Experiments During Weightlessness: A Study of the Oculo-Agravic Illusion

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DURING STUDIES of the effects of angular acceleration and centrifugal force in flight, Graybiel, Clark and McCorquodale observed two illusory phenomena which they termed the "oculogyral" and the "oculogravic" illusion.[3-5,11,13,14] They attributed the oculogyral illusion to angular acceleration. This change in velocity of rotation produces an adequate stimulus to the semicircular canals. Reflex connections through the extraocular muscles produce nystagmus and the associated illusory effects.

The oculogravic illusion, on the other hand, refers to the apparent displacement of an object in space because of linear or radial accelerations. The latter, and the centrifugal force associated with it, result when the pilot turns about an axis at some distance from that of his body; for example, during a normal turn, a pull-out or a push-over. The accelerative force involved causes some generalized changes in bodily pressure and stimulates the otoliths, but—if the radius of the maneuver is large enough—the endolymph maintains equal pressure on both sides of the cupula within the ampullary ends of the canals so that no stimulation occurs.[12,16]

To supplement Graybiel's data it was believed necessary to investigate the vestibular function when the forces involved are smaller than the force of terrestrial gravitation. Extrapolating from Graybiel's previous findings, we predicted an apparent motion under conditions of reduced gravity which would be opposite in direction to the one observed at increased accelerative force.[8] This hypothetical phenomenon, which may be observed best in the zero-gravity state, is called the *oculo-agravic* illusion. It was investigated experimentally after the means were available to produce conditions of sub- and zero-gravity.

METHOD

The method used to produce states of reduced gravity has been described in detail elsewhere.[7,9,17] Periods of sub-gravity and zero gravity were obtained by flying an F-94C aircraft along parabolic arcs. For this particular experiment, the ascent to 23,000 feet was made at a rate of about 3,000 feet per minute. The altitude at which the parabolas were flown varied from 17,000 to 25,000 feet, depending upon the type of maneuver to be executed. To investigate various kinds of vestibular stimulations in flight, several

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flight maneuvers were performed producing accelerations of different directions and magnitude, and the state of weightlessness.

Flight Maneuvers.—1. Turns—from straight-and-level flight at 23,000 feet the pilot gradually lowered the wing to a maximum bank of 60°, attained a rate of turn of 3° per second without losing altitude, and returned after completing a coordinated turn of 180° in one minute to straight-and-level flight. The radius of the turn was about 1.3 mile. The acceleration acting on the body did not exceed 2 G units of force. One tu:n was flown in either direction.

2. Parabola—The pilot started a smooth dive at 23,000 feet 100 per cent engine rpm and maintained the glide at 1 G until the indicated air speed (IAS) reached 425 knots. At that point, the aircraft was gradually pulled into a climb resulting in a radial acceleration not exceeding 1.5 G. As the IAS dropped to 380 knots at full throttle and an angle of climb of 65° from the horizontal was reached, forward stick pressure was applied and thus the push-over initiated. A push-over is a vertical planar maneuver in which the angle of climb changes continuously from a plus to a minus value. During this maneuver the IAS decreases uniformly until a minimum value—the speed at which the craft is still fully controllable while rotating around its lateral axis (y-axis)—is approached at the top of the arc, and then increases uniformly back to its initial value.

Air speed fell to about 200 knots when the aircraft was going over the top of the parabola at 25,000 feet, and stick pressure was continued until the plane was diving at 380 knots. When the angle of dive was approximately 65° again, a smooth pull-out was initiated to prevent an acceleration of more than 1.5 G during recovery. While going through the horizon, the normal state of 1 G was usually restored for one or two seconds. The parabolic arc obtained in this fashion usually yielded about 20 seconds of virtual weightlessness. The actual state of zero gravity lasted for about 50 per cent of this time, while during the other period the gravitational force acting on the body was drastically reduced. The maneuver was repeated after regaining altitude and starting position.

3. Pull-out—A dive was started at 20,000 feet at 96 per cent engine rpm and maintained at 1 G (indicated) for about 10 seconds. As the IAS built up to 400 knots, an altitude of 17,000 feet was usually reached. Now, the aircraft was pulled up rather abruptly resulting in a radial acceleration of 3 G acting on the body for about 5 seconds. The stick pressure was then eased to normal, and the pilot climbed back to starting altitude. After making sure that the observer in the back seat was in good condition, the maneuver was repeated.

4. Double-parabola—A parabola pattern consisting of three pull-outs and two push-overs in a row was flown starting at 23,000 feet and recovering from the dives at 17,000 feet in order to obtain longer periods of weightlessness and radial accelerations of about 3 G for from 3 to 5 seconds. This acceleration was used for propelling the aircraft into the second parabola. The relatively violent maneuver yielded from 25 to 35 seconds of weightlessness after preceding states of relatively high radial accelerations.

5. Coordinated aileron rolls—This maneuver was begun at 96 per cent rpm at 300 knots IAS. The pilot pulled the nose of the aircraft up approximately 10° from horizon and applied aileron pressure in the direction of roll. At the 90° point, slight opposite top rudder, at 180°, slight forward stick pressure, and at 270°, slight top rudder in direction of roll were employed to keep the plane from falling through. The entire maneuver was flown without appreciable change of altitude and gravitational normalized force (GNF). The diameter of roll (there was a slight barrel effect present) was about 100 feet. The aircraft rolled for approximately 5 seconds

in either direction with a short straight-and-level period in between the two maneuvers.

Technique.—For our experiments the visual after-image (VAI) technique was employed because of its efficacy as a research tool and its easy application in the rear seat of the F-94C aircraft. The pilot sat in the front seat and the observer in the rear part of the cockpit. The first piece of equipment consisted of a black satin curtain which was attached to the top of the canopy over the back seat, and which was used as a hood by the observer. The second was a Mohawk Midgetape recorder, which was connected through a junction box to the inter-communication system in such a way that it would record continuously the communication between the pilot and the observer when the latter switched the recorder on. The third device used was the base of an ophthalmoscope carrying an improved Bausch & Lomb long-life centered filament bulb (daylight blue 2.5V). The light bulb was protected by a cylindrical cap with a 2 mm. hole on one side to provide a bright point-like light source. In order to induce a bright VAI and to secure its appearance during the experimental run, the observer closed the curtain. He then switched the recorder on, gave his name, and announced number and type of experimental run. He counted aloud until 20 while staring at the light source, switched it off, closed his eyes, and reported appearance and location of the VAI. During each run, which lasted from about 20 to 60 seconds, depending upon the type of experiment, the observer was firmly strapped to his seat by his shoulder harness and safety belt. No provision was made to immobilize the head, but the observer was instructed to keep his eyes and his head steady, and most of them did so by pressing the helmet against the head rest of the ejection seat. At this moment, the experiment was started.

The observer, his eyes closed and his head at rest, gave a running account of the position and apparent motion of the VAI during the maneuvers. In each case he reported the direction of apparent motion, the maximum displacement (in some instances in degrees of arc from the assumed center of the visual field), and the return of the VAI to its original position. Furthermore, the observer was questioned by the pilot about the three criteria if his own account did not contain clear statements. In this way, a continuous description of the stimulus-sensation conditions from the beginning to the end of each experimental run was obtained, in which the flight maneuver, the acceleration, the type of force acting on the observer, and the effects of these forces on the appearance of the VAI could be studied. Because a reliable accelerograph was not available, the stimulus-response relationship is described qualitatively in terms of the maneuver only.

A typical experiment involved about one hour flying time. Keeping track of the VAI and recording its movements and displacements during such unusual and sometimes violent maneuvers was a highly complicated task requiring a considerable amount of insight and practical experience.

Subjects.—Only trained and sophisticated observers familiar with jet flying and weightlessness, and experienced in observing and reporting the effects of accelerations during flight, were accepted. They were all healthy males, officers, airmen, and civilians from the School of Aviation Medicine, qualified for jet flying, from 20 to 48 years of age. Eight of them underwent the whole flight pattern consisting of nine experimental runs; the remaining seven of the group flew all maneuvers except the two turns. In three cases out of fifteen, the two rolls were not recorded due to the end of the tape. The recordings were transcribed after the flight, checked for accuracy and completeness by the observer, and supplemented by diagramming the apparent motion and displacement of the VAI on separate cards. After all the data were complete, they were analyzed by one of us (S. J. G.).

RESULTS

The results obtained from fifteen reliable observers under closely controlled experimental conditions are described here as examples of the oculogravic and the oculo-agravic illusion. They are tabulated systematically in Table I. The data therein concern the direction of apparent movement of the VAI only. The letters in each column of each of the nine maneuvers indicate the position of the VAI before, during and after the critical acceleration. Thus, *c-d-c* designating the sensation during a right turn means that the VAI was seen *centered* during straight-and-level flight, *down* during the 60° bank, and *centered* again after rolling back to straight-and-level. Again, *d-u-d, d-u-c* during the double-parabola means *downward* movement during the first pull-out, *upward* displacement during the first push-over, *downward* motion during the second pull-out, *downward* displacement during the upswing into the second parabola, *upward* motion during the push-over, and a *centrally* located VAI during recovery from the third dive. In case of vertical and lateral movement, *r* and *l* represent *right* and *left.* The first letter always designates the dominant direction.

Turns.—Movement of the VAI was observed in all sixteen turns. The VAI started to move with the onset of bank and the increase of force of acceleration associated with it. The direction of apparent movement was down in fourteen cases; in one case (Moore) the VAI rose during the first experimental run and, in the other case, it was seen to move laterally only. The observers were interviewed after the analysis of the data. One explained his result by difficulties in maintaining the VAI when the aircraft turned into the sun; the other (Stephens), due to a misinterpretation of instruction. In seven cases lateral motion was also observed. In six, it was opposite to the direction of the turn. Recovery from the bank usually returned the VAI back to center; in three cases it was associated with an upward movement of the VAI, but it went back to its center position during the final straight-and-level leg of this maneuver. A schematic diagram of the maneuver is given in Figure 1.

TABLE I. EGOCENTRIC LOCALIZATION OF THE VISUAL AFTER-IMAGE (VAI) DURING DIFFERENT FLIGHT MANEUVERS PRODUCING ACCELERATIONS OF VARYING DIRECTIONS AND MAGNITUDES

Observer	Right Turn	Left Turn	1. Parabola	2. Parabola	1. Pullout	2. Pullout	Double Parabola	Right Roll	Left Roll
Quashnock	— — —	— — —	c u c	c u d	c d u	c d c	d u d d u d	c l c	c r c
Prigmore	— — —	— — —	d u d	d u d	c d c	c d c	d u d d u d	c c	r l r
Knight	— — —	— — —	d c d	d u d	c d c	c d c	d u d d u d	c l c	c r c
Yarwood	— — —	— — —	d u d	d u d	c d c	c d c	d u d d u d	d l c	d r c
Gerathewohl	— — —	— — —	c u d	c u d	u d u	c d u	d u d d u d	— — —	— — —
Roth	— — —	— — —	u u d	d c d	c d c	— — —	d u d d u d	c ul c	c ur c
Dornes	— — —	— — —	c u c	c u c	c d c	c d c	d u d d u d	— — —	— — —
Burwell	c d c	c d c	c u c	c u c	c d c	c d c	d u c d u c	c l c	d u c
Dupraw	c d c	c dr c	d u d	d u d	c d c	c d c	d u c d u c	c l c	c r c
Moore	c u c	c d —	d u d	d u d	u d c	c d c	d u d c u c	c d/u c	c d/u c
Stephens	c l c	c d c	c u c	c u c	c d c	c d c	d u c d u u	c c c	c r c
Hawkins	c d c	c d/l c	c u c	c u c	c d c	c d c	c u c d u —	— — —	— — —
Robbins	c d c/u	c dr c	d u d	c u c	c d c	c d c	d u d d u c	c d/l c	c u/r c
Robinson	c d c/u	c r/d c	d u d	d u d	c d c	c d u	d u c d u d	c l/u c	c r c
Taylor	c d c/u	c d u	d u d	d u d	c d c	c d c	c u c d u c	c d/r c	c l/u c

Legend: c, centered; d, downward; l, left; r, right; and u, upward.

Parabola.—The acceleration pattern of the smooth parabola usually consisted of a 1 G dive, a slight increase of G due to radial acceleration before and after the actual push-over, a period of sub- and zero-gravity during the parabola, and a 1 G climb back to starting altitude. During the phase preceding the push-over, movement of the VAI vertically downward was observed in eight cases, while in six it was reported in the center, and one observer saw it stationary and slightly displaced upward. During sub- and zero-gravity the observer reported a sensation of weightlessness characterized by the feeling of floating and elation. In this state, movement and displacement of the VAI into the upper half of the apparent visual field was seen in fourteen cases, while in the fifteenth it moved back from the bottom of the field to about center position. Upon recovery from the dive movement vertically downward, either to or beyond the center, was reported by all observers. Thereafter, the VAI seemed to move back to its original position.

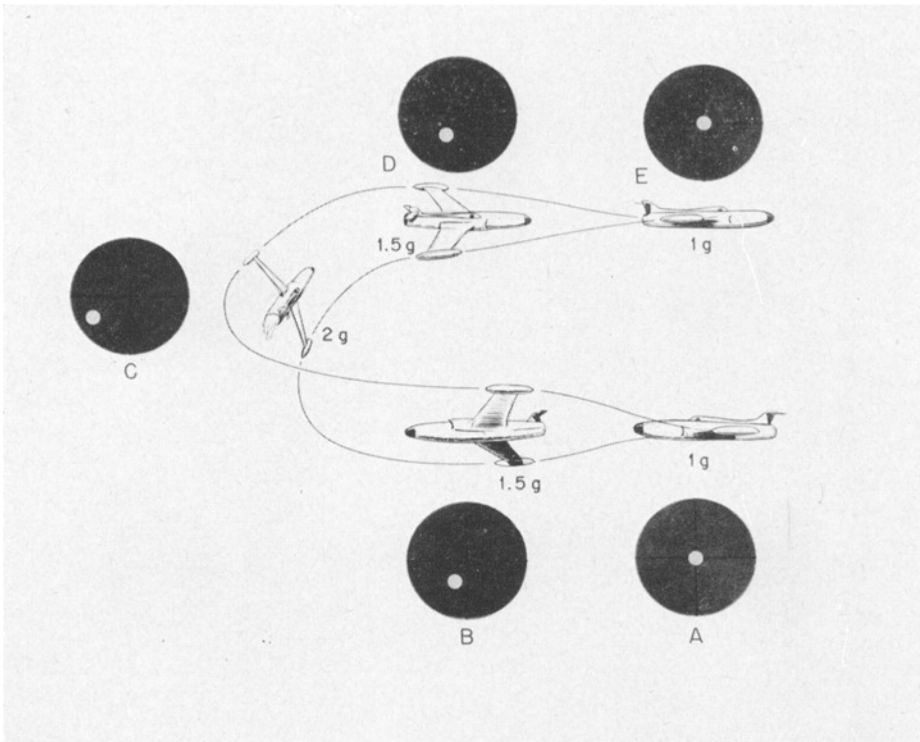

Fig. 1. Apparent displacement of the visual after-image (VAI) during a turn to the right. With increasing G force the VAI is moving downward and, in a few instances, to the left.

Acceleration and motion pattern of the second parabola were identical to that of the first one. Eight observers saw the VAI moving downward, and eight reported it centrally located during the first pull-out. It rose in all cases during the push-over; and it went down to or below center during recovery. With one exception, the same persons reported the image at rest in the first pull-up as had been the case in the first parabolic flight maneuver. A schematic diagram of this maneuver is given in Figure 2.

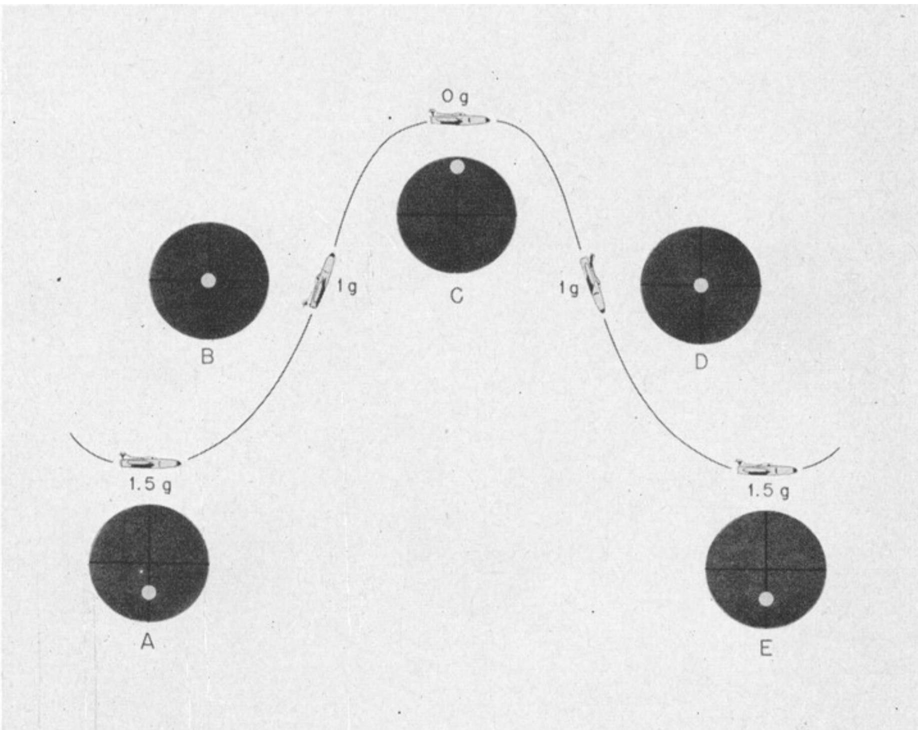

Fig. 2. Apparent displacement of the VAI during the parabola. The VAI is moving upward during the state of virtual weightlessness.

Pull-outs.—The pattern of apparent motion and displacement of the VAI was even more uniform during the pull-outs. Thirteen observers had the VAI centered during the glide; the two other cases were associated with a slight seat-to-head acceleration during the initial part of the dive (nose-over). All observers reported a striking illusion of movement downward during the 3 G pull-out, and in some cases the VAI seemed to overshoot the lower limit of the apparent visual field. Shortly before or upon recovery, the VAI moved back to its initial center position; in four cases out of twenty-nine it came to rest slightly above the center during the 1 G climb. The results obtained during the repetition of the maneuver were almost identical with those obtained during the first one. A schematic diagram of the maneuver is given in Figure 3.

Double parabola.—There was complete agreement about the cardinal directions of apparent movement and displacement of the VAI by all observers during the double parabola. Downward motion to the bottom of the apparent visual field was seen during the first pull-up. In general, the sensation of weightlessness occurred already before the "going-over-the-top" signal as the VAI climbed vertically up to the upper part of the visual field. In most cases it reached the top of the field and stayed there for the entire period of weightlessness, and in a few cases it went back to center during the descending leg of the parabola. It went straight down again during the subsequent pull-out, and returned to normal as the 1 G condition was reached during the final climb. This maneuver is shown in Figure 4.

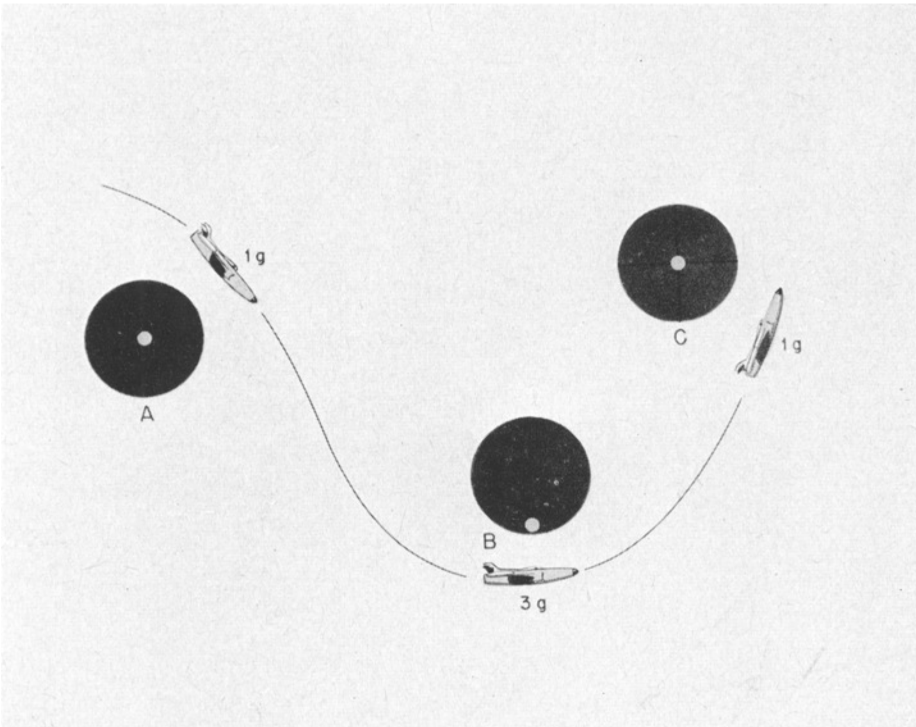

Fig. 3. Apparent displacement of the VAI during the pullout. The VAI is moving downward during increased radial acceleration.

Rolls.—During the roll to the right, the VAI moved to the left then circled around and moved to the right and back to its rest point. Normally, no post-roll displacement of the VAI was reported. During the roll to the left, the VAI seemed to move to the right, then circled back to the rest point in the center of the apparent visual field. No appreciable movement of the VAI was experienced after level flight was attained. The apparent movement of the VAI during the roll is shown in Figure 5.

maneuvers. Motion was reported by all observers during the turn, too, but the direction of apparent motion of the VAI varied slightly. When the

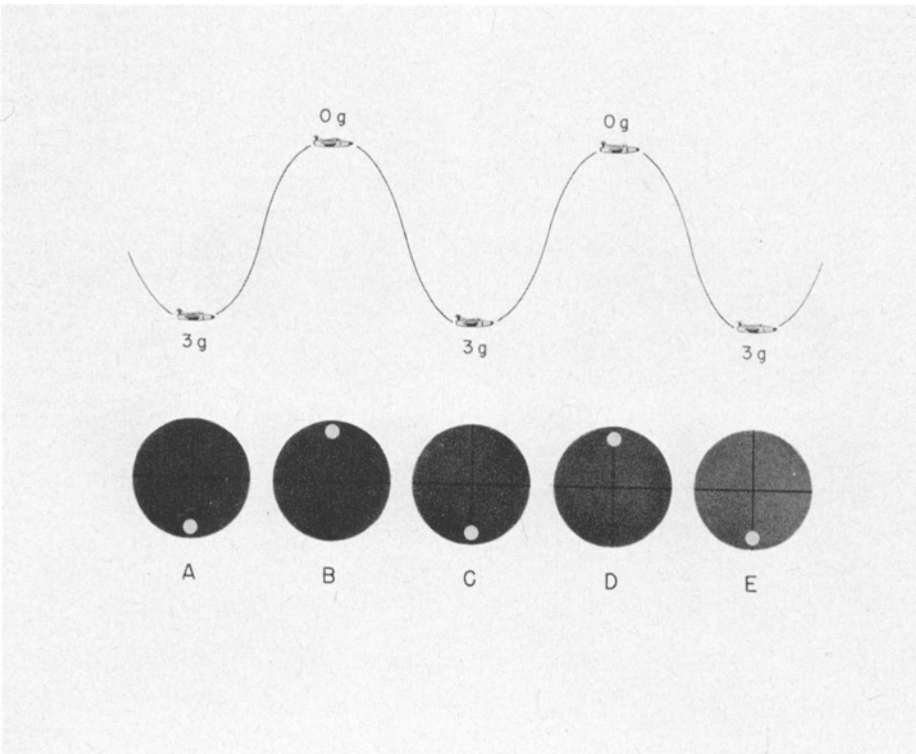

Fig. 4. Apparent displacement of the VAI during the double-parabola. The VAI is moving downward and upward during increased and decreased acceleration.

In general, the results show that during the vertical planar maneuvers, motion and displacement occurred in the egocentrically vertical meridian only. During the pull-outs, which were associated with an increase of acceleration, the VAI went down. During the push-over maneuvers, which were associated with a decrease of acceleration and gravity, the VAI moved upward. The picture was somewhat different in the non-planar

VAI was reported to move down, it meant to indicate the direction of the resultant between the gravitational vertical and the direction of radial acceleration. This was the egocentric direction of the contact force that pressed the observer in his seat. Occasionally, lateral motion was also observed in the turns, which must be attributed to either transversal accelerations stimulating the otoliths or to angular accelerations associated with a turn not well-coordinated.

The aileron rolls were flown with a slight "barrel" effect at a diameter of about 100 feet. Since this maneuver was flown with slight changes in acceleration only, the egocentric sensation of roll usually was poor. In thirteen out of sixteen instances the VAI was reported to move in the direction opposite to that of roll; this indicated the slight alterations of acceleration, in the lateral direction. In some cases the VAI "circled" back to its rest point due to slight additional accelerations in the vertical meridian. On the other hand, the pre-run and after-run periods, in which the pilot maintained the aircraft in straight-and-level flight, were largely uneventful.

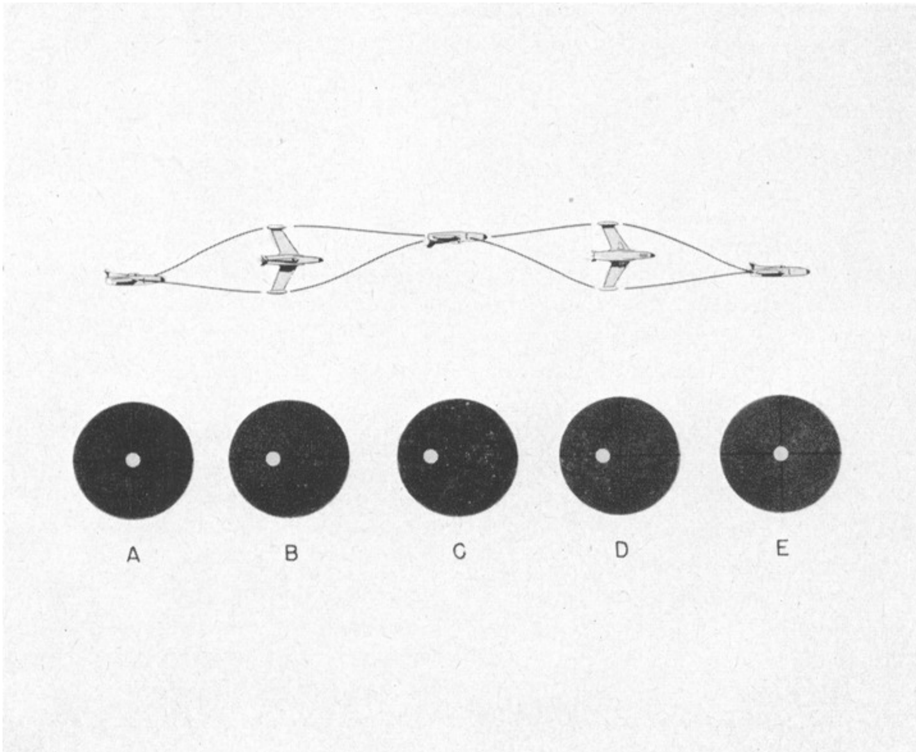

Fig. 5. Apparent displacement of the VAI during an aileron roll to the right. The VAI is moving slightly to the left.

DISCUSSION

The purpose of this discussion is to coordinate our findings with those obtained on the oculogravic illusion, as mentioned before, and to interpret all data available with regard to the physiologic and psychologic processes involved.[1,10,18] It will also serve to supplement Graybiel's "law of the otolith organs" as to its validity for the zero-gravity condition.[15]

First, there is the possibility that

involuntary movements of the head may account for the phenomena observed. In our experiments the head of the observer was not fixed, and appreciable displacements of the head were brought about by the changes in acceleration. There is a conflict between the movement, while the VAI seems to stay for a moment in its original position. However, it follows rather fast in the direction of motion, and it resumes its original place in the apparent visual field at about the end of a slow head movement. There is no evidence from Graybiel's nor from our data that ocular nystagmus or rotation of the eye-ball produce the illusory movements observed. The apparent motion resulting from nystagmus is characterized by a rapid rate of movement without a corresponding degree of displacement of the object or target in space, whereas in the case of the oculogravic illusion the correspondence is good.[6] Thus, nystagmus and cyclotorsion of the eye probably are not the cause of the illusory phenomena for several reasons. First, the magnitude of the apparent displacement can exceed the range of eye-movements and in our experiments sometimes overshot the upper or lower limit of the apparent visual field; second, regardless of the meridional direction of apparent motion the target always appeared sharply defined indictating foveal retention; and third, "real" target and VAI separate during ocular nystagmus.

During the ascending arc of the parabola, the VAI usually went back to its center position when the pilot took the aircraft through the horizon; and, upon entry of weightlessness, the VAI rose and reached its highest position in the upper part of the apparent visual field. This shows that the VAI moved geometrically in the direction of the decreasing G forces, and then stabilized during the weightless state, at a point higher than its original position. After the force of gravity vanished completely and no gravitational vertical was experienced by the observer, the VAI remained in the upper half of the apparent visual field. Thus, the agravic illusion persisted during the period of weightlessness in most of the cases. While changes in the directional vector from increased to decreased acceleration and back were unanimously recorded, the experience of changes due to the alteration of magnitude of G forces was rather individualistic. Moreover, laterally acting accelerations seem to move the VAI in the direction of the apparent resultant force. From this it appears that downward pressure of the (utricular) otoliths causes downward movement; and upward movement of the otoliths, because of loss of weight or centrifugal forces acting opposite to the force of gravity, causes upward movement of the VAI. This is in agreement with Graybiel's data obtained during centrifugation when the subjects faced the center of rotation; in this case the increase of resultant force displaces the otoliths in the direction outward and upward as shown in his Figure 1.[11] These findings also support the assumption of a geometric relationship between gravireceptoric stimulation and target displacement.

Finally, the following supplements can now be made to the "law of the otolith organs" previously formulated by Graybiel, Hupp and Patterson:[15]

1. If, in the presence of visual orientation, man finds himself in a zero-gravity condition, he experiences absolute weightlessness associated with a sensation of floating or elation.
2. If, in the absence of visual orientation, man is subjected to a zero-gravity condition, the direction of the vertical is maintained by definition only.
3. If, in a state of zero-gravity, visual orientation relative to the earth is excluded, an object in space may be egocentrically located higher than under normal gravitational condition.

SUMMARY

To investigate visual illusions during flight, an F-94C type aircraft was flown through various maneuvers. They included turns, push-overs, pull-ups, and aileron rolls producing accelerations of different directions and magnitude, as well as short periods of weightlessness. The observer induced a strong visual after-image and described its apparent motion and displacement associated with the maneuver. Increase of radial acceleration was found to be associated with an apparent downward movement, and subgravity or weightlessness, with an apparent upward movement of the visual after-image. This latter phenomen was called the "oculo-agravic illusion."

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