards AFB, produced zero- and sub-gravity states in both upright and inverted flight. Crossfield reported a sensation of "befuddlement" during the transition. This effect—probably of a psychological nature—was largely overcome after the fifth flight. He felt no sensation of falling, but he did observe a tendency to overshoot while reaching for the landing-gear switch. The most disconcerting effect was dizziness at about weightlessness on the pullout after the run.

Similar findings in jet-flight exposures to zero-gravity were reported by Ballinger[3] to the Aero Medical Association in 1952. On several of these flights, the subject would voluntarily move his head. While Coriolis effects were noted during increased gravity, no such disturbances occurred during zero-gravity, aside from a mild tendency to overreach. This tendency was then controlled by visual fixation of the target.

So long as the test subject was strapped to his seat and had strong visual references, he was able to maintain his orientation with moderate effort. However, the participants reported that "had they been unrestrained and blindfolded, disorientation might have been extreme."

This belief was confirmed by Major Charles Yeager, USAF, who made several zero-gravity flights about two years ago. He had a brief sensation of falling in the transition period, and after several seconds he noticed certain orientational disturbances. After he pulled out of the parabola, his orientation was soon restored.

Von Beckh performed a series of experiments in visual orientation and motor co-ordination on human subjects under gravity-free conditions very recently. In an aiming test, the subject had to draw crosses in seven squares arranged diagonally from the left top corner to the right bottom corner of a sheet of paper, which was placed on the instrument panel in front of him. The experiment was done in straight and level flight, again during radial acceleration in the turn, and finally during zero-gravity, both with eyes open and with eyes closed.

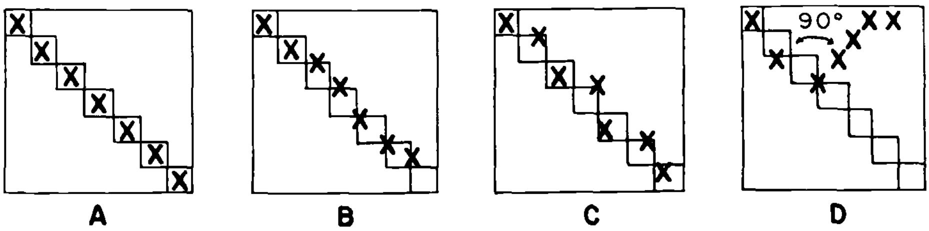


Fig. 3. Cross-drawing test. A and B were made during straight and level flight; B and C were made during the dive under sub-gravity and zero-gravity conditions. A.—eyes open: no difficulties or deviations; B.—with eyes closed some irregularities of the markings can be observed; C.—eyes open: irregularities due to sub- and zero-gravity; D.—eyes closed: a typical deviation of about 90° toward the right-hand corner occurred after the third cross was drawn.

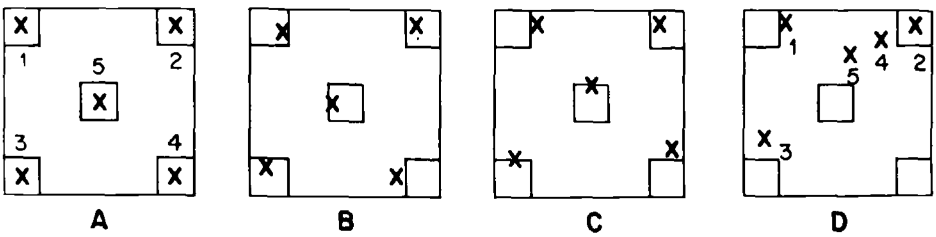


Fig. 4. Cross-drawing test used by von Beckh in his second series of experiments on muscular co-ordination in the state of weightlessness. For details see Fig. 3.

During radial acceleration, the subject had some difficulty in placing the marks in the squares. This difficulty was extreme during zero-gravity. Without visual control it was impossible to place the crosses in anything like a diagonal direction (Fig. 3).

After the third cross was drawn, a typical deviation of about 90° toward the right-hand corner was found in most cases. This was also true when another pattern was applied. The results of these tests are shown in Figure 4. A great number of flights was required, before the subjects were able to place the marks in the prescribed manner; and even then the results were never so accurate as those obtained under normal conditions.

In still another series of experiments von Beckh studied the effect of post-acceleration weightlessness. Here, the pilot produced a blackout in the pullout after the dive at about 6.5 g, and immediately afterwards flew along the ascending arc of the parabola. Under these conditions, the blackout lasted longer than after a normal pullout, and the effect on orientation was extreme during the weightless phase.

Summarizing the findings of all experiments, we can say that almost all normal animal and human subjects have shown symptoms of disorientation and loss of motor co-ordination during the transition into weightlessness and during its early stage. The animals without labyrinthine functions were less disturbed than the normal ones in the attempt to keep their balance or to aim for food. The animals and the humans performed better, the more tactile and visual cues were provided. Henry and his co-workers interpreted this to mean that the orientational state of the animals corresponded to that of a pilot, firmly strapped to his seat, who orients himself by his instruments. It may be mentioned too, that von Beckh's experienced instrument fliers performed better in the cross-drawing test than the inexperienced ones. These are indications that it may be possible to adapt to the gravity-free state.

This last remark would seem to be the most important one, because it may free us from further troubles. Yet it must be considered very cautiously. First, we should be aware of the fact that an adaptation to the transition phase was observed so far. We still do not know what would happen if the subject had to stay in the gravity-free state for a long period of time. What we do find is a decrease of the initial disturbances of orientation in most cases.

Light is also shed upon this problem by some electrophysiological studies. Experiments of this kind made by Adrian[1] and by Lowenstein,[17] with nervous stimulation of the otoliths of the cat and of the Thornback Ray-fish (Raja clavata), had shown that the frequency of nerve impulses sent to the brain depends upon the position of the head, and therefore upon the vector of gravity. There is some experimental evidence that, after the cessation of weight, the otolith organs

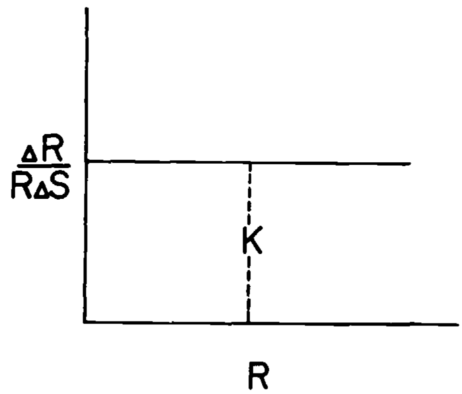


Fig. 5. Schematic representation of Weber's belief: $\frac{\Delta R}{R \Delta S} = K$. R = a measure of the "stimulus," usually expressed in absolute (c.-g.-s.) units; ΔR is a necessary change of stimulus to produce a just noticeable difference ΔS in sensation (Modified after Holway and Pratt 1936).

will settle down at a "basic" pulse frequency which is characteristic of weightlessness. This frequency will be altered by linear acceleration, for instance, through voluntary head movements. In summing up Adrian's and Lowenstein's results, Slater[19] concluded that "if a particular nerve always transmits some impulses, whatever the position of the head, then the nerve endings are always being stimulated to some extent, in whichever direction the otoliths are pulling. Such a nerve, therefore, is stimulated even when the otoliths are pulling towards the macula, but that stimulus should be absent when gravitational pull is absent, in which case no false messages will be sent to the brain." In this case, the subject would soon learn to interpret the absence of nerve impulses correctly.

There is still another problem which must be mentioned in this connection: enough, though, no such disturbances were observed when the subjects moved their heads during zero-gravity. This finding suggests several alternative possibilities.

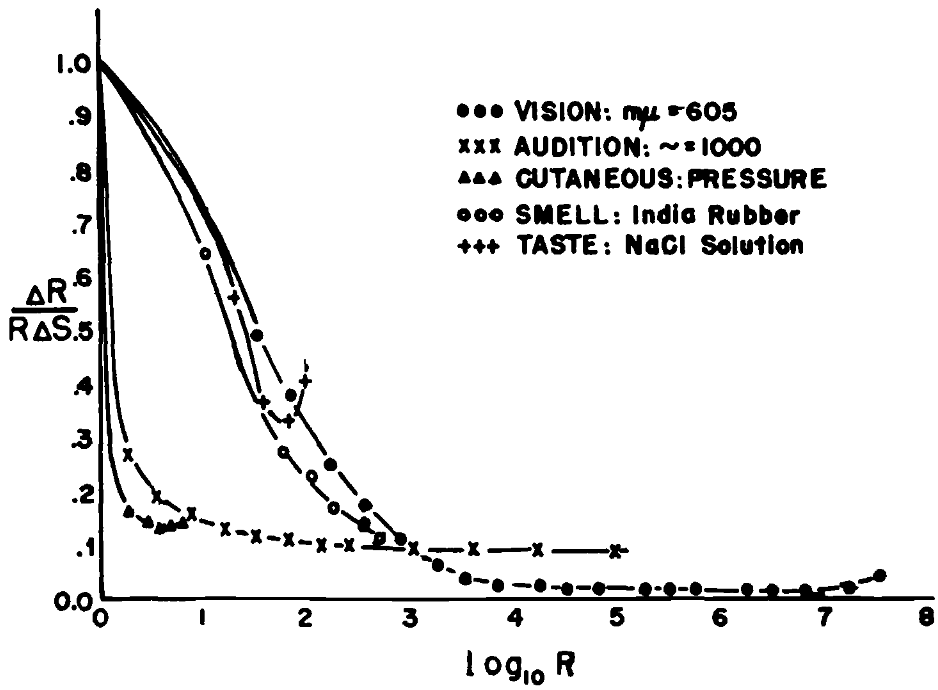


Fig. 6. Weber-Fechner functions representing five different sense modalities. Weber-ratios shown as functions of the logarithm of the stimulus. Except for the rise after passing through their minima the curves can be approximated by the function $\frac{\Delta R}{R\Delta S} = \frac{1}{b}\left(\frac{1 + a}{R}\right)$ rather than by the function given in Fig. 5. (Modified after Holway and Pratt 1936.)

namely, the aggravation of vestibularly-produced disturbances according to the Weber-Fechner law, predicted by Gauer[9] in 1950.

It is a well-known fact that orientational disturbances occur through additional acceleration—the so-called Coriolis-forces—during increased weight. Ballinger's test subjects noted this effect in their flights. Strangely

The first is that the otolith organs do not furnish direct information about position and gravity, but only affect our sense of equilibrium indirectly, by control of the balancing muscles and of the eyes (Slater).[19] The Coriolis effects during increased weight may then be caused solely by endolymph movements in the semicircular canals. At any rate, what we know is that the disturbances are caused by the *additional* acceleration. We cannot expect any Coriolis forces to be produced by head movements,

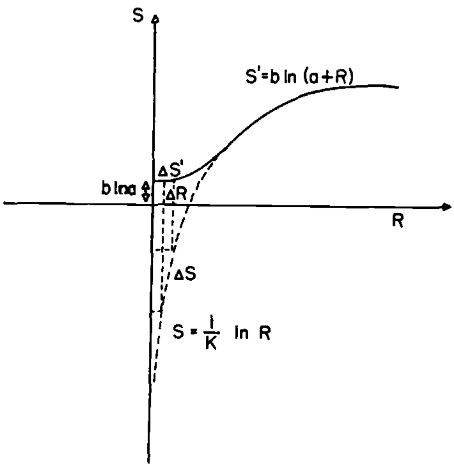


Fig. 7. Schematic representation of modified and unmodified Weber-Fechner function. According to the unmodified form of the Weber-Fechner function, strong sensations are caused by minute changes of stimulation in the region of small stimuli. According to the modified form only a small change of sensation is produced under the same conditions.

however, when the system is at rest. This conclusion would in turn mean that the vestibular system is not stimulated by the loss of weight alone; or at least it is not excited in such a fashion that acceleration produced by voluntary movements would have a confusing effect.

Secondly, we may argue that the application of the Weber-Fechner law is not appropriate to demonstrate the relationship of stimulus to sensation in the gravity-free state (Fig. 5). While it is not my intention to discuss the limitations of this psychophysiological law here, I should remark that it is far from being universal. The exceptions to it are neither negligibly small nor are they unimportant. It has been shown by numerous investigators that the assumption of a constant fraction of the stimulus magnitude in each barely noticeable difference of perception is merely an approximate statement of a special case, and that Fechner's logarithmic formulation does not represent the true relationship between the intensity of the stimulus and the magnitude of sensation over the whole range of perception. Figure 6 shows the data from experiments on threshold discrimination of various senses. If we plot the general mathematical function expressing these stimulus-sensation ratios, we usually obtain an S-shaped curve. Such a curve has an approximately linear region at about the inflection point near the center, when the scale of intensity is extended in both directions, as shown in Figure 7. Furthermore, the Weber-Fechner law expresses the relation of the scales only if there is homogeneity between the two series of magnitudes. The question in our case is: what properties can be associated with both stimulus and sensation magnitudes? One might think of units associated with the activity of nerve discharge, as demonstrated by Adrian. But we cannot definitely settle this question, and we think it is very hard to measure. So there is much doubt as to the stimulus-sensation ratio, and as to the interpretation of results of that kind.

Finally, von Beckh's experiments on post-acceleration weightlessness yielded strong effects of disorientation. Even the sensation of inverted flight was noted shortly after the beginning of the gravity-free state. We may hypothesize that this effect was the result of an enhanced "contrast" between increased acceleration and weightlessness thereafter; but we still cannot explain the sensation of flying upside down connected with it.

This survey of the work done on the investigation of weightlessness, and the progress made on it during five years of research in this field of space medicine, is by no means exhaustive. There are other problems which have not been treated here, and which must be investigated before we understand definitely the stimulus-sensation mechanism, the process of adaptation, the tolerance-differences between individuals, and other problems of the gravity-free state. Slater proposed the investigation of nerve discharges from the otolith organs during weightlessness. Von Beckh suggested that we study the otolith reactions in zero-gravity with various positions of the head. We are also planning to investigate the eye movements and visual illusions during the transition into the weightless state. Not only because of its scientific value, but also because of its practical application for space flight, the exploration of human behavior under gravity-free conditions should be considered as an important goal.

ACKNOWLEDGMENT

The author wishes to thank Dr. Oskar Ritter, School of Aviation Medicine, for the mathematical interpretation of our physiological findings and reformulation of previous hypotheses.

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