Experiments with Animals and Human Subjects under Sub-and Zero-Gravity Conditions during the Dive and Parabolic Flight

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SUB-GRAVITY and zero-gravity states are becoming more and more important in aviation, because they frequently occur in high-speed, high-altitude flight. It is therefore necessary to answer the question whether the powers of orientation and muscular co-ordination may be seriously disturbed in these states, as others have suggested. If so, the safety of the pilot and of his crew would necessarily be endangered.[7,8,9,10,12]

Before World War II, H. von Diringshofen described some experiments with sub- and zero-gravity, which he carried out for a period of about ten seconds at a time in vertical dives with his plane.[4] In 1951, Haber and Haber suggested zero-gravity flights with fast-flying airplanes along a Keplerian trajectory to obtain gravity-free conditions up to about thirty seconds for medical research.[12] This method was successfully employed by Ballinger in experiments with human subjects, as he reported in this Journal.[1] Other valuable results were obtained by Henry, Ballinger, Maher, and Simons (1952) by photographing the behavior of animals during sub- and zero-gravity conditions in V-2 and Aerobee rockets.[13]

EXPERIMENTS WITH ANIMALS

Since 1951, the author has been studying the behavior of certain species of Chelonia, notably Chrysemis ornata and Hydromedusa tectifera, which are found on parts of the South American Continent. These turtles would seem to be especially suitable for studies of orientational behavior and muscular co-ordination, because of their ability to move under water with extraordinary speed and skill in all directions during their quest for food. The animals belong to an extremely voracious class of water turtles. Under normal gravity conditions, i.e., on the ground or in horizontal flight, they strike like snakes at their food, projecting their S-shaped necks with pin-point accuracy at the bait. They will also snatch a piece of meat hanging from the mouth of another animal. In fact, when they are hungry, they try to pull out the bait which is already in the mouths of other turtles.

For behavioral studies under sub- and zero-gravity conditions several normal animals and one turtle with a permanent injury of the labyrinth were used. This animal had been left for some days by accident in an overheated aqua-terrarium. As a result, he showed a complete loss of orientation, which was particularly obvious in the water. Offered a piece of meat, this *Hydromedusa tectifera* tried to attack it with strong but unco-ordinated movements that contrasted strangely with his normally smooth, swift locomotion. Moreover, when striking, the head of this animal would pass over, under, or to one side of the bait. After two weeks, the turtle slowly began to recover. The improvement was shown by his movements, and later also by his aim in taking the bait. At the end of three weeks from the time of the accident, the animal was able to eat normally. I concluded that this turtle had suffered a permanent labyrinthine injury, from the extreme thermic irritation to which he had been exposed, but that he had then learned to compensate for his loss of labyrinthine cues, by developing his visual orientation.

In order to test the permanence of the injury, I tied a hood over his head. The animal then displayed complete disorientation again, both in and out of the water. He did not even try to displace the hood, as did the control animals. Nor did the latter show any orientational difficulty when they were subjected to the same experiment.

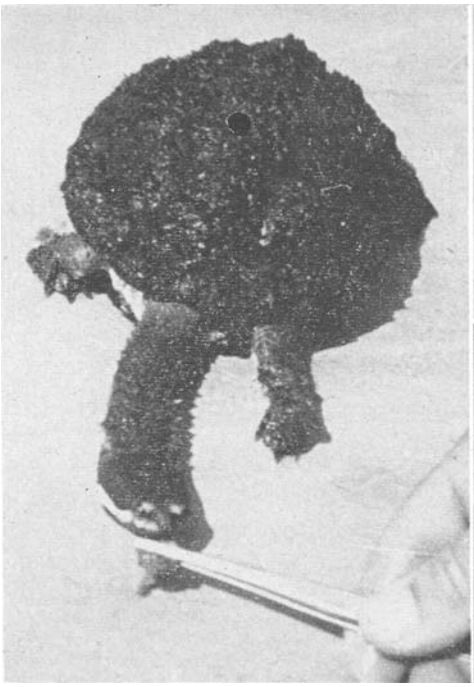
Experiments in the air were then begun with this "adapted" animal, with other *Hydromedusa tectifera,* and with the two *Chrysemis ornata.* The animals were carried in a cylindrical jar, open at the top and filled with water. They were subjected to vertical dives that produced sub-gravity and zero-gravity conditions for as long as seven seconds. During these, the animals were offered samples of meat, either individually with pincers or by pushing the bait into the jar. The latter procedure was extremely instructive because of the fight that followed among the animals in their attempt to seize the food.

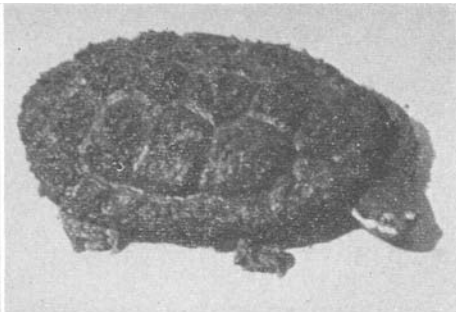
In the transition from horizontal to vertical flight, some brief negative acceleration was produced. At this time the water (and occasionally the animals with it) would rise up, forming an ovoid cupula to a height of 20 or 30 cm. above the top of the jar. However, most of the water would flow back when the jar was lifted to the same height. The acceleration was measured with g-meters in each of the three axes of the plane. These were specially prepared to record values from zero to plus 1 g or minus 1 g.

RESULTS

The results of these flights may be summarized as follows. Only the *Hydromedusa tectifera* without labyrinthine functions, but visually adapted, behaved with complete normality under sub- and zero-gravity conditions. He moved with speed and accuracy, and demonstrated the same skill and ease in eating as on the ground.

The other three turtles, by contrast, moved only a little, quite slowly, and insecurely. They were unable to attack the offered bait. Even pieces of meat that were placed directly in front of their mouths could not be taken, due to their inability to project their heads in an aiming movement. Yet it was obvious to the observer that they were hungry and were doing their best to strike at the bait. Their failure to take it followed the same pattern that had been observed in the case of the injured animal before adaptation took





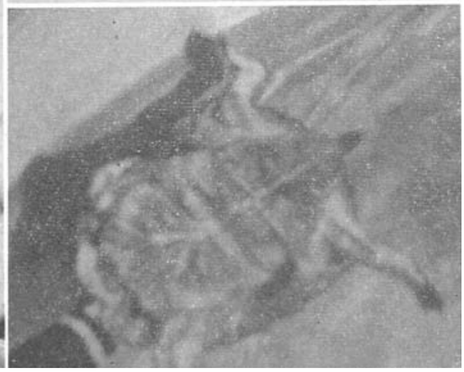


Fig. 1. *(upper right)*—Hydromedusa tectifera on the ground in a defensive position. The long S-shaped neck is partly covered by the shell.

Fig. 2. *(left)*—Hydromedusa tectifera attacking: The animal strikes at the bait.

Fig. 3. *(lower right)*—The animal in the water bowl has an injured labyrinth but is visually adapted. The hood-covered head is partly visible. The animal is disoriented and swims in an abnormal inverted position.

place. After the return to horizontal flight, all the animals behaved normally. While these symptoms of disturbed orientation and co-ordination gradually diminished after twenty to thirty flights, the improvements was by no means so great that the normal turtles reached the same mobility and eating skill as shown by the "adapted" animal.

DISCUSSION

The experiments described above demonstrate once more that the senses of equilibrium, vision, and kinesthesis provide the means of orientation and co-ordination under normal or sub-gravitational conditions. During sub-gravity, all the uninjured animals showed considerable difficulty in both orientation and co-ordination. This was exhibited by their inability to aim the neck and head toward an offered bait. The same animals, disturbed by the absence of weight during zero-gravity, became more or less adapted after a certain number of dives (twenty to thirty).

The animal without labyrinthine functions had experienced orientational troubles of a similar kind immediately after the injury, but had become adapted in the following three weeks. During all zero- and sub-gravity flights, he behaved in a complete normal way.

Magnus and de Kleyn (1924) had demonstrated previously that some of the higher mammals, such as cats and monkeys, are able to walk and climb in a normal fashion several days after labyrinthectomy. Moreover, it has been observed that they can even jump, landing precisely on the target.[14] This proves that they "aim steadily at their target by means of optical postural reflexes at first, then bring the body into a corresponding position." The two authors thus cited found no lasting decrement of muscle tonus in these operated animals. Where it was found at all, it disappeared after a while.

Similarly, the *Hydromedusa tectifera,* according to my observations, executes his movements with no less force after labyrinthine injury, but with impaired co-ordination. After adaptation, he then behaved with complete normality on the ground, and he outperformed by far the normal animals under sub-gravitational conditions. This paradox can easily be explained by the dominant role of the optical sense in orientation. It also appears that the labyrinth has only a partial function in the general regulation of tonicity, and may be compensated for by other senses without serious difficulty when the need arises.

It should be noted, though, that in our case adaptation occurred under normal gravity conditions. A decrement of muscle tonus might possibly be found when gravity and weight are reduced or entirely removed for long periods.

Finally, it may be mentioned that the labyrinthectomized animal in the experiments described by Henry, Ballinger, Maher and Simons (1952) also did better than the normal animal during sub- and zero-gravity conditions. However, no disturbances of co-ordination were observed in those experiments. Hence, it seems to me that water animals of the species employed in my tests are especially suitable for studies of orientation and motor co-ordination in the gravity-free state. The reason is that they ordinarily move in three dimensions, as most animals do only under exceptional circumstances, and they can be impelled to demonstrate their motor efficiency when hunger is used as the motivating drive.

EXPERIMENTS WITH HUMAN SUBJECTS

A series of experiments in visual orientation and muscular co-ordination of human subjects under gravity-free conditions also was performed. In these tests, the subject had to draw crosses in seven small squares, which were arranged diagonally from the left top corner to the right bottom corner of a sheet of paper (21 x 21 cm.) attached to the instrument panel of an airplane. No support was available for the hand of the subject because of the distance between the seat and the panel. The subject was held by his shoulder belts firmly in his seat.

A fighter plane with two seats was used in these experiments. The 1,500-h.p. engine gave a diving speed of about 365 knots. Two kinds of experiments were made. In the first, each subject took the test (1) in horizontal flight, (2) during radial acceleration in the direction from head to feet, and

(3) during the dive, under sub-gravity and zero-gravity conditions. The tests were made both with eyes open and with eyes closed; and two different test forms were employed.

In the second type of experiment, the effect of post-acceleration weightlessness on orientation was investigated. The pilot dived from about 10,000 feet to about 7,200 feet and pulled out of the dive rather abruptly. This maneuver produced a positive acceleration of about 6.5 g, causing the subject to black out. (The pilot was protected against the effects of high acceleration by a crouching position.) Immediately after the pull-out, the aircraft was flown along the ascending arc of the parabola, in which aerodynamic forces are equalized by the power of the engine. In this way, post-acceleration weightlessness was achieved for about twelve seconds.

RESULTS

In the first experiment, the following observations were made:

1. During horizontal flight, with eyes open, the crosses were placed in the squares without difficulty.
2. During horizontal flight, with eyes closed, the crosses were placed diagonally in the prescribed manner with only slight irregularity due to the lack of visual control.
3. During zero-gravity, with eyes open, drawing the marks became difficult. They were made inaccurately, and deviated from the established pattern, although a diagonal direction was generally followed. This of course was due to the visual control.
4. During zero-gravity, with eyes closed, deviation from the diagonal direction was so pronounced that it could not be attributed solely to the lack of visual control. The subjects experienced great difficulty in placing the crosses in the squares.

After the third cross was made, a typical deviation of about 90° toward the right-hand top corner was noted in most cases. However, the execution of this test improved after several

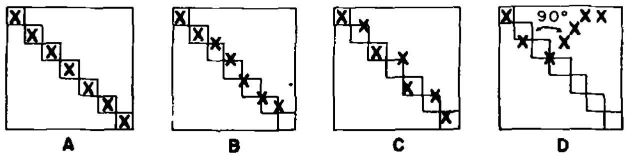


Fig. 4. Cross-drawing test. In horizontal flight: (a) with eyes open, and (b) with eyes closed. During the dive: (c) with eyes open, and (d) with eyes closed.

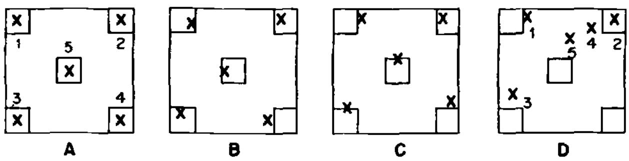


Fig. 5. Cross-drawing test with differently arranged pattern. For details see Fig. 4 a-d.

flights. The person with the longest record in instrument flying showed a very remarkable improvement already after the second flight. The results of one test subject on the two tests are shown in Figures 4 a-d, and 5 a-d.

A further decrease in accuracy was found after the well tightened safety and shoulder belts had been replaced by a loosely adjusted seat belt alone. Besides visual control and positional stability, another psychological factor seems to influence the performance of this test.

The results of the second type experiment may be summarized as follows:

1. During post- acceleration weightlessness orientation was extremely affected. The disturbance occurred shortly after the beginning of the gravity-free state. The subject had the sensation of flying in an inverted position, although no negative acceleration had been present.

2. The black-out lasted longer than after a normal pull-out. Vision was not restored until the plane entered the descending arc of the parabola.

3. Only after the fifth second of weightlessness could the drawing with visual control be started. The crosses then showed the same deviation from the diagonal direction that had been found under sub- and zero-gravitational conditions.

DISCUSSION

Although the interpretation of our results is hampered by the relative small number of experiments, some tentative conclusions may be drawn. Von Diringshofen attributes the deviation from the line in the drawing test to the dominant tonus of the elevating arm muscles during the state of weightlessness. It also seems to me that the muscular equilibrium of the arms can be better maintained during increased acceleration than with decreased gravity. This observation is in accord with the Weber-Fechner law, as suggested earlier by Gauer and Haber (1950).[7]

Garten (1917) and Strughold (1950) have already pointed out the importance of the tactile sense in maintaining orientation during flight.[6,16] In this connection, I would like to add that disorientation, due to incorrect labyrinthine cues, can be prevented by the toxic effect of streptomycin on the vestibular apparatus. This effect has been demonstrated by Berg (1949) and by Northington (1950).[3,15]

So far as visual orientation is concerned, disturbances in the transition phase from the normal to the zero-gravity state may take the form of optical illusions, as suggested earlier by Gerathewohl.[8,9,10] It seems possible that an illusory effect of this sort may be partly responsible for the deviations in the drawing tests.

As von Diringshofen suggested (1952), the serious disturbances during post-acceleration weightlessness may be caused by poor reaction of the haemostatic regulators in the circulatory system. These are normally adjusted to 1 g.[4] Moreover, relaxation of the muscles (fall reflex) may cause delay in the flow of blood from the lower parts of the body to the right ventricle (Magnus and Kleyn 1924) with the same result.

The practical side of our problem

should also be mentioned here. A pilot, pulling sharply out of a dive, may experience greying or blackout. In order to recover quickly, he may push the stick so far that the airplane enters a parabola. In this event, the pilot may become weightless, and his loss of sight and orientation caused by the increasing g's may even be prolonged.

Such a situation will occur when the plane is maneuvering in an air battle. Combinations of dives and pullouts into parabolas do occur when fighter craft make, for instance, high-side gunnery runs on bombers. The attacking plane penetrates the fighter defense by diving from a high altitude, makes its pass at the bomber from below as he pulls out, then evades the bomber's guns by another dive. In evolutions of this kind during World War II, pilots frequently experienced negative accelerations, weightlessness, and thereby disturbances of vision.

Not only because of its theoretical interest and its application in the future to space flight, but also because it has an immediate bearing on combat flying, the author intends to continue experiments on this problem. It is planned to improve the methods and equipment. Various positions of the head will be used to compare the reactions of the otoliths under sub- and zero-gravity conditions. The optical illusions, predicted by Gerathewohl (1952) during changes of acceleration in the sub-gravity state, also will be investigated further.

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