Physics and Psychophysics of Weightlessness Visual Perception

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IN A PREVIOUS paper the attempt was made to elaborate some physical and psychophysical principles which determine the behavior of the human body under conditions of partial or entire lack of weight.[35] It was shown that subsequently to a transition of the body into the gravity-free state the field of elastic forces acting in the interior and on the surface of the body will attain a new state of equilibrium, in which the sum of all elastic forces acting on each point of the body's interior and surface vanishes. In this situation the stimulation of the vestibular apparatus is changed decisively; probably accompanied by the sensation of falling freely. One may assume that this sensation will prevail as long as the individual is not adapted. If adaptation takes place, the individual's situation will be accepted as a new psychophysical zero-state. The consequences of this transition with regard to the stimulus-sensation relationship also was discussed.

The entire range of phenomena treated in the above-mentioned paper was related exclusively to the stimulation of the mechanoreceptors. Other perceptual cues, especially visual ones, were considered but little. It is the rationale of this paper to arrive at some theoretical conclusions concerning the interaction of the proprioceptive and visual senses under conditions of sub-gravity and zero-gravity.

One may object that a study of this intricate problem on a purely theoretical level is not warranted at this time. It is believed, however, that an attempt of this nature is of value for a number of practical and theoretical reasons:

1. The phenomenon of reduced or eliminated weight is about to become an important environmental factor of man with the advent of the high-altitude, high-velocity craft. In a modern fighter or rocket plane the pilot is likely to experience kinematic conditions which involve the reduction or even entire loss of weight.[36]
2. The effects of increased weight on man were studied thoroughly during the past decades. No or only little efforts were made, however, to investigate the effects of decreased weight on the human organism.
3. The medical and psychological literature makes available a wealth of information about the relationship between proprioceptive and visual senses, which can intelligibly be used for an extrapolation to the conditions of sub-gravity and zero-gravity.

Opinions or conclusions contained in this report are those of the author. They are not to be construed as necessarily reflecting the views or the endorsement of the Department of the Air Force.

In the field of space medicine* a number of basic concepts and terms came into usage which are of necessity for the understanding of our problem and which will be defined briefly for the benefit of the reader:

1. *Weight.*—Within the gravitational field of the earth a body derives its weight from the mechanical support that prevents it from falling freely. On the other hand, a body is weightless as soon as it is allowed to move freely under the influence of gravitation and its own inertia. In this case, the body finds itself in accelerated (decelerated) motion along a Keplerian trajectory, and the resultant of the forces of inertia exactly compensate the gravitational pull directed toward the center of the earth (see reference 36, p. 389, Fig. 2).

2. *Gravity.*—Gravity is the vectorial sum of the forces of gravitation and inertia acting on a body. In this sense, gravity is synonymous with weight. According to the Newtonian relation: force = mass x acceleration, the force of gravity is measured most conveniently in terms of acceleration, with the acceleration due to the terrestrial gravity $g = 981$ cm. sec.$^{-2}$ as the unit. Normally, with a body being at rest, the forces of inertia are absent and the body finds itself in the "normal state of gravity" of $g = 1$.

3. *Sub-gravity.*—If a body is subjected to a downward acceleration smaller than 1 g, the forces of inertia associated with acceleration are subtracted from the gravitational force acting on the body. In this state, the body finds itself in a state of sub-gravity. Similarly, if a force of inertia is added to the gravitational force, such as is on a centrifuge or at an upward directed component of acceleration, the forces involved add vectorily and produce a state of "super-gravity," i.e., $g > 1$.

4. *Zero-gravity.*—In the special case that a body is subjected to a downward acceleration of 1 g, the forces of inertia exactly eliminate the force of gravity and the body finds itself in the state of zero-gravity. This case is realized in all motions of unpropelled bodies in ideally frictionless space.

Possible methods of producing these states for research have been outlined elsewhere.[36] Here, we may only mention the fact that within the gravitational field of the earth gravity can be reduced or removed by kinematic means. Although the problems connected with weightlessness are of first importance in aviation, the behavior of perception under conditions of reduced gravity is of general interest. In view of this, we invite the attention of the reader to the possible effects of zero-gravity on vision. It is the purpose of this paper to gather some data obtained under conditions of more and less than 1 g and to apply these findings to our problem.

PERTINENT ANATOMICAL AND PHYSIOLOGICAL DATA OF THE EYE

Since we are dealing with partial or entire lack of weight in this study,

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*Space Medicine: The human factor in flights beyond the earth. Ed. by John P. Marbarger. The University of Illinois Press, 1951.

these functions directly related to mechanical characteristics of the body and its parts, will be of first concern. As to the problem of visual perception, the anatomical and structural characteristics of the eye will be discussed first, for it is from the mechanical side of the optical sense organ that alterations of perception may eventually be expected.

As is generally known, the human eyes are slightly asymmetrical spheres inclosed by the sclera and the cornea. Both inclosures are relatively rigid and unelastic providing a stable hull for the eye. The weight of the eyeball is about 7 grams, its volume about 6.5 cc., and its specific gravity varies from 1.02 to 1.09.[15]

Within the eye a hydrostatic pressure of about 20 to 25 mm. Hg is maintained under normal conditions. There is always an equilibrium between the intra-ocular pressure, the tention of the tissue and the blood pressure so that an adequate circulation is secured. Disturbances of the equilibrium can be balanced by the safety mechanism of the canal of Schlemm. Since the latter is relatively small, the intra-ocular pressure may be varied by altering the volume occupied by any of its content. A dilatation of the capillaries, for instance, brings about a transitory rise of pressure, and their contraction a corresponding fall. So, if osmotic or mechanical forces act upon the intra-ocular pressure, a reactive system of mechanical and nervous processes serves to re-establish the normal pressure.

The action of the external muscles also influence the intra-ocular pressure in such a way that the latter is raised when the muscles of the eye are activated and that the pressure falls when these muscles are paralyzed.[15] No direct relation, however, exists between the intra-ocular pressure and the intra-cranial pressure. In the following a description of the physiological processes in the eyes in relation to acceleration is given as a simple model only; actually, these processes are much more complex. At any rate, this model is thought to depict the circumstances affecting perception under conditions of un-normal acceleration.

"Positive" Accelerations. — During changes in acceleration only organs of considerable mass are subject to stress due to increase of weight. As to the fluids within the body, the blood and the cerebrospinal fluid need special consideration. Centrifugal forces acting in the direction head-to-seat bring forth a hydrostatic pressure differential along the large vessels and in the cavities of the body. Below the heart, the efferent blood flow is facilitated while the venous inflow becomes difficult. Above the heart, the conditions are reverse. On the other hand, forces acting on fluid contained within the ventricles of the brain or in the subarachnoid spaces may give rise to disturbances of the intra-cranial pressure.

The failure of the circulation to the head due to centrifugal force results in ischemical hypoxia of the brain and probably of the retina and consequently in the disturbance of vision. As soon as the pressure in the retinal artery falls below the normal intra-ocular pressure, the artery is compressed by the prevailing pressure of the intra-ocular fluid and the retina fails to function due to circulation disturbances. Proper circulation is maintained to about 4 g. From here on, a distinct diminution or a complete loss of vision commonly known as "black out" may occur. As the acceleration is decreased vision returns quickly.

"Negative" Acceleration. — During negative acceleration (seat-to-head) a reversal of the processes described above takes place. Then, the blood pressure rises according to the seat-to-head direction of the acting force, and the hydrostatic pressure produced in the carotid arteries acts in the same direction as the force of the heart. Consequently, there is little inertia to be overcome and both forces give rise to the high pressure: the lids and the eyes are congested and swollen, the vessels of the conjunctiva stand out prominently, and subjunctival hemorrhages have been described.[58]

From both types of acceleration it may be concluded that the eye is affected but indirectly by mechanical forces. There are no data available that vision may be affected directly when the centrifugal force acts on the eyeball.

Accelerations Smaller Than 1 g (Sub-gravity and Zero-gravity).—The weight of the body and its parts will decrease or vanish under the condition of sub-gravity or zero-gravity, respectively. At the same time weight of the eyeball and intra-ocular pressure will be changed. Fortunately, however, these changes will be relatively small and unimportant as to their effect so that no disturbances in vision may be anticipated.

During sub-gravity the weight of the total amount of blood will decrease, and during zero-gravity the weight of the blood will vanish entirely. This reduction of the weight may cause an increase in blood pressure in the vessels located above the heart and a decrease of pressure in the lower part of the body. If the system of the blood vessels would operate as a rigid system of pipes, the loss of weight and the increase of the systolic pressure might affect the blood circulation. Since, however, the vessels vary as to their capacity due to the elasticity of the walls, part of the increase in pressure will be abolished within the system of the blood vessels. Furthermore, the systolic work of the heart muscles acts directly on the amount of blood in the left ventricle only indirectly but to a much larger amount on the resistance of the blood during its circulation through the vessels. It is this effect which causes the hydrostatic pressure within the blood vessels, while the volume of blood in the heart is only of minor importance for the total amount of pressure. An increase of the blood pressure in the skull and consequently in the eye produced by weightlessness would also necessarily require that no nervous regulation takes place beforehand.

We know, however, that the human organism is able to compensate alterations of the hydrostatic pressure and of the blood volume. This is chiefly accomplished by the influence of the carotid-sinus reflex upon the tonus of the vessels and upon the speed of pulsations.[58] By this it becomes evident that the body possesses a system of regulators for balancing the small disturbances which may occur by the lack of weight of the blood. Practically, these regulation mechanisms become active already during 1 g conditions when the body is in any other than a vertical position. When lying horizontal for instance, the mechanical conditions as to the circulation of the blood in the body and in the head are changed considerably compared to the standing or sitting position, respectively. Nevertheless, no significant alteration in blood pressure does occur. Hence, no disturbances of vision caused by the effects of zero-gravity on the blood are expected.

Similarly, the loss of the weight of the eyeball will not have a disturbing effect on visual perception. The pressure or weight, respectively, of the liquid of the eye on its support is only a fraction of the hydrostatic pressure within the eye, which, therefore, will remain fairly constant in the subgravity and zero-gravity state.

Finally, the influence of weightlessness of the eyeball on the external eye muscles must be considered. There may be some disturbances in the balance and control of eye movements due to the cessation of weight; but we have some reason to assume that the balance will be restored very fast. Again, the weight of the eyeball in relation to the rigidity of its structure is so small that no pronounced effects are anticipated.

Consequences of the weightlessness of the brain, if any, may eventually influence visual perception. The alterations of the intra-cranial pressure, for instance, may be of greater importance due to the larger dimensions of the brain and the cranial liquid. Hence, these alterations may cause deteriorations of the activity and the proper functioning of the brain, which may seriously impair the perceptual processes. The possible neurological and psychological aspects thereof, however, are beyond the objective of this paper.

ORIENTATION UNDER CONDITIONS OF VARYING GRAVITY

Normally, man lives under conditions of 1 g, and most of his phenomena of life come to pass in the three-dimensional space. In this environment he has to orient himself; and in order to do so, a system of references must be at his disposal. The main determinants of this system are of optical and gravitational origin. They furnish the frame of reference within which the spatial orientation takes place.[19,21,37]

By orientation, the ability of the individual to localize his position with reference to the three-dimensional space is understood, in which the act of localization is guided by a complex of perceptions. It is this complexity, and the role of visual perception for space orientation, which requires an investigation of this problem from the standpoint of zero-gravity.

Visual Spatial Orientation

In another paper an attempt was made to demonstrate that the visual perception of depth is indispensably based upon the elements of space, time and matter.[9] For the determination of an object in space its position in the two-dimensional visual field of the observer and in depth is necessary. The act of localization, then, will be made by means of all orientational cues available.

1. *Under Normal Conditions.*—The crucial indices for the localization of the body or of an object within the two-dimensional plane of observation are the vertical and the horizontal directions, which can be determined by the individual with great accuracy. Jastrow (1893) found that the average error in judgment of the visual vertical and horizontal was less than 0.6 degree deviation from the true position; whereas the mean error of judgment of lines tilted at an angle of 45 degrees amounted to 4 degrees in a direction toward the horizontal.[38]

Koffka (1935) states that the precision in the perception of the visual vertical is due to the development of a visual spatial framework which he calls an "anchorage in space."[41] More recently, Mann and Berry (1949) investigated the accuracy with which the individual is able to determine the vertical and horizontal by setting a target (two 8-inch parallel strings treated with luminous paint and illuminated by an ultraviolet lamp) to that position.[47] They found that the mean errors of judgment were less than 1 degree for each subject and that there was no significant difference between the errors in judgment of the visual vertical and the visual horizontal.

From this one can conclude that the individual is able to judge the visual vertical and horizontal with a considerable accuracy under normal gravitational conditions.

2. *In Situations of Postural Conflict.*—Already Aubert (1860) noted that when an individual views an upright visual target with the head tilted there is an apparent rotation of the vertical target in the direction opposite that of the inclination of the head.[4] Later, Mueller (1916), when repeating Aubert's experiments, found that a vertical line appeared tilted in the same direction as the head when it was tilted only by a small degree; but that for large amounts the Aubert phenomenon is valid.[52] Passey (1950) and Passey and Ray (1950) confirmed both Aubert's and Mueller's findings up to 20 degrees, insofar as some of their subjects noticed the Aubert and some the Mueller phenomenon.[54,56]

Witkin and Asch (1948) placed subjects in positions of head and body tilt and measured their ability to establish the true vertical.[68] From an angle of 45 degrees the mean deviation from the vertical was about 6 degrees during head tilt. Three positions of body tilt were employed: 28 degrees, 42 degrees and 90 degrees, the average errors being 7.6 degrees, 5.9 degrees and 16.1 degrees, respectively. In a later experiment, Witkin (1950) used a tilted room instead of the target.[67] The errors were much greater than in the foregoing experiment (mean error from a position of 22 degrees amounted to 12.8 degrees and 22.3 degrees, when the room was tilted either in the direction of body tilt or in the opposite direction, respectively), and this can be interpreted as a tendency of the subject to accept the tilted room as vertical.

Passey (1950) reports a significant increase in mean and constant error with increase in magnitude of body tilt. The mean average errors range from 1.6 degree at 5 degrees to 2.9 degrees at 20 degree tilt; the mean constant errors from 0.4 degree at 5 degrees to 2.3 degrees at 20 degree tilt. He thus concludes that in conditions of conflict, adjustments were made more nearly to the gravitational vertical than to the tilted visual framework.[54]

Finally, Ray and Niven (1951) confirmed the hypothesis that postural cues dominate over visual ones in the perception of the true vertical. Moreover, postural factors were found to influence the judgment of the visual vertical, whereas no modification of the postural vertical by visual factors was demonstrated.[57]

Summing up the findings it may be said that body tilt alone, up to a magnitude of 20 degrees, does not seem to impair the perception of the visual vertical. With tilts of higher degrees, however, vertical orientation appears to be influenced as much by the degree to which the individual identifies himself with the tilted visual as by the body tilt itself.[46]

3. *Under Conditions of Visual Conflict.*—Visual perception under conflicting visual cues is no paradox, but it may occur under certain static and dynamic conditions.

Wertheimer (1912) reports an experiment in which the image of a room was tilted by means of a mirror at an angle of 45 degrees.[65] The room appeared at first tilted, but soon it appeared vertical and the floor horizontal. Under similar conditions Asch and Witkin (1948) observed an apparent tilted room and had the vertical set to the true position.[2] The total tilt of the frame of reference was 30 degrees; the mean value of the errors amounted to 21.5 degrees. Wertheimer's experiment was also repeated by Gibson and Mowrer (1938) who found that the room appeared tilted, although the amount of tilt seemed to decrease with time.[25] They, therefore, conclude that there is an adaptation to the inclination, which makes the picture appear more natural but will not eliminate entirely the impression of tilt.

In another experiment Asch and Witkin (1948) tested Wertheimer's theory that with continued observation the mirror image of the room appears to right itself.[3] They found that during an observation time of six minutes the mean errors of the vertical and horizontal increased only slightly. About 50 per cent of the subjects perceived the complete righting of the room.

The effect of adaptation to visual tilt was investigated by Gibson and Radner (1937).[26] They found that the amount of tilt decreased with the increase in observation time. There was a considerable adaptation effect with five seconds observation and an increase up to 45 seconds; then, the curves flattened out. Recently, Passey (1950) and Passey and Ray (1950) reported that with increasing amounts of tilt there is an increase in the size of the average error of adjustment and an increase in the amount of constant error in the direction of the tilted room.[54,56]

By a critical perusal of the findings given above the hypothesis of Koffka, Wertheimer, Asch and Witkin that the main lines of visual space are of most importance for the determination of the vertical and that in case of visual conflict these lines are accepted as determinants of the vertical to the neglect of gravitational and postural guidances must be doubted. One is inclined to suspect that the adjustment to one set of the cues is more or less the result of "projection or identification" rather than the result of a true perceptual change.[46] On the other hand, it was demonstrated by these findings and by Evert's results (1930 and 1937) that vision can be adjusted to all kinds of changing circumstances.[16,17] From this, one must agree that visual perception is labile, when the perceptual conditions are altered by decreasing the number of cues or by introducing contradictory cues causing situations of conflict.

Non-visual Spatial Orientation

Under favorable conditions the intact organism will make use of all appropriate cues for the maintenance of the equilibrium and the determination of the postural vertical. After the visual cues, labyrinthine and proprioceptive cues are most important for the orientation in space. A reduction of the number and quality of the cues will result in a reduction of the precision of postural determinations. Since we have seen that visual orientation proved to be labile under certain conditions, it seems to be indicated to investigate now the reliability of non-visual space perception.

1. *On the Ground.*—Early investigators as Burt (1918), Garten (1920), Backhaus (1920), Gemelli, Tessier and Galli (1920), Fisher (1923), and Kleinknecht (1923) found that individuals are able to maintain and restore their equilibrium as well as to judge the vertical and horizontal in the absence of visual cues with a high accuracy (average error 1 degree or less). They report only a slight amount of improvement of the results due to practice.[5,8,20,22,23,40]

Recently, Mann and Dauterive (1949), and Mann and Berry (1949), tested the ability of the subject to judge the gravitational vertical from positions of lateral tilt (5 to 90 degrees).[47,48] They found a mean variable error of 1.9 and 3.2 degrees, when he had to turn himself back into the vertical and when he had to signal the vertical position while moving, respectively. The constant error for both conditions was 0.8 degree and 2.4 degrees, respectively.

When individuals are placed in position of tilt and are required to return themselves to the postural vertical without visual cues, there is the possibility of occurrence of adaptation. Passey and Guedry (1949) report this effect as an increase in tilt from the true vertical and in the numbers of errors in direction of initial inclination.[55] Delay in readjustment also served to produce significant difference in variability.

The effects of varying duration of exposure upon adjustment to the true vertical were confirmed by Mann, Passey and Ambler (1950).[50] As far as variability is concerned, they are in conformity with Mann and Passey's results (1949), who found no increase in variability with delay as opposed to immediate readjustment.[49] The latter studied the adaptation effect to tilt under modified and nonmodified somesthetic conditions. They succeeded in proving adaptation to postural inclination by a shift of the constant error toward the direction of initial tilt and by an increase in the number of errors in the direction of inclination.

By the experiments described above it becomes evident that under these conditions the individual is able to make accurate judgments of the postural vertical in the absence of visual cues. Delay in readjustment, however, brings forth an adaptation effect which is expressed as decrement of the accuracy of postural orientation. The same effect was produced by a modification of the somesthetic cues. This justifies the assumption that the nonvisual postural orientation will be endangered after support and weight are abolished in the gravity-free state.

2. *Under Flying Conditions.*—Van Wulfften-Palthe (1922) was one of the first to investigate the problem of postural orientation in aircraft.[69] He found with untrained subjects, as well as with trained pilots, that in none of the test series was the correctness of the judgments greater than would be expected by chance. Even the relatively high angular accelerations during loops and rolls were not perceived by the individuals and it was only during spinning (about 120 degrees per sec.) that marked sensations of motion and posture occurred.

In 1931, Tschermak and Schubert experimented with a luminous line in the aircraft and found that with a lateral inclination of 40 degrees the apparent vertical deviated from the true vertical at an angle of 6 to 10 degrees.[60]

The ability of the individual to judge his posture in flight was also investigated by Jones, Milton and Fitts (1947). Experienced pilots of the Air Force were used as subjects. They were required to judge the attitude of the plane during a series of simple maneuvers. The average of erroneous statements amounted to 39 per cent. With certain maneuvers the errors increased up to 80 per cent. They also observed effects of adaptation as described above.[39]

At about the same time, MacCorquodale (1946) studied the nonvisual perception of motion and body position during flight.[42] He reports that nonvisual spatial orientation is subjected to gross limitations and to deceptions. The perception of turning and tilting appears after a considerable time lag from the onset of the maneuver, the direction of bank and turn may be erroneous, and the estimates of amount of bank are markedly depressed. Perceptions of both tilting and turning are transient and disappear before the plane recovers. The recovery is accompanied by sensations of tilting and turning away from the direction of the preceding turn, which persists into the period of following straight and level flight.

Additional data were collected by MacCorquodale, Graybiel, and Clark (1946) on the nonvisual orientation problem after it was found that a strong sensation of backward tilt occurred during a turn, and forward tilt on recovery from a turn.[43] It could be shown that this feeling of tilt is independent of the angle of attack in starting the turn and that adaptation effects also became evident.

The effects of linear acceleration and deceleration on the flyer's spatial orientation in the absence of visual cues were investigated by Clark and Graybiel (1947).[10] Strong sensations of tilt were reported in both cases during flights in an SNJ-6 type aircraft. The tilt was always in the direction of the resultant of the accelerative or decelerative forces, respectively, and the force of gravity.

These results demonstrate that the perception of posture and position during flight is relatively difficult. Without visual cues it is almost impossible to make precise judgments of the true vertical and horizontal with respect to the ground. Position orientation in flying is a function of the resultant of the force of gravity and the accelerative force acting on the body.

Visual and Gravitational Conflict

Through the presentation of the data and the discussion of the result given above it should be made clear that the problem of orientation must be seen in the role of visual and gravitational factors for the perception of space. It is still a controversal question whether, in the event of conflict, one set of factors would predominate in the determination of verticality.

The answer to this question will be of importance for the problem of orientation in the state of weightlessness. If, on the one hand, it could be proved experimentally that visual perception is the dominating factor in postural orientation, the chances would increase that the normal orientation scheme could be maintained without serious difficulties after the modification of the somesthetic cues brought about by the lack of weight. If, on the other hand, gravity is the prime factor, vision may not prove so stable to withstand the effects of zero-gravity.

The problem seems to be serious enough to be inquired in detail. First of all we must consider the methods, which can be used for provoking a visual and gravitational conflict. In order to establish a conflict situation, the magnitude of gravity—not only its direction—should be altered. In the first case, one obtains a real conflict between vision and gravitation; in the second case, contradictory visual and postural cues are present which were dealt with in the last paragraph.

1. *On the Human Centrifuge.*—The factors involved in space orientation when gravity is changed by adding a horizontal centrifugal force were studied by Mach (1873-74). He hypothesized that under the influence of centrifugal and gravitational forces the individual would accept the resultant force as the true vertical. When an additional visual cue was presented, the vertical was set occasionally at a compromise position halfway between the visual vertical and the subject's body axis.[44,45]

Breuer and Kreidl (1898) rotated subjects in a centrifuge with accelerations yielding a resultant of 15 degrees to the vertical. The subjects were required to adjust the vertical to a vertical afterimage. The mean results for three subjects were 8 degrees, yielding again a compromise between the gravitational vertical and the resultant.[6]

These early results were later confirmed by Noble (1949) and by Clark and Graybiel (1949). When an individual, who is in a stable position with respect to the vertical, is subjected to accelerations on a centrifuge, he becomes aware both of the changing direction and increasing magnitude of the resultant between centrifugal force and gravity.[53] It can be felt that the seat is tilted and that he is pressed against it with increasing force. "It is just as though the center of the earth had shifted with respect to him and the mass of the earth had increased."[12]

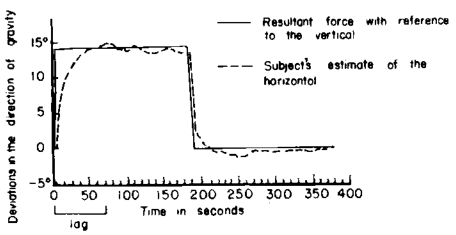

Fig. 1. Average lag of time from three subjects during visual orientation on the centrifuge at 6 r.p.m. (Computed after data by Graybiel and Brown, 1949.)

Similarly, the position of a luminous line seen in the dark is also subjected to a directional change determined by the resultant. When the subject faces the direction of turn and the center of rotation is at left, the luminous line seems to rotate clockwise, subsequent to the onset of rotation. In order to keep the target line subjectively horizontal, it must be rotated counterclockwise.

Under these conditions, threshold determinations were made of the apparent deviation of the line from horizontal with a variable and a constant resultant force. As mean values 2.71 degrees for acceleration and 3.37 degrees for deceleration were computed on several levels of stimulus intensity and duration. The general tendency of the subjects was to set the line at an angle from the horizontal which was greater than the deviation of the resultant force from gravity. No adaptation effect but a time lag before the response was observed.

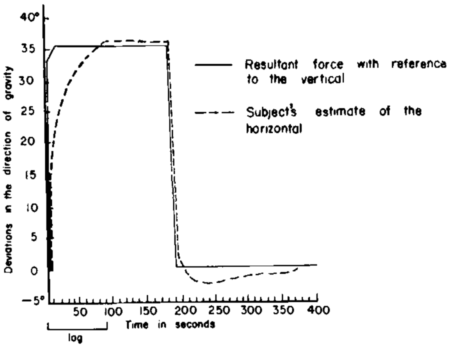

Fig. 2. Average lag of time from three subjects during visual orientation on the centrifuge at 10 r.p.m. (Computed after data by Graybiel and Brown, 1949.)

The delay in visual reorientation to the resultant was measured by Graybiel and Brown (1949). The mean value of the time lag was 73.2 seconds at 6 r.p.m. and 89.1 seconds at 10 r.p.m. The mean duration for all subjects in all trials was 81 seconds. Individual differences were not great; but there is a difference at the two levels of acceleration used. The lag following deceleration was relatively short: 35.0 seconds at 6 r.p.m. and 23.3 seconds at 10 r.p.m.; and there was overshoot.[27] The mean values of the results of three subjects are displayed in Figures 1 and 2.

These curves show that during acceleration the responses to the visual sensation caused by alteration of the gravitational vertical are the more delayed, the more the new state of gravity deviates from the normal psychophysical zero-state of the individual. After the new level finally has been reached and maintained for a while, changes in the opposite direction, i.e., toward the normal state of gravity, are perceived and responded to with great promptness but with less accuracy due to an effect of overcompensation. From this we may conclude that orientation to changes in direction of resultant gravity will be either inaccurate or hampered by a considerable time delay.

Finally, Wing and Passey (1950) investigated the visual vertical under conflicting visual and acceleratory factors.[66] They report that in the absence of a visual frame of reference the resultant was accepted as vertical whether or not the body was in line with the resultant. In contradiction to Witkin (1950) who imputes dominance to the visual factors in the determination of the vertical, Wing and Passey found that in the presence of a visual frame of reference neither visual nor gravitational cues are accepted to the exclusion of the other. With increased intensity of the centrifugal force, however, the visual vertical is located relatively nearer to the vertical determined by the resultant force.

2. *Under Flying Conditions.*—It was learned by experience during flying, position orientation in the aircraft in situations of visual and gravitational conflict is problematic. Two different cases must be considered in this respect: first, accelerational forces versus direct vision of the ground and the horizon, as is the case in contact flight; and second, accelerational forces versus artificial perceptual cues, as is the case in instrument flight.

Every person who is not an experienced flyer knows the sensation of apparent tilt of the horizon and of the ground when the airplane is assuming a turn. It then seems that the positions of sky and ground have been shifted. These sensations are due to the fact that the observer incorrectly regards his environment as shifting and the direction of resultant force as fixed, rather than vice versa.

In instrument flight the pilot very often finds himself in a situation of conflict when the gravitational cues are in contradiction to the visual ones. In these situations the pilot must rely entirely on his instruments, since the information brought about by the machano-receptors by no means indicate the true position of the body and of the aircraft with respect to the ground.

The visual perception of a star-shaped target during flight when centrifugal forces are acting on the body was investigated thoroughly by Graybiel, Clark, and MacCorquodale (1946). They report the occurrence of phenomenal motion, displacement and rotation of a target during flying maneuvers including turns, bank (10 to 60 degrees), glides and dives. All displacements were observed in or close to the vertical plane whereas motion was observed not only upward and downward but to the right and to the left. At the onset of the bank the star was usually seen to move and to be displaced upward with a slight deflection in the direction of turn. It remained there until the plane began to recover to straight and level. The observations during and following recovery were perceptually the reverse of those observed during the banks. The target appeared to move and to be displaced downward with a slight inclination opposite to the direction of the turn, i.e., back to the true position.[28] In another study, a time lag of about five seconds in average was observed.[29]

Summing up the experimental evidence, we can assume that in situations of visual-gravitational conflict, position orientation will be made in a compromise direction between the main lines of the visual field and the resultant of the mechanical forces. In no case was the stimulation of the mechanoreceptors neglected completely when centrifugal forces were applied, nor were the main lines of visual space accepted as determinants of the orientation scheme. We may, therefore, conclude that in the opposite case when gravity becomes smaller than 1 g, disturbances of the orientational scheme may also occur, even if a visual frame of reference is secured. In transposing the human body into this new state of equilibrium, the stimulation of the mechanoreceptors, as a whole, will be altered decisively. The otoliths are known to be of importance for the orientation to the direction of gravity. When the physical characteristics of this organ are considered, one understands that if the calcareous parts of the otoliths lose their weight there will be a loss in pull and pressure on the sensory hair cells. Consequently, a stimulation of the macula will be caused which is experienced only in the situation of falling freely. Since, at the same time, other proprioceptive senses will be stimulated in a similar way, only a few somesthetic cues will act against the fall sensation.

From the foregoing, it can be assumed that the use of the eye will be of some help for overcoming the sensation of falling freely subsequent to the transposition of the individual into the gravity-free state, if a visible movement of the body relative to its surroundings does not exist; for this would be in contradiction to the fall situation experienced under normal gravitational conditions. On the other hand, we know that visual perception is apt to compromise and that a complicated mechanism of labyrinthine reflexes acts directly upon the eyes under extraordinary accelerative conditions. It was found that then the individual is not aware of the illusory nature of rotations, movements, and displacements and his environment and may take these apparent changes for granted. Furthermore, it has been demonstrated that the individual is not able to recognize illusions brought about by discrepancies between visual and gravitational cues except after a considerable lag of time. Hence, bodily disorientations as well as dislocations of objects in space, which may accompany the transition from $g=1$ to $g=\angle 1$, will not be recognized by the subjects at all or only after a considerable and even dangerous delay.

VERTIGO AND VISUAL ILLUSIONS

In the foregoing chapter it was demonstrated that in situations of perceptual conflict illusions occur, which can give rise to disorientation in space. As far as these illusions are related to the effect of modified gravitation they will be of some importance for our subject under investigation. It is this type of illusions which also may bring forth disorientation in the gravity-free state.

Illusory effects and orientational disturbances caused by changes in gravitation, centrifugal forces, acceleration, et cetera, are often referred to as "vertigo." Under this heading we understand any sensation or feeling, which is brought about by discrepancies between subjectively experienced sensations on the one side, and objectively correct environmental facts on the other. Characteristic features in these sensations are an emotional, a psychosomatic component and a disconcerted state of mind, associated with a presentiment of danger. Vertigo and the types of mistaken perceptions akin to this phenomenon have been thoroughly studied and described by Vinacke (1946).[61-64]

Most illusory perceptions of this kind can be considered as effects of a complex of stimulation of the inner ear. The factors causing the perception as a whole cannot be separated with proper precision to identify clearly the direct stimulus-sensation relationship and the mediating sense organs. Even in laboratory tests on the centrifuge Coriolis forces generally are acting in addition on the sensory organs. However, it seems to be possible to estimate within certain limits the role of the sensory nerves for a special type of illusion. Graybiel and his co-workers (1946-1950) have studied and described two specific illusory phenomena:

1. *The oculo-gravic illusion* concerns the apparent displacement of an object in space, which may occur when the sensory receptors in the otolith organs are stimulated by a force forming a resultant vector with the force of gravity.[32] Graybiel, Clark and MacCorquodale (1946) found that this illusion occurred during flight maneuvers, when a target (luminous star) was viewed by the observer.

During climbs and glides, motion was seen in the vertical meridian. At the beginning of both maneuvers, the target seemed to move down more frequently than up. On recovery from the climb there was a marked tendency to see motion down, and from glides to see motion up. Motion was observed in fourteen out of twenty-two climbs and glides and in twenty out of twenty-one recoveries from climbs and glides.[28]

The illusory perceptions caused by centrifugal force during flight depends mainly on a stimulation of the otoliths. It was found that during the turn proper there is a direct relationship between the g-forces and the amount of displacement of the target (Fig. 3). When the gravity increased, the star moved upward and remained in the position of maximum displacement until the pilot begun the recovery. During and shortly thereafter the star was seen moving downward to the "true" position. Only in one case, the target seemed to be displaced about 10 degrees below its initial "true" position and moved up to "true" shortly after recovery.

The vertical motion and displacement during the bank and turn were complicated by lateral motion in many trials. This involved apparent motion to the sides without displacement. Displacement was perceived predominantly upward but mostly deflected to the right or left. Motion and displacement upward may be brought forth by stimulations of the semicircular canals and of the otoliths.[30]

In another study, Clark and Graybiel (1947) report illusory motion of the target during acceleration and deceleration in flight. When the subject faced to the left, the star appeared to rotate about its central point in the direction of the resultant of the accelerating or decelerating forces and the force of gravity.[11] When the subject faced the direction of flight, no regularity in displacement of the star was observed. "On the basis of the forces involved the star could be expected to rise during acceleration and fall during deceleration" (Am. J. Ophthalmol., 32:555, 1949). The relationship between linear accelerations and apparent displacement of the visual target will be discussed later.

2. *The oculo-gyral illusion* can occur during and after stimulation of the crista ampullaris of the semicircular canals produced by angular accelerations. It is the result of nystagmus produced reflexly and consists of apparent motion and/or displacement of an object observed under these conditions.

The direction of the apparent motion is in concurrence with the sensation of rotation. If, for example, a subject is rotated to the right, a target appears to move in the same direction with the onset of the rotation. It comes gradually to a standstill after which it may appear to move slowly to the left. With a constant rate of rotation, the target appears motionless. When the subject is suddenly stopped, the target appears to rush toward the left. This first effect is followed by a second one in which the target appears to move to the right. This second effect may persist as long as the first one or even longer. More after-effects with changing directions and fading intensities may occur.[33]

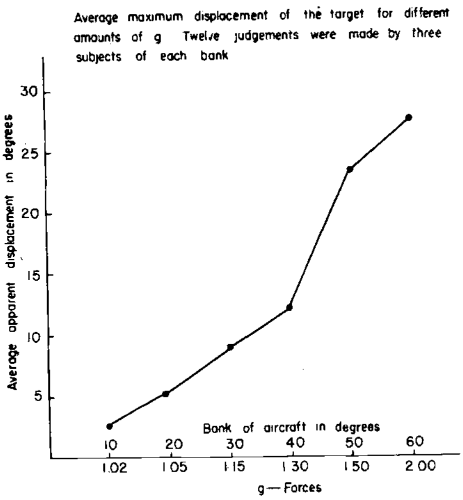

Fig. 3. Relationship between g-forces and target displacement. (Graybiel, Clark and MacCorquodale, 1946.)

The direction of the apparent movements of induced afterimages during and following rotation is exactly opposite to that observed when a real target is fixated. Graybiel and Hupp (1945), therefore, hypothesize that eye movements are responsible for the apparent motion. (Fig. 4).[31,32]

Stronger and more confusing illusions were obtained when a moving target was observed during angular accelerations. At first, a rapid displacement of the target in the opposite direction of turn was noticed; although, the target appeared motionless at the same time. As the target went by on successive rotations, it appeared to pass more rapidly until after approximately thirty seconds, the subject felt to be in rest while the target seemed to rotate rapidly around him. Post-rotational phenomena after deceleration were in the opposite direction and stronger.

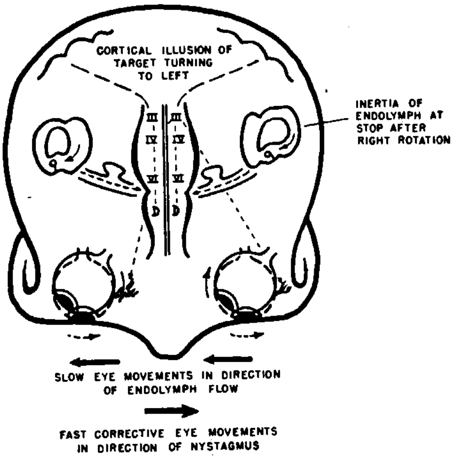

Fig. 4. Schematic diagram of the stimulation of the semicircular canals at stop after rotation to the right. The endolymph still moves to the right. The target seems to move and to be displaced in the opposite direction (direction of nystagmus). (Moffitt, Torndorf and Guild, 1948).

The relationship between apparent displacement and motion was studied by Brown, Imus, Niven and Graybiel (1949). The target was observed as displaced always in the direction of the apparent motion. There were large individual differences in reports of amount and duration of apparent displacement. Correlations of independently observed nystagmus were related to both phenomena.[7]

At this point, a short recapitulation of the stimulus-sensation mechanism governing the illusory perceptions seem to be indicated. The otoliths must be considered as indicators of linear accelerations. They have a quantitative and a qualitative function because they indicate alterations of the resultant force in both intensity and direction. We further know that the discrimination of positive and negative acceleration is important for the stimulation of the otoliths only with regard to the position of the head relative to the direction of the centrifugal forces. When accelerative forces act in the direction of the horizontal (front-rear), the stimulation of the macula may be basically the same during linear acceleration and deceleration in or near the horizontal meridian. There may be brought about an essentially different sensation, however, when the otoliths are stimulated in or near the vertical meridian by forces of inertia. Since there is no doubt about the mechanical characteristics of the sensory epithel cells and their physiological functions, we can expect that in the first case they will be moved in the horizontal (back and forth); while they will be moved in the vertical meridian (up and down) in the second case. Only in the latter case definite displacements of the target above and below the "true" zero-point may appear.

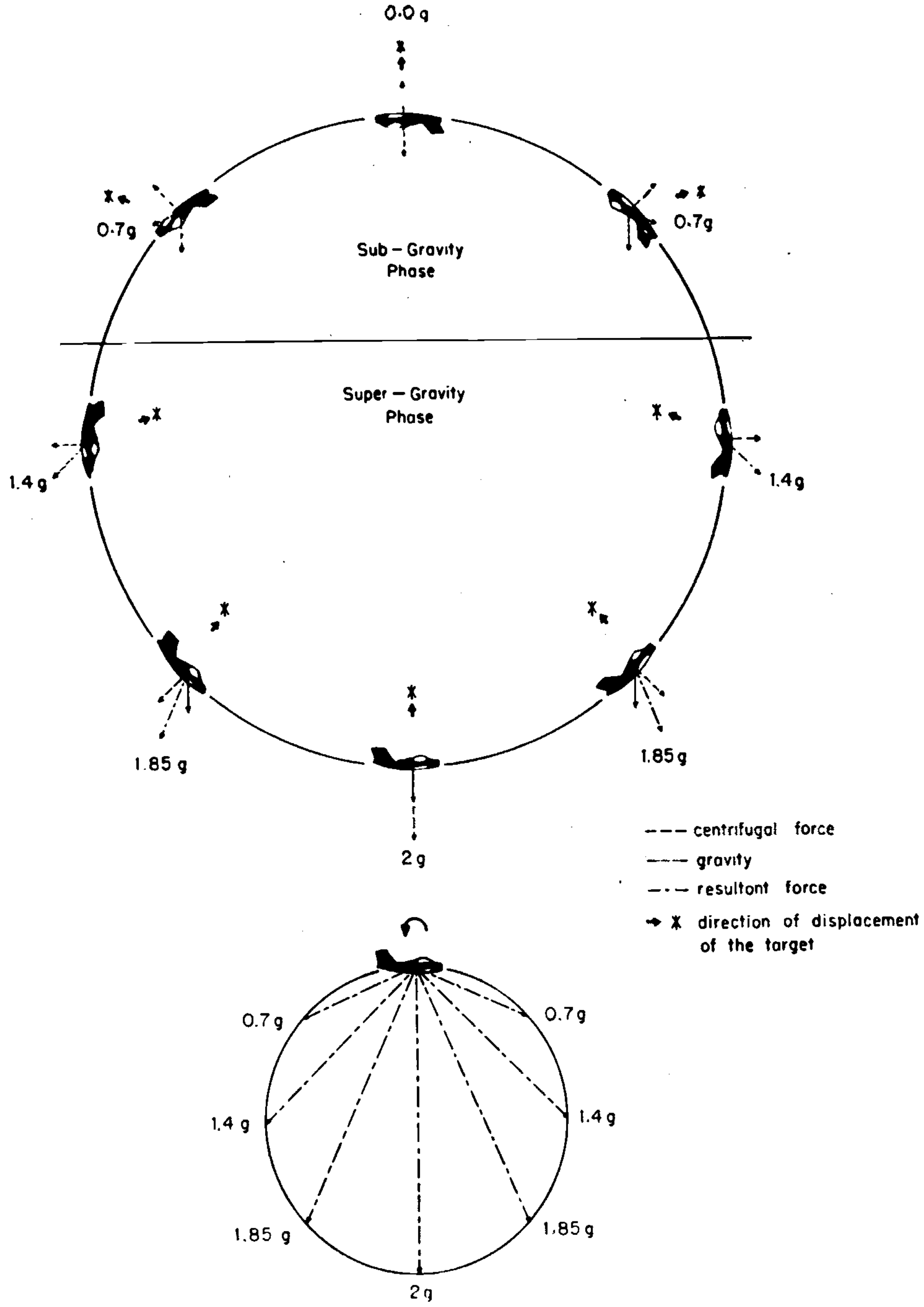

Fig. 5. Schematic diagram of the apparent displacement of the target relative to the resultant and the visual frame of reference. The aircraft is making a loop with an effective centrifugal force of 1 g.

The relationship between the labyrinth and the eye muscles is preserved in regular geometrical planes which permit the simplest of reflex arcs for adjustment of the eyes.[51] So it is obvious that motion to the right and left and displacements to the sides occur when the horizontal canal is activated by angular accelerations; and that movements and displacement up and down occur when the otoliths and the vertical canals are concerned. Graybiel's findings indicate that there was rotary motion and "rotary displacement about the central point of the star" in a clockwise direction during deceleration, and counterclockwise rotation and rotary displacement during acceleration, when the subject was facing the left. This apparent motion was probably produced by stimulations of the semicircular canals and of the otoliths, indicating the direction deviation of the resultant force in the lateral meridian of the body (Fig. 5). Furthermore, an upward deflection of the target was noted in case of inincreased g-forces during radial accelerations and a downward movement during some flight maneuvers, especially during the first parts of the dive and during recovery from the climb. There is reason to believe that during the latter maneuvers the subject was in a state of sub-gravity—a fact which Graybiel did not take into consideration. Wulfften-Palthe (1926) already described reflex movements of the eyes upward and downward during sudden climbs and dives associated with increased and decreased force. In these cases, one is not simply dealing with a change in the direction of the resultant, but in the first place with an alteration of the amount of gravity. We, therefore, expect that during transition into the zero-gravity state the individual will perceive a sudden apparent downward motion of the visual field in the direction of the feet accompanying the sensation of falling; since we also have to expect in this case reflex movements of the eyes brought forth by stimulations of the otoliths and the semicircular canals. A schematic diagram showing the displacement of the star during an ideal looping in the vertical meridian is given in Figure 5.

At any rate, sensations of falling have been observed in the aircraft during sub-gravity as well as during abnormal stimulation of the semicircular canals on the ground. During sub-gravity there is a feeling of weakness, especially in the legs, which may be interpreted as symptom of a sudden loss of muscle tonus, caused through the discontinuing of the normal excitation level of the otolith organs.[18] By caloric stimulations or by Coriolis forces disturbances of the equilibrium and thereby fall reactions can be produced, which are accompanied by vertigo and illusory perceptions of movement.[59]

While these sensations during sub-gravity and zero-gravity may occur when the individual is at rest, disturbances of visual perception must also be expected when the body finds itself in passive or active motion. Under these conditions the end organs of the semicircular canals are necessarily stimulated. These stimulations may vary depending on the posture of the head relative to the direction of the accelerating force moving the body. The occurrence of illusions of being rotated and a corresponding activation of the reflexes coupled with the stimulation of the vestibularis must be anticipated with certainty.

As far as adaptation to weightlessness is concerned, little conclusive can be said, since contradictory data on related problems have been reported. Clark, Graybiel and MacCorquodale (1946), Clark and MacCorquodale (1948), and Brown, Imus, Niven and Graybiel (1949) report no habituation to repeated angular accelerations and regard the Griffith hypothesis—that all of the effects of ampular stimulations are highly modifiable under repetition—as disproved.[7,13,14] Guedry, on the other side, found pronounced habituation to post-rotational stimulation by introducing visual cues.[34] Since all of them observed great individual differences in perception and habituation, it can be concluded that the perceptual pattern of the individual will not stay uniform, for it was found that at least some of the variables involved in perception do not show signs of habituation and adjustment. It was found, for instance, by Gerathewohl (1944) and by Brown, Imus, Niven and Graybiel (1949) that great differences exist between individuals as to intensity and duration of sensations of apparent motion as well as to susceptibility to perceptual disorientation.[7,24] Therefore, we may thus formulate the hypothesis that differences in adaptability to zero-gravity conditions will also exist among individuals. Since there is an adaptation to the conditions causing vertigo, a similar habituation may be possible to the state of weightlessness.

SUMMARY

The rationale of this study was an investigation of the problem, whether and how visual perception will be affected during the transition of man in the sub-gravity and zero-gravity states. Since the medical and psychological literature makes available a great deal of information on the relationship between proprioceptive and visual perception, an extrapolation to the conditions of weightlessness was made on a purely theoretical basis.

In considering the pertinent anatomical and physiological characteristics of the eye it can be concluded that reduction or entire lack of weight of the eyeball will not produce disturbing alterations of the intra-ocular pressure. As to the effect of weightlessness of the eye on the external eye muscles we may assume that slight variations in muscle balance will be compensated in a short time.

On the other hand, there is a high probability that visual perception will be affected by psycho-physiological stimulations, which will occur at least during the transition period from the normal state of stimulation (1 g) into the state of weightlessness. There is sufficient evidence through experiments on varying acceleration on the ground, on the human centrifuge, and in the aircraft indicating that visual illusions are brought about by alterations of the stimulation of the mechanoreceptors due to changes of gravity. These illusions are not recognized as inaccurate perceptions by the individual, but accepted as normal results of the prevailing effect of gravity. Incidentally, the subjective alteration of

the visual reference scheme is recognized by the individual but only after a considerable time lag.

In conventional aviation medicine the terms "positive" and "negative" acceleration are used with reference to the directional component of the vector of gravity. In order to clarify the problem under investigation, the direction and the size of acceleration and of the forces of inertia must be considered as to their effect on the stimulus-sensation mechanism. The following conclusions may be drawn by an analysis of the effects of the vector of acceleration (gravity):

1. By alterations of the subjective vector of acceleration (gravity) visual perception is markedly affected. In situations of visual-gravitational conflict, position orientation will be made in a compromise direction between the visual frame of reference and the resultant of the mechanical forces.

2. There is a direct relation between the acceleration acting on the human body and the apparent displacement of an object in space.

3. The intensity of visual illusions of this type (oculo-gravic and oculogyral illusions) depends upon the rate of acceleration and of its alterations and upon the sensitivity of the individual.

4. The direction of the subjective displacement of an object in space depends upon the direction of the acceleration. In the normal mechano-psychophysical state of the body (1 g) no sensations of force and acceleration are generally experienced and—under conditions of rest—an object in space is perceived as being at rest. When an individual, who is in a stable position with respect to the vertical, is subjected to accelerations different from 1 g, he becomes aware of the vectorial changes by both mechano-receptor and visual sensations. Under these conditions the perceived object seems to move opposite to the direction of rotation of the resultant between centrifugal force and gravity. With increasing acceleration (gravity) in the vertical direction an object or the objects within the visual field appear to be moving in an upward direction; at decreasing accelerations (in the subgravity and zero-gravity states) apparent motion and displacement of the objects in the direction down (opposite to the direction of gravity) occur.

It is very difficult to make a good guess as to the importance of these illusory perceptions for the position and direction orientation in the state of weightlessness. It was demonstrated that the pattern of mechano-receptor stimulation will be decisively changed in the gravity-free state. Normally, the mechano-receptors are adjusted to the stimulus-sensation conditions of 1 g. When flying—and especially during blind flying—the mechano-receptor stimulations can be subliminal or subpressed, while the eye can take over the control of position and direction orientation without illusory disturbances. During the transition in the gravity-free state, however, the stimulation of the mechano-receptors is changed in such a way that visual illusions will occur. This effect may be serious, since the stimulus-sensation rato is changed toward a hypersensibility of the receptors. It is obvious then that under these conditions the ability proper of the individual to control his environment visually may be impaired.

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Military Surgeons' Meeting

Reserve officers of the medical services of the Army, Navy and Air Force will be given complete information on all new directives, including pending Congressional legislation, governing their commissions, active duty requirements and retirement benefits in one of the feature presentations of the 59th annual meeting of the Association of Military Surgeons which will be held at the Statler Hotel, Washington, D. C., November 17-19, 1952, under the presidency of Major General Harry G. Armstrong, Surgeon General of the Air Force. Point credits for retirement will be given all eligible reserve officers attending the scientific session.

The program will include the following speakers: Louis H. Bauer, M.D., President of the American Medical Association; Otto Brandhorst, DD.S., President of the American Dental Association; Melvin Casberg, M.D., Chairman, Armed Forces Medical Policy Council; Brig. Gen. J. A. McCallam, President-elect, American Veterinary Medicine Association; Rear Admiral Lamont Pugh, Surgeon General of the Navy; Isador S. Ravdin, M.D., Philadelphia, Pennsylvania; Howard A. Rusk, M.D., New York, New York; Brig. Gen. Oscar P. Snyder, Dental Corps, USA; Brig. Gen. William L. Wilson, USA, Federal Civil Defense Administration.