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on

Spatial Disorientation in Flight

A Handbook for Aircrew

by

A.J.Benson and E.Burchard

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ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

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SPATIAL DISORIENTATION IN FLIGHT

A Handbook for Aircrew

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PREFACE

This handbook was prepared at the suggestion of the Editorial Committee of the Aerospace Medical Panel of AGARD who had recognised the need for a text on the topic of spatial disorientation in flight. It has been known for many years that aircrew suffer from false sensations and perception of aircraft motion and that these illusions may hazard the safety of the aircraft and its occupants. Yet, despite the many papers in the technical literature which deal with differing aspects of the problem of spatial disorientation there are few which are comprehensive and none provide the non-specialist reader with an explanation of the causes of the sensory illusions which reflect contemporary biological and medical knowledge.

The text which follows was prepared in an attempt to redress this deficiency. The approach was primarily didactic though not to the extent that problems were oversimplified in order to obscure deficiencies in our understanding of the mechanism of certain illusions. Neither was the use of medical terminology rejected when this was considered to facilitate description and aid communication.

This account of the various manifestations of spatial disorientation, their causes and their consequences will, it is hoped, be of interest and benefit both to aircrew and their medical attendants who will find within the following pages an amplification rather than a reiteration of previous accounts of the topic. It is for the reader to judge if these aspirations have been fulfilled.

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CHAPTER 1

SPATIAL DISORIENTATION – THE PRACTICAL PROBLEM

What is spatial disorientation?

Spatial disorientation is a term used to describe incidents in which aircrew fail to sense correctly the position of their aircraft relative to the surface of the earth or its attitude relative to the vertical reference – the force of gravity. Apart from false sensations, or more precisely perceptions, of aircraft orientation there are also incidents where the aviator has an erroneous or disordered perception of his own orientation relative to the aircraft and these too may be embraced within a broader definition of "spatial disorientation in flight".

Spatial disorientation is not a new problem in aviation, for early in the history of powered flight it was found that when the pilot was deprived of external visual cues, as when flying in dense cloud, control of the aircraft was soon lost, because he was unable to sense correctly the attitude or motion of his aircraft. In the ensuing half century much has been done to supplement the sensory system of the aviator by aircraft instruments and other aids. Yet the fact remains that the sense organs of man have developed over millions of years to be appropriate for life in a terrestrial environment. In the unnatural environment of flight man, the aviator, is exposed to motion for which his sensory systems are not functionally adapted and hence, at times, they provide inadequate or erroneous information.

Despite a wide understanding of the various causes and manifestations of spatial disorientation in flight the problem is not yet solved. Each year aircraft crash and aircrew are killed because the pilot based his control of the aircraft on an erroneous perception of its spatial orientation. Much more common are these incidents in which the aviator has to resolve a perceptual conflict, for example, he may feel that he is flying in a wing low attitude, but instruments tell him that he is wings level. Commonly, the conflict between correct and false information is resolved and control of the aircraft is not impaired in any way. Nevertheless, it must be acknowledged that conscious attention to conflicting sensations can degrade the aviator's ability to deal with other aspects of the flying task.

Indeed, it is because of the undeniable fact that spatial disorientation jeopardizes flight safety that this manual has been prepared so that aircrew may understand better the causes of disorientation and the ways in which the incidence of this condition may be reduced. After all, control of the aircraft depends upon correct spatial orientation which is crucial in all flight operations.

The incidence of spatial disorientation

Spatial disorientation in flight is, by definition, a perceptual phenomenon. Incidents embrace a variety of sensations – of perceptions – which are a private and personal experience, so it is only by aircrew telling others what they "felt" that we have learnt about the differing manifestations of disorientation and the particular conditions of flight in which they occur. It is not therefore surprising that the majority of incidents to be reported are those in which the aviator – usually the pilot – was aware of the fact that he was disorientated. Table 1 lists a number of different types of disorientation and shows the proportion of pilots who had personally experienced such incidents in flight.

All aircrew have spatial disorientation at some time or other during their career. Indeed, the presence of a sensation which is in conflict with the true orientation of the aircraft is a quite normal, physiological, response to particular aircraft motions. However, the nature of the false sensation, its intensity and the ease with which orientation conflict is resolved do, of course, differ widely, as does the frequency of occurrence of incidents. Some pilots may be aware of disorientating sensations on almost every flight, others may be troubled only once in every 50 or even 100 sorties.

The orientation error accident

A good deal less common are those incidents in which the pilot has allowed his control of the aircraft to be based entirely on a false perception of aircraft orientation. Fortunately, the pilot usually detects the disorientation on checking instruments, and re-establishes appropriate control once the conflict between erroneous and correct cues has been reconciled. However, situations do occur in which the pilot fails to realise that control is based on false cues, or finds out too late to take corrective action. Such is the orientation accident. Available figures suggest that in military aviation some 3 – 7% of all accidents are caused by spatial disorientation which represents 5 – 14% of all fatal accidents. In private flying, excluding commercial flying, spatial disorientation probably accounts for a considerably greater proportion of the aircraft accidents. Disorientation also features in other accidents which have, as a prime cause, some other factor, such as the failure of an aircraft system or the impairment of the pilot by alcohol or hypoxia.

The orientation error accident poses the investigator with one of his most difficult problems. If the pilot is unable to recount what happened immediately before the accident, then the evidence upon which the label "disorientation" may be attached is at best circumstantial, at worst conjectural. Nevertheless, few would disagree that a significant proportion of accidents to both fixed and rotating wing aircraft have been caused by spatial disorientation or that this type of perceptual error will continue to feature in accident statistics.

TABLE 1

Flight experience of spatial disorientation based on questionnaire completed by 137 pilots in 1956 and 321 pilots in 1970. (From Clark, 1970)

Incident	*% of Pilots Reporting Incident*	
	1970	*1956*
Sensation that one wing was low although wings were level	60%	67%
On levelling off after bank, tended to bank in opposite direction	45%	67%
Felt as if straight and level when in a turn	39%	66%
Became confused on attempting to mix "contact" and instrument cues	34%	31%
On recovery from steep climbing turn felt to be turning in opposite direction	29%	55%
Feeling of isolation and separation from earth when at high altitude	23%	33%
On dark night a flare floating straight down appeared to move erratically	21%	23%
Intent on target, failed to check altimeter and came too close to ground	12%	12%

CHAPTER 2

PERCEPTION OF SPATIAL ORIENTATION

Before describing why and how spatial disorientation occurs, it is first necessary to understand how the aviator achieves correct spatial orientation in the flight environment. This means that certain aspects of the structure and function of sensory receptors must be considered, and how the signals from these receptors are interpreted within the brain. In order to provide this basic information some facets of human anatomy, physiology and psychology must be explored, for without this basic knowledge of orientation, disorientation cannot be explained, nor can methods of reducing orientation error accidents be given a logical foundation.

The ability of man to sense – to perceive – his orientation in three dimensional space depends upon him having learned how to interpret the continuous and changing input of signals from many sensory receptors (Fig. 1).

Some of these receptors are grouped together to form a specialized sense organ, like the eye, or the vestibular apparatus of the inner ear. Others are more generally distributed in the body and are to be found in the skin, the capsules of joints and supporting tissues. The "seat of the pants" is not endowed with any special sensory receptors. By usage, this phrase has come to mean, not just cutaneous sensations, but all non-visual sensory mechanisms which contribute to the perception of spatial orientation in flight.

When in our natural environment, i.e. when standing, sitting or moving about on the ground, then adequate and accurate perception of the spatial orientation of our own body relative to the immediate surroundings is readily achieved by the use of visual cues. These cues, along with those from non-visual receptors, also allow us to sense our position, attitude and motion relative to a stable frame of reference, namely the surface of the earth and the gravitational vertical.

In flight, the perceptual task is somewhat more complicated, for the "immediate surroundings" is the aircraft which has a changing orientation relative to the earth's surface and to the vertical (Fig. 2). The cues which allow the aviator to perceive his orientation with respect to the aircraft are very strong, for part of the aircraft is nearly always visible, and he is in physical contact with aircraft structures. The close perceptual bond between pilot and aircraft means that the pilot's appreciation of the orientation of his own body in space is rarely separated from his perception of the orientation of the aircraft relative to the fixed spatial reference. The pilot and his aircraft are as one. The motion and attitude of the aircraft, as indicated by cockpit instruments, is perceived by the pilot as motion and attitude of both the aircraft and himself. Similarly, signals from the inner ear which may tell the pilot that *he* is turning are perceived as angular motion of himself and angular motion of the aircraft.

Accurate perception of aircraft orientation, which is essential if adequate control of the aircraft is to be achieved, is dependent primarily upon the correct interpretation of visual cues, whether these be obtained from outside the aircraft or from cockpit instruments. These visual cues can be supported by information from non-visual sense organs, though in normal flight operations they play a subservient, but not insignificant role in the correct perception of aircraft orientation.

THE EYES. For aircrew, and indeed for non-flying personnel, the eyes are the most important sense organs to provide information about orientation of the body with respect to the immediate environment. In addition they tell the pilot about the position of the aircraft relative to the surface of the earth as well as its attitude relative to the vertical reference provided by the force of gravity. When visual cues outside the cockpit are used to determine orientation, as when flying in conditions of good visibility, the pilot usually has little difficulty in interpreting the information passed from the eyes to the brain. The task of determining the orientation of the aircraft is relatively straightforward and is but an extension and development of the interpretative skills first acquired in early childhood.

In conditions of poor visibility, as when flying in cloud or at night, the aviator must determine aircraft orientation from the cockpit instruments. Now, the pilot has to interpret symbolic information displayed on the instrument dials. The visual information lacks the familiarity and hence the "strength" of external visual cues. Nevertheless, pilots acquire the necessary integrative and interpretative skill and can usually determine with accuracy aircraft orientation, whether flying on instruments or by external visual cues.

THE INNER EAR. Even when deprived of vision, man can still sense his orientation to gravity as well as the movements which occur during normal activity on the surface of the earth. The sense organs which allow him to orientate himself, and indeed maintain his balance, are those of the inner ear and other receptors more widely distributed in the body. The sense organs in the inner ear are the most specialized and will be described first.

The inner ear can be divided, both anatomically and functionally into two parts, (Fig. 3) the organ of hearing – the cochlea, and the organ of equilibrium – the vestibular apparatus. The sense of hearing is of limited importance in the determination of body orientation, though it should not be overlooked that significant information about aircraft position and flight path can be obtained over the R/T during flight operations, and the noise made by the aircraft or engine can contribute to the perception of aircraft speed and attitude. In contrast, the vestibular apparatus is the sense organ, above all others, which by its form and function is especially adapted to sense movement of the head. Hence, it provides essential information which allows man to orientate himself and so preserve his equilibrium when moving about on the earth's surface. In flight, as on the ground, it transduces the linear and angular motion to which the individual is exposed, though because of the different intensities and durations of aircraft motion from those which occur during natural activities on the ground, the information provided by the vestibular apparatus may frequently be misleading, and produce spatial disorientation.

The nature of these limitations of normal function will be discussed in the following pages. Yet despite this preoccupation with the role of the vestibular system as a cause of disorientation, it must be recognised that this sensory system does provide the aviator with correct information about rapid, transient angular and linear movements. Hence, in certain circumstances, vestibular cues do contribute to the correct perception of orientation and the maintenance of aircraft control.

OTHER RECEPTORS – KINAESTHESIS. A variety of sensory endings in the skin, the capsules of joints, ligaments and deeper supporting structures are stimulated mechanically and hence are influenced by the forces acting on the body. In general, these forces arise from linear accelerations, so the receptors signal the direction of action of the acceleration of gravity as well as the accelerations associated with linear motion. Many of the sensory endings, particularly those in the skin concerned with the sensation of touch and pressure, adapt fairly rapidly, so that they are better at signalling a change in the force environment than steady state conditions. They work in conjunction with the specialised receptors of the inner ear which sense linear accelerations and complement the dynamic rather than the static component of the response of these receptors.

These generally distributed mechano-receptors also provide essential information about the spatial relationships and movement of one part of the body with respect to another. In the absence of vision, man can sense with some accuracy the relative position of his limbs with respect to other parts of his body. This is called the *proprioceptive* or *kinaesthetic* sense and is achieved mainly by information signalled by receptors in the capsules of joints. It is possible that specialised length receptors in the muscles and other stretch receptors in the tendons of muscles also contribute to this kinaesthetic sense.

The kinaesthetic receptors thus play an important role in the perception of body orientation relative to external references. The vestibular apparatus signals the angular movement and attitude of the head with respect to the gravitational vertical, but unless the brain is informed about the position of the head on the trunk and of the limbs relative to trunk, man is not able to build up an adequate perception of the spatial orientation of his body and its appendages. Apart from these spatial references, man also needs to know about the structures with which he is in immediate contact. Such information is provided by the receptors in and below the skin which respond to touch and pressure. In flight, these cutaneous receptors link the aviator to his immediate environment – the aircraft. They are responsible for the close perceptual bond between man and aircraft which ensures that vestibular cues, whether they be true or false, are perceived not only as motion of the head and body but as motion of the aircraft.

CHAPTER 3

FORM AND FUNCTION OF THE VESTIBULAR APPARATUS

The vestibular apparatus is about the size of a pea, yet within this small volume are sensory receptors which are stimulated by angular accelerations as low as $0.05°/\text{sec}^2$ and linear accelerations of less than 0.01 g. In form and function the vestibular apparatus may be divided into two parts, though not without reason is it called "the labyrinth". The *semicircular canals* contain the receptors responding specifically to angular accelerations and the sac-like *utricle* and *saccule* house the *otolith organs*, the specialised receptors of linear accelerations.

Figure 3 is a diagram of the inner ear and shows the arrangement of the membraneous structure which forms the vestibular apparatus. Basically there are three ducts, the semicircular canals, which open into the sac of the utricle; below and in connection with the utricle lies the saccule. The membraneous labyrinth is filled with a watery fluid, called endolymph, and the whole system is surrounded and supported within an appropriately sculptured bony cavity by another fluid, the perilymph. Thus when the head moves, the vestibular apparatus moves with the head and hence experiences the same angular and linear accelerations as the head.

The three membraneous ducts are roughly semicircular in shape and lie in bony canals having an internal diameter approximately four times that of the duct itself; perilymph fills the space between duct and canal. Each semicircular duct has a swelling, called the ampulla, where the sensory cells are congregated in a ridge – the crista. These cells have many hair-like projections arising from them, and are covered by a gelatinous structure – the cupula. As shown in Figure 4, the cupula fills a cross-section of the ampulla, and can be considered as a watertight swing-door which is deflected by movement of the endolymph within the membraneous duct. The activity of the sensory cells is determined by the bending of the hair-like processes, which in turn is dependent upon the position and movement of the "swing-door" cupula.

The sensory cells in the ampulla of each semicircular canal are maximally stimulated by angular acceleration in the plane of the canal. As the three semicircular canals on each side of the body are arranged approximately at right angles to each other (see Figure 5), then an angular acceleration in any plane will always stimulate the sensory cells of at least two "canals". The "canals" work as functional pairs in a push-pull type of configuration. The two horizontal canals (*h* in Figure 5) work as a pair and sense angular motion in yaw. The vertical canal pairs lie at 45° to the conventional roll and pitch motions so that the forward canal of one side (*a.v.*) works in conjunction with the rearward canal of the opposite side (*p.v.*). Although this arrangement does not correspond with the orthogonal axes in which the aviator normally appreciates angular motion, the brain is well able to sort out the signals from these three pairs of canals, and can sense accurately the plane, direction and magnitude of an angular movement provided that these parameters of the movement are within the range for which the sense organ is "designed" to work.

How the semicircular canals work

The way in which the sensory receptors of the semicircular canal provide information about angular motion of the head may best be understood by considering what happens when the head is suddenly turned (Fig. 6). During such a movement the semicircular canals and the whole of the membraneous labyrinth will move with the head, but in those semicircular ducts which lie in the plane of the angular movement, the rings of endolymph will tend to remain in their original position because of their inertia. Thus, during angular acceleration, a force will develop between the cupula and its associated ring of endolymph. The cupula "swing-door" will be deflected, and the activity of the sensory hair cells altered. During normal head movement, where angular acceleration is followed shortly by deceleration, the dynamics of the hydromechanical system is such that the cupula deflection and the associated signal from the sensory cells closely matches the angular *velocity* of the head; the semicircular canal acts as a rapidly responding tachometer, although the effective stimulus is the angular acceleration of the head movement and not its velocity. Indeed, this transducer works very well for the type of head movement made in normal life on the ground, and it has a good frequency response (up to about 10 Hz) so is able to respond to the rapidly changing angular accelerations of the head that occur during walking, running, and jumping etc., as well as quick voluntary movements of the head.

Although the semicircular canals provide accurate information about angular movements of the head in the natural environment, difficulties arise when the speed of rotation is held steady for several seconds, or when the rate of turn increases or decreases at a steady rate (i.e. a constant angular acceleration). In order to illustrate how the semicircular canals provide erroneous information, consider their response to a prolonged rolling or spinning manoeuvre in flight (Fig. 7).

Before the pilot begins a roll, the cupulae of the semicircular canals are in their neutral position, provided the aircraft has been in a straight and level flight for half a minute or more. As soon as the roll begins, the cupula of the semicircular canals in the plane of the roll motion will be deflected by the angular acceleration in the roll axis and will generate a signal which reflects accurately the increasing angular velocity in roll. However, as soon as the rate of roll becomes constant, the cupulae of the stimulated canals begin to return to their neutral position because there is no longer any angular acceleration and hence no deflecting force. The rate of return of the cupulae and the decay of the evoked sensation of turning is determined primarily by the dynamics of the cupula-canal system. Typically, for a roll at 100°/sec the sensation of roll dies away in some 10 – 15 seconds; thereafter, roll at a constant rate can continue indefinitely without any sensation of angular motion in roll being engendered by the semicircular canals, provided the position of the head with respect to the axis of rotation is not altered.

If after some 30 seconds, the pilot now recovers from the roll, there is angular acceleration in the opposite direction to that which occurred on entering the roll. The cupulae of the "roll axis" canals will be deflected and hence will signal roll in the opposite direction, with an intensity equal to the *change* in roll velocity of the aircraft. Yet as soon as the aircraft returns to straight and level flight, there is no angular acceleration and the deflected cupulae slowly return to their normal positions. The lack of information about turning or rolling at a constant rate and the erroneous signal of rolling in the opposite direction on recovery from a constant rate roll are brought about entirely by the hydromechanical features of the semicircular canals. These are normal physiological responses.

The otolith organs

The fluid filled sacs, called the utricle and saccule (Fig. 3), lie below the semicircular ducts and contain plate-like congregations of sensory cells (Fig. 8). These cells, like those found in the ampulla, have many hair-like projections, which when deflected alter the activity of the sensory cells. In both the utricle and saccule the cells are grouped together in an irregular saucer shaped area. They are covered with a gelatinous layer the outer surface of which is invested with small calcium carbonate crystals. In life, this has the appearance of a white stony plaque and is called the otolithic membrane; hence the common name for these specialised sense organs – the otoliths. Because the otolithic membrane has a higher density than the endolymph which fills the utricle and saccule, the sensory hairs are bent as the attitude of the head alters relative to the force of gravity (Fig. 9). Thus the sensory cells signal the position of the head with respect to the gravitational vertical and also changes in the force environment due to linear acceleration of the head (see Figure 9).

There are two otolith organs on each side of the head, those of the utricle lie in an approximately horizontal plane when the head is in a normal upright position, and those of the saccule lie in the vertical plane (Fig. 10). Thus the brain is able to sense a linear acceleration in any direction, provided the time course and intensity of the stimulus is within the range for which the receptor mechanism is functionally adapted.

Reflex responses to vestibular stimulation – eye movements

So far, the discussion of vestibular mechanism has been concerned with the sensations produced by the receptors of the semicircular canals and otolith organs. However, the prime function of the vestibular apparatus is the maintenance of equilibrium – an activity which is normally achieved automatically, without willed or volitional control, it is a reflex action.

The way the vestibular system controls the muscles of the body to maintain equilibrium is complex and need not concern us here, but for the powerful control exercised over the eye muscles. The function of this vestibular reflex is to stabilize the position of the eye, relative to an object fixed in space, when the head moves. Thus, when the head suddenly turns, say to the left in yaw (Fig. 11), then the eye is reflexly moved in its socket to the right in order to stabilize the image of the outside world on the retina. If the eyes were to move with the head, the retinal image would also move and vision would be seriously degraded because we can only see clearly when the retinal image is more or less stationary. We know that for natural head movements the semicircular canals sense correctly the instantaneous angular velocity of the head, therefore the compensatory eye movements, engendered by signals from the semicircular canals also have an angular velocity which is equal and opposite to that of the head (Fig. 12). This is true irrespective of whether the motion is in pitch, yaw or roll. Vestibular stabilization is remarkably accurate, particularly for the rapid, small angular movements of the head which occur during natural movements. Indeed, without the vestibulo-ocular reflex man is not able to see clearly and resolve fine visual detail when he walks, runs, or is exposed to vibration.

During prolonged angular movement of the head, the compensatory eye movements take on a characteristic form (Fig. 13). On entering a turn, say to the right, the eyes initially move in the opposite direction (relative to the skull) in order to compensate for the head movement. Once they have deviated about 10° from their initial position they quickly flick in the direction of the turn and then begin another slow compensatory movement. The alternating slow and fast eye movements are called nystagmus. The speed of the slow component of the eye movement – the one that is physiologically significant in the stabilization of the eye with respect to an object fixed in space – is closely related to cupula deflection. Accordingly, during a prolonged spin or rolling manoeuvre, the compensatory eye movement is only correct during the initial change in angular velocity. Once a steady angular velocity is achieved, the signal from the stimulated canals decays and with it the velocity of the nystagmus. On recovery from the manoeuvre, the semicircular canals signal rotation in the opposite direction. The information is inappropriate, as is the associated nystagmus which serves only to degrade the aviator's vision for objects both inside and outside the aircraft.

Emphasis has been placed on the nystagmus engendered by the semicircular canals, but changing linear accelerations also generate this type of eye movement which, though compensatory in nature, is less accurately matched to the stimulus than the nystagmus produced by angular motion. When the linear acceleration stimulus is constant, as when the head is tilted on one side, a sustained deviation of the eye from its rest position may be observed. These sustained eye movements occur in the expected compensatory direction, but in amplitude are only 5 – 10% of the angular deviation of the head. The inadequacy of the "static" vestibulo-ocular reflex stresses the essential dynamic nature of the control of eye movements by the vestibular apparatus.

CHAPTER 4

SOMATOGYRAL ILLUSIONS

This chapter and the next are concerned with several types of spatial disorientation in which the aviator has a false sensation – an illusory perception – about his own orientation in space, which directly influences his perception of aircraft orientation. These illusions are caused principally by inappropriate vestibular and "seat of the pants" cues.

In order to describe the false perceptions of angular motion the term *Somatogyral illusion* is used. The word vertigo means the same thing, namely a sensation of turning, but in aircrew jargon "vertigo" has come to be used to cover all types of spatial disorientation even when there was no false perception of angular motion. *Somatogravic illusion* describes those illusions in which the aviator has a false perception of his attitude relative to the gravitational vertical.

The use of the words somatogyral and somatogravic, hopefully, also serves to differentiate the illusory perceptions of *body* (hence *soma*) orientation from the *oculogyral* and *oculogravic* illusions, names which should be confined to *visual* illusions of angular and linear motions (described in Chapter 6).

SOMATOGYRAL ILLUSIONS

Effect of prolonged rotation

SPINNING. Earlier it was pointed out that the sensory receptors of the semicircular canals are stimulated only by angular accelerations and hence signal only changes in angular velocity. Thus, during a prolonged turning manoeuvre at a constant angular speed, whether this be a co-ordinated turn, a sustained roll, or a prolonged spin, these receptors only give correct information during the first few seconds of the manoeuvre (see Figure 7). Once a steady speed of rotation has been achieved the signals from the semicircular canals, stimulated by the initial angular acceleration, die away progressively to fall below the threshold value after about 10 – 20 seconds. The time taken for the sensation of turning to die away depends upon a number of factors, namely the speed of rotation, the axis of rotation, the nature of cues from other sensory receptors and the extent to which the aviator is familiar with the motion stimuli (level of habituation). But for a typical spin, in which the aircraft may reach a steady rotational speed of 120 – 150°/sec in 2 – 3 seconds, it can be reckoned that most pilots will be unable to perceive rotation, by purely vestibular mechanisms, after 15 – 30 seconds. They can however detect continuation of the spin and determine its direction from the blurred view of the outside world or by checking cockpit instruments.

Visual cues are usually adequate to allow the appropriate recovery action to be taken, but as soon as the aircraft begins to come out of the spin, there is an angular acceleration in the opposite direction to that which occurred on entering the spin. The semicircular canals are stimulated again and engender a sensation of spinning in the opposite direction (Fig. 7); a sensation which occurs at a time when the pilot has to decide when the rotational component of the spin has ceased in order to make the correct control movement in order to bring the aircraft to level flight. This decision can only be made on visual cues, which may be either the rate of turn indicator or the appearance of the external visual scene.

In addition to the false vestibular sensations, involuntary eye movements (nystagmus) also occur (Fig. 13). This nystagmus is as inappropriate as the illusory sensations, and causes a blurring of the pilot's vision of objects both inside and outside the aircraft. No matter how hard he may try to "see", it commonly takes several seconds before these eye movements are completely suppressed, though it is usual for normal vision to be restored long before the false sensations have died away. Nevertheless, vision is degraded at the very time the pilot is so dependent upon visual cues. (The disturbances of vision, during and after rotation, are more fully described in Chapter 6.)

The presence of false sensations and impaired vision can have serious consequences during spin recovery. On the one hand, the pilot may feel that the spin has been neutralized before this has actually happened, and subsequently get into difficulties on attempting to pull out. Alternatively, having recovered correctly, he may feel that the aircraft is spinning in the opposite direction, and may make inappropriate control movements to counteract this illusory spin. If he does so the aircraft can enter a spin in the original direction. This can give rise to an even more complex and confusing impression of motion, so that finally, it might be impossible for the pilot to regain control of his aircraft. Since spins usually result in very high rates of descent there may be no time for recovery and the aircraft must be abandoned.

In a *steep descending spiral turn or spiral dive the rotational motion* takes the form of a co-ordinated high rate turn rather than a spin. Yet as in the spin, once a constant rate of rotation has been established, there is no longer any angular acceleration to stimulate the semicircular canals; these receptors signal a progressively decreasing rate of turn and after 20 seconds or so the sensation of turning is lost.

The inexperienced pilot on attempting to recover from such a manoeuvre, aware only of the high rate of descent, may be tempted to pull back on the stick and add power in order to pull out from the dive. However, these movements of the controls only serve to increase the rate of turn and tighten the spiral dive. Recovery is possible only if the angle of bank is first reduced.

Immediately on recovery from the prolonged spiral dive to straight and level flight, the pilot experiences a sensation of turning in the opposite direction to that of the original spiral. Recovery by reference to instruments may be impaired, firstly, because vision can be degraded by nystagmic eye movements, and secondly, because the motion of the aircraft is complex and rapidly changing. In such a stressful situation, quick action and rapid determination of aircraft orientation are of paramount importance, for altitude is lost very rapidly.

Comparable problems arise on recovery from prolonged rolling manoeuvres in level flight, where the illustory sensation in roll may cause the pilot to re-enter the roll. However, on recovery the illusory sensations tend to be of shorter duration than those following rotation in yaw, as the otolith organs and other gravireceptors provide correct information about roll attitude which is in conflict with the erroneous signal from the semicircular canals.

OTHER MANOEUVRES. There are other aerobatic manoeuvres where the semicircular canals give inadequate information which leads to inappropriate control responses. For example, during the latter half of a looping manoeuvre, the pilot may feel that the angular velocity in the pitch axis is progressively diminishing. Here again, the erroneous perception occurs because of the decay in the signal from the semicircular canals, stimulated by the initial angular acceleration in pitch as the aircraft entered the loop, but not sustained during angular motion at a constant rate. In such circumstances the inexperienced pilot may pull harder on the stick, during the descending part of the loop, in order to maintain the same apparent pitch rate.

In all aerobatic manoeuvres the pilot should have an adequate view of the ground and/or the horizon, for with the rapidly changing position and attitude of the aircraft interpretation of an instrument display is a task beyond the capabilities of all but the exceptional pilot. Furthermore, the absence of easily interpreted external visual cues makes it extremely difficult for the pilot to ignore vestibular sensations, which during aerobatics may be particularly powerful and at the same time erroneous. It can require great mental effort to resolve the sensory conflict, for the pilot's attention tends to be drawn by the unusual and distracting sensations.

Illusions caused by cross-coupled (Coriolis) stimulation of the semicircular canals

So far only the illusions produced by angular acceleration and deceleration of the aircraft have been described. However, the semicircular canals can also be stimulated powerfully, and strong false sensations generated, without any change in the rate of turn of the aircraft. These illusions arise when the aviator moves his head in an aircraft which itself is turning, and may best be illustrated by considering the response of the semicircular canals of a pilot who is rolling at a constant rate (Fig. 14).

Once the effect of the initial angular acceleration has died away, the cupulae of the semicircular canals are in their neutral position and the pilot has no information from the canals about the rate or direction of roll. If now the pilot tilts his head forward quickly from the normal erect position through an angle of say 90°, he changes the orientation of all six canals relative to the axis of motion. The canals which sense angular motion about the x axis of the skull (i.e. roll) will be taken out of the plane of rotation and immediately receive a stimulus equivalent to a change in angular velocity from ω (where ω is the angular velocity in roll of the aircraft) to zero. Conversely, the canals which sense yawing motion of the skull (z axis) are brought into the plane of rotation and hence receive a stimulus equivalent to a change in angular velocity from zero to ω. In the pitch axis there is no change in the orientation of the *plane* of the canals, relative to the axis of aircraft motion, when the head is pitched forward through 90°. These canals sense correctly the angular movement of the head is pitch, but unlike yaw and roll canals there is not "abnormal" stimulus.

Thus the effect of a simple head movement made in an aircraft turning at a constant speed is to generate a stimulus to the semicircular canals in both yaw and roll axes, the net effect of which is to give rise to a sensation which is the combination of the apparent change in velocity in yaw and in the roll axis. This sensation is bizarre, and quite different from the true angular motion of the aircraft. Furthermore the intensity of the resulting sensation is greater than that produced by the "simple" angular stimulus of recovery from the roll to straight and level flight.

Cross-coupled or Coriolis stimulation of the semicircular canals occurs when any angular motion of the head is made in a plane other than that of the co-existing angular motion. The sensation evoked always has at least one component which is at right angles to the plane of the head movement, and more often than not there are components in both orthogonal planes.

Provided the head movement is made fairly quickly, say within 2 – 3 seconds, then the effective stimulus to each semicircular canal can be expressed as a change in angular velocity, the magnitude of which is the product of the angular velocity of the aircraft and a trigonometric function of the angular position of the plane of the canal at the beginning and end of the head movement. The physics of the situation is such that movements of the head through only a few degrees can readily bring about supra-threshold stimulation of the canals. If the pilot of an aircraft rolling at 90°/sec made only a rapid 10° forward movement of the head, the "yaw axis canals" would receive a stimulus equivalent to a change in angular velocity of nearly 16°/sec; in contrast, the "roll axis canals" would only sense a change in angular velocity of 1.4°/sec. The dominant illusory sensation would be in yaw and not the combination of yaw and roll which occurs with the 90° head movement.

Illusions due to cross-coupled (Coriolis) stimulation are probably one of the most important causes of severe spatial disorientation experienced by aircrew. The inappropriate sensations frequently have a sudden and unexpected onset at a time when the pilot's attention is directed to some other aspect of the flying task. The classical situation is one in which the pilot, during a descending instrument turn, has to turn his head to operate controls on the side-consoles in the cockpit, such as the selection of a new R/T frequency. The action, involving the rotation and tilting of the head to look at the frequency selector switch, engenders false vestibular sensations at the very time that the pilot has no reliable visual cues about the orientation of his aircraft. An immediate and ill-considered response to this false sensation can easily lead to loss of control and jeopardize the safety of the aircraft. If disorientation occurs at low altitude in a high performance aircraft, the time available for appropriate recovery action to be taken is small and an aircraft accident the more likely.

It is unfortunate that aircraft designers have failed to devote sufficient attention to cockpit designs which are far from ideal from a human engineering standpoint. Many aircraft in use at the present time require considerable head motion for the manipulation of important equipment. Under visual flight conditions the effects of Coriolis stimulation are unlikely to be grave, since a short glance at the horizon or the surface of the earth is sufficient, on most occasions, to regain complete orientation. But in night and instrument flying the Coriolis illusion will create a particularly unfavourable situation, since orientation then requires the interpretation of several flight instruments, which of course is a more complicated, cumbersome and, above all, time-consuming task than when flying on external visual cues.

Pressure vertigo (alternobaric vertigo)

In some individuals the receptors of the semicircular canals can be stimulated by sudden pressure changes within the *middle* ear. In flight this occurs when the ears are "cleared", i.e. pressure in the middle ear cavity is equilibrated with ambient (cabin) pressure during ascent or descent. Typically the aviator hears a click as air enters or leaves the middle ear cavity through the Eustachian Tube and at the same time has a strong sensation of turning or vertigo, just like that evoked by a sudden angular stimulus to the semicircular canals. The vertigo may also be associated with blurring of vision and apparent movement of the visual scene. Fortunately the false sensations and visual disturbance are short lived, and die away in 15 – 30 seconds or so, as the cupulae of the stimulated canals return to their neutral position, though atypically a less intense vertigo may persist for several minutes. The direction and plane of the illusory sensation of turning may be in pitch, yaw or roll or even an intermediate axis, but it is usually of a consistent and repeatable pattern in any one individual.

The mechanism underlying this particular manifestation of semicircular canal stimulation is not fully understood. The sudden pressure change in the middle ear is transmitted to the inner ear presumably via the membranes covering the "round" or "oval" windows which separate the inner from the middle ear. The sudden movement of fluids within the inner ear produces an abrupt deflection of the cupula of one or more of the semicircular canals on the affected side, and the aviator experiences the typical sensations associated with stimulation of canal receptors.

Pressure vertigo occurs most frequently when there is a "stickiness" of the Eustachian Tubes, usually due to mild congestion and inflammation brought about by a common cold or other infection of the upper respiratory tract. The majority of aircrew (about 80%) are never troubled by pressure vertigo – the minority suffer from this disability and their safety in flight is jeopardised by the sudden appearance of disorientating sensations. Aircrew prone to this type of vertigo should never fly when suffering from even a slight upper respiratory tract infection and should seek medical advice for appropriate therapy.

CHAPTER 5

SOMATOGRAVIC ILLUSIONS

On the surface of the earth man can sense "up" and "down" through information provided by the specialized receptors of the otolith organs and other receptors stimulated by forces acting on the body – the "seat of the pants". We live in a "force environment" in which the earth's gravity represents a stable up-down (i.e. vertical) reference. Although the body may be exposed to transient linear accelerations during normal movement and locomotion, these do not normally interfere with our perception of body orientation relative to the gravitational vertical.

In flight there are significant differences in the "force environment" from that occurring on the surface of the earth. There is still the force of gravity, but the forces due to other linear accelerations are frequently of longer duration, though not necessarily of greater intensity, than those which occur on the ground. As Einstein pointed out, the acceleration of gravity is the same physical phenomenon as a linear acceleration and hence is indistinguishable from it. Therefore when an aircraft undergoes a linear acceleration (or deceleration) of several seconds duration, the pilot tends to regard the resultant of aircraft acceleration and gravity as the true vertical in his perception of the spatial orientation both of himself and his aircraft.

In order to illustrate this statement consider a high performance aircraft which accelerates in the line of flight (aircraft longitudinal or x axis) at say $0.45\,g$ ($4.4\ \mathrm{m/sec^2}$) (Fig. 15). The combination of the force of gravity and the inertial force, which can be represented as a force which pushes the pilot backwards into his seat, produce a resultant force equivalent to $1.10\,g$ which makes an angle of 24° with respect to the true vertical – the force of gravity. If the pilot now considers the resultant force to be the vertical he will feel as if he and his aircraft had pitched up and were in a 24° nose-up attitude. The danger in this situation, as in many others where the pilot has an illusory sensation, is for control movements to be made on the basis of the false perception of aircraft orientation. The danger is intensified when disorientation occurs at low altitude; there is very little time for the pilot, who puts the nose of the aircraft down, to correct his mistake.

Once the pilot pushes the stick forward to correct for what he feels to be an excessive pitch up attitude, recovery becomes more difficult because the aircraft moves in a curved flight path which, of itself, introduces a radial acceleration. The force environment is now modified by a third linear acceleration, which causes an even larger deviation of the resultant force vector from the true vertical. Thus the pilot on making what he thinks to be an appropriate corrective response may feel that the nose up attitude is increasing rather than becoming less, and he may be tempted to push the stick even further forward. This response increases the tightness of the bunt manoeuvre with further rotation of the force vector which can result in the pilot being exposed to negative *g*. Pilots who have experienced this type of force environment, at a sufficiently high altitude to appreciate and recover from their disorientation, say that the aircraft felt as if it pitched up and flipped over onto its back. Recovery was usually made from a near vertical dive many thousands of feet lower than the height at which the illusion first occurred. Figure 16 shows the flight path and direction of the force vector of an aircraft which crashed shortly after an overshoot was initiated; no subjective report from aircrew or passengers was available.

The illusion of a pitch-up change of attitude produced by acceleration in the line of flight has been considered at some length as it is probable that many accidents on night take-off over unlit terrain or water must be attributed to this type of illusion. However, it should not be forgotten that the same type of false perception can occur when an aircraft is decelerated by, for example, operation of the air brakes. The resultant vector of the force of gravity and the inertial force attributable to the deceleration points forwards and downwards (Fig. 15), which may give the illusion of a nose down change of attitude. If the pilot eases the nose of the aircraft up, airspeed may fall excessively and a stall be precipitated. Fortunately, this particular manifestation of disorientation is relatively rare, presumably due to the lower accelerations achieved and the more careful monitoring of instruments during the phase of flight in which airbrakes are commonly applied. Furthermore, time is usually available for recovery because of the greater altitude at which this illusion occurs.

The preceding explanation of the somatogravic illusion has been based on the premise that the subjective vertical is aligned with the resultant of aircraft linear acceleration and gravity. However, laboratory experiments have shown that this illusion can take a minute or more before the perceptual vertical is coincident with the resultant. In addition, quite large differences exist in the magnitude of the illusion experienced by different individuals when exposed to the same force environment; some habitually feel less tilt than the deviation of the resultant from the true vertical, others more.

An alteration in the direction of a linear acceleration without any angular acceleration is an unusual stimulus. In everyday life, a head movement in roll or pitch alters the orientation of the head relative to gravity and is accompanied by an angular acceleration which stimulates the vertical semicircular canals. It is the absence of a concomitant signal from the canals which is thought to be responsible for the time lag in the development of the somatogravic illusion. Yet even a brief acceleration, such as that of an aircraft during catapult launch (5 *g* peak, 2 – 3 sec duration), has been shown to give rise to an illusory perception of a nose-up change in attitude. Admittedly, the mean magnitude of the illusion was only 5°, but despite the brevity of the stimulus about 1 minute elapsed before the false perception was completely dissipated. Illusions of this type are quite capable of influencing aircraft control in a critical phase of flight.

EFFECT OF HEAD MOVEMENT. The disorientation caused by cross-coupled stimulation of the semicircular canals when the head is moved in a turning aircraft has already been described and is a well recognised phenomenon. The effect of head movement in an abnormal force environment, has, however, only recently been investigated. Experiments carried out in an aircraft performing a large radius banked turn at 4°/sec with a resultant of 2 *g* have shown that an angular movement of the head in pitch, roll or yaw, could induce false sensations of aircraft attitude. The illusions were not caused by cross-coupled stimulation of the canals because the rate of turn was so low, and the plane of the illusory sensation was not in accord with such a mechanism. Rather, the false perception of attitude was considered to have been caused by the transient stimulation of otolithic receptors when their orientation to the abnormal force vector was altered by the head movement. Commonly, subjects reported an illusory sensation of climb or dive on making a head movement, though neither the direction nor the magnitude of the illusion were consistent between individuals. Nevertheless, in some subjects the illusions were very powerful (e.g. a climb and dive of 90°), particularly when the head moved rapidly, and most of the other subjects found the sensations confusing and difficult to describe in terms of aircraft motion and attitude.

Thus head movements can induce disorientation both by the cross-coupled stimulation of the semicircular canals and by "*g* excess" effects on the otoliths. These two modes of stimulation engender illusory sensations in planes which are at right angles to one another, a feature which underlines the perceptual conflict – the disorientation – which frequently ensues when head movements are made during flight manoeuvres where there is a high rate of turn and linear accelerations higher than 1 *g*.

THE "LEANS". One of the commonest types of disorientation experienced by aircrew is called "the leans" and is characterised by a false sensation of bank when the aircraft is in level flight (Fig. 17). Despite the widespread occurrence of "the leans" the way in which this illusion develops and is sustained is not fully understood. Nevertheless it is acknowledged that sensory mechanisms concerned with the perception of angular motion and attitude relative to the gravity vector are involved.

Consider an aircraft which is given an angular acceleration in the roll axis of 2.5°/sec^2 for 0.5 sec. At the end of the half second the angular velocity in roll is 1.25°/sec and will remain constant until another angular acceleration is made. Now for a sensation of turning to be evoked, the change in angular velocity must be of the order of 2°/sec. Indeed this *threshold* value can be a good deal higher in flight where the pilot is exposed to noise, vibration and other distracting stimuli. Thus initiation of a roll with an angular velocity of 1.25°/sec is unlikely to be sensed by the pilot. Likewise roll at constant velocity will not be sensed by semicircular mechanisms because of the absence of angular acceleration. The non-visual cues which could tell the pilot that the aircraft is banking are from otolithic and "seat of pants" receptors as the attitude of the aircraft changes with respect to the gravitational vertical, and even these will be absent if the aircraft is in a co-ordinated turn. It must also be remembered that the linear acceleration receptors and associated sensory systems adapt fairly rapidly so that a slowly changing roll attitude can occur without evoking an appropriate sensation.

Thus the pilot can allow one wing to drop without this change in attitude arousing a corresponding sensation. However, he may become aware of the wing-low attitude from sight of the real or artificial horizon and initiate recovery to level flight. This corrective manoeuvre is likely to take a second or so and the aircraft will rotate in roll at an angular velocity well above sensory threshold. The ensuing perception of the magnitude and direction of the change in angular position will be essentially correct, but as the pilot felt that he was wings-level before the manoeuvre began, the resulting perception will be one of bank away from a level attitude. Therefore, one type of spatial disorientation, an unperceived movement in roll, can give rise to another, a false perception of roll attitude, when the pilot brings the aircraft back to a wings-level position.

If the pilot has the sensation of being in a banked attitude yet the artificial horizon shows that he is straight and level, there is a sensory conflict to be resolved. Most pilots in such a circumstance attempt to ignore their own sensation and maintain the correct flight path by instrument reference. Yet once attention has been directed to the false sensation it can be very difficult to ignore, especially when there is no powerful (i.e. external) visual cue to tell the pilot that his sensation really is wrong. When flying on instruments, the false sensation of bank may persist for many minutes and on occasions much longer, indeed, durations of over an hour have been reported. Control is maintained by instrument reference, but the continued sensory conflict can drain the nervous energy of even the most experienced pilot. During an incident the pilot may feel compelled to align his body, not with the normal axis of the aircraft, but with the apparent vertical. In doing so he *leans* in the direction of the original sub-threshold roll (Fig. 13). Alternatively, he may roll the aircraft in order to neutralize the false sensation of bank, so that he may once again feel straight and level. We know that when the pilot leans his head and upper body slightly to one side he also has a tendency to pull the control stick to the side assumed to be the vertical. This, in turn, causes an alteration of aircraft attitude and necessitates further supra-threshold corrections, with possible aggravation of "the leans".

The illusion of "leans" can also be generated in another way. For example when an aircraft is suddenly banked by turbulence, the pilot may correct the change of attitude slowly, so that the aircraft rolls back into the original attitude at a sub-threshold rate. The semicircular canals will register only the original roll motion and the pilot is likely to maintain the sensation of the original bank. He will perceive the vertical to be in a direction opposite to the original roll motion, and he may feel compelled to align either himself or the aircraft with this false vertical; in doing so he *leans* in the direction opposite to that of the original roll.

In the preceding paragraphs the "leans" has been explained in terms of roll movements which are either above or below the sensory threshold for semicircular canal mechanisms. This is an oversimplification, which in part ignores the fact that man's concept of "the vertical" or "the horizontal" is not constant but changes in an adaptive manner. If a subject is rolled from the vertical through say 45°, and kept in that attitude for, say 1 minute, then on being returned to the true vertical he feels as if he is tilted in the opposite direction. The magnitude of this false perception is a function of the time the individual spent in the initial banked position and the angle of the bank, rather than the rate at which he returns from this position to the vertical. From this type of experiment it has been established that an individual's internal reference of what he considers to be "the vertical" is not fixed, but changes in an adaptive way, appropriate to the pervading force environment. Accordingly, if a pilot has been flying for several minutes in a banked attitude, this attitude tends to become his perceived vertical, and any subsequent movement from the banked position feels like a movement away from the vertical. Such an alteration in the apparent vertical undoubtedly works in conjunction with "threshold perception of angular motion" mechanism described earlier and serves to intensify the illusory perceptions.

Finally there is another possible cause of "the leans" which relates to semicircular canal function. It is known that the ability of individuals to sense angular motion is not absolutely symmetrical; one man may have a lower threshold for detecting roll, say, to the right than to the left; another may be more sensitive to rolling movement to the left than to the right. In the flight environment, where the aircraft is continuously exposed to small displacements in roll attitude, such a threshold asymmetry can on occasions give rise to an illusory perception of angular motion or of angular displacement in the direction of greater sensitivity.

Whenever "the leans" occurs, the frequent cross checking of instruments, in particular the artificial horizon, is vital. Reference to instruments allows correct control to be maintained, but it does not necessarily dispel the illusory perception. Some aircrew have found that a redirection of attention to other aspects of the flying task, e.g. a call over the R/T, a change of heading or the adjustment of straps, is sufficient to terminate the illusion, but this is not always effective. A clear sight of the ground is the only certain cure.

CHAPTER 6

VISUAL ILLUSIONS OF MOTION

In the preceding two chapters the emphasis was on the illusory sensations evoked by inappropriate signals from vestibular receptors. However, these signals also generate reflex eye movements which can have a profound effect upon what the aviator sees and his perception of spatial orientation.

Effect of rotation on visual acuity

The basic features of the eye movements caused by stimulation of the vestibular apparatus were described in Chapter 3, in recapitulation it is only necessary to emphasise that the normal function of the eye movement is to stabilize the angular position of the eye when the head is turned and so preserve acuity of vision for an object which is fixed in space relative to the observer. There is also another reflex which stabilizes the retinal image, namely the fixation or pursuit reflex. This does not involve the vestibular system but relies upon information from the retina to control the eye position in order to maintain the alignment of the eye with the object under observation.

During natural head movements vestibular and pursuit reflexes work together. Likewise in flight, at the beginning of a prolonged rotational manoeuvre when the semicircular canals correctly signal an increase in angular velocity, these two reflexes allow the aviator to see clearly objects outside the aircraft, which move in respect to him (Fig. 18). However, objects within the aircraft, like cockpit instruments, have no motion relative to the observer. The eye movements of vestibular origin are now inappropriate and must be suppressed by fixation in order to achieve a stable retinal image and clear vision of the instruments or any other feature of the aircraft within the field of view. If the nystagmus is not suppressed there is a blurring of vision and apparent motion of the observed target in the plane of the reflex eye movement.

The effectiveness of the suppression of vestibular nystagmus depends upon a number of factors, notably, the intensity of the stimulus, the plane and direction of the angular motion and, as will be described later, the blood alcohol concentration; there are also quite large differences between individuals in their ability to suppress nystagmus. However, as a guide, the nystagmus produced by a prolonged spin at 120 – 150°/sec is typically suppressed in about 5 seconds to a level where visual acuity is not significantly impaired and cockpit instruments can be read without difficulty (Figures 18 and 19).

With continuation of rotation at a constant speed the signal from the stimulated canals dies away and promotes progressively less assistance to the pursuit reflex. The aviator finds it more difficult to visually track, and hence see clearly, objects outside the aircraft. Indeed, when the relative velocity of the visual target exceeds about 100°/sec the eyes may fail to follow and vision of the outside world becomes very blurred. As with the suppression of inappropriate nystagmus, there are quite large individual differences in ability to follow and see clearly a moving object; this dynamic visual acuity does not appear to correlate with static visual acuity, as is tested in the routine aircrew medical examination.

On stopping a sustained rotational manoeuvre, the semicircular canals signal the change in angular velocity and evoke nystagmus, but these eye movements are inappropriate and, if not suppressed, will degrade the aviator's vision irrespective of whether he looks inside or outside the aircraft. The suppression of nystagmus is influenced by the same factors and follows a similar time course to that which occurs at the beginning of the rotational manoeuvre. However, the impairment of vision on recovery is potentially more dangerous because the aviator's only reliable source of information about aircraft orientation is degraded at the very time illusory sensations are the most intense.

Laboratory experiments have shown that the period for which vision is degraded by inappropriate nystagmus is reduced when the brightness and contrast of the observed object is increased. Thus the advice to aircrew, who may find themselves in the unfortunate position of being unable to read the aircraft instruments because of nystagmus, is to increase the level of illumination to the maximum available. This applies irrespective of whether the nystagmus is due to a change in the angular velocity of the aircraft, cross-coupled stimulation or pressure vertigo.

Another factor influencing the period of visual impairment is the plane of the nystagmus. Nystagmus in yaw is suppressed more rapidly than in roll. Thus on recovery from a prolonged spin, nystagmus dies away more rapidly if the pilot has tilted his head backward and tried to look at the horizon during the spin than if he bent his head forward and looked at the ground. However if recovery from the spin has to be made by reference to instruments, the movement of the head on transferring gaze from the horizon to the instrument panel can produce a cross-coupled stimulus which potentially contributes more to the disorientation of the pilot than the concomitant nystagmus.

MODIFICATION BY ALCOHOL. Amongst the many effects of ethyl alcohol on man the way in which it modifies nystagmus has recently come into prominence. Experiments have shown that alcohol increases the duration and intensity of nystagmus by attenuating the suppressive action of the fixation reflex (Fig. 19). A blood alcohol concentration as low as 20 mg/100 ml has been shown to prolong the nystamic response on stimulating the semicircular canals and to cause a significant impairment of visual performance. With substantially higher levels of blood alcohol; the nystagmus recorded while the subject tries to fixate is hardly of lower velocity or shorter duration than that recorded in the absence of fixation in a subject who has not taken alcohol.

The oculogyral illusion

Even when nystagmus is suppressed sufficiently for objects to be seen with an acuity adequate for operational needs (i.e. instruments can be read) there are residual eye movements which can alter visual perception. These cause an apparent cyclical motion of objects within the visual scene, which are stationary with respect to the observer. The apparent motion has opposing slow and fast components in the same rotational axis as the nystagmus; thus nystagmus in yaw causes apparent motion in yaw, and similarly for vertical (pitch axis) and rolling nystagmus. The slower and hence more easily detected motion is in the same direction as the concurrent somatogyral illusion (the vertigo).

With the decay of the signal from the stimulated semicircular canals the visual scene becomes stable, though the aviator may still feel that he is turning. If on recovery from prolonged rotation external visual cues are unambiguous, then the somatogyral illusion is rapidly attenuated. However, if there are no external cues, or they are inadequate (e.g. an isolated light or star in an otherwise featureless night sky), then the false sensation of turning is likely to take many seconds, even minutes, to die away. During this time an isolated light will not only seem to rotate with the observer, but may also appear to be displaced in the direction of the sensed motion. As the sensation of turning dies away, the observed light drifts back towards its true position; though on occasions it may appear to oscillate slowly about this position, while still continuing to rotate with the observer until the false sensation of turning has disappeared.

There is some uncertainty about which feature, or features, of these visual illusions should be called the oculogyral illusion, but precise nomenclature is superfluous if it is remembered that when a fixed light source (or other visual target) is observed after the sudden cessation of turning the target is initially blurred with apparent movement in the direction of the sensed rotation. After a few seconds the target is seen clearly and appears to move round with the observer, but is not correctly localized. Commonly it appears to be displaced in the direction of apparent rotation, relative to the observer. This displacement becomes less as the sensation of turning dies away, though the apparent displacement and the sensation of turning do not necessarily follow the same time course. Figure 18 attempts to illustrate the various components of the oculogyral illusion.

Thus an inappropriate semicircular canal signal can, in certain circumstances, give rise to an illusory perception of motion of objects within the visual scene. These illusions are the more common when the overall structure of the visual scene is ill-defined. Accordingly, errors in perception are the more likely to occur when flying at night. Stationary light sources in the sky or on the ground may appear to move and be interpreted as belonging to another aircraft. The pilot usually appreciates the false nature of his perception before an accident occurs, though this type of incident, in common with many other manifestations of spatial disorientation, can be a frightening and anxiety provoking experience.

Oculogravic illusions

Oculogravic is an adjective that should be used to describe visual illusions produced by a change in the force environment and may be considered to be the otolithic counterpart of the oculogyral illusion. Unfortunately the term "oculogravic illusion" is loosely used to describe the false perception of attitude produced by an abnormal force vector, namely the "somatogravic illusion", yet this illusion is as potent with the eyes closed as when they are open. The coexistent visual illusion may modify the perception of spatial orientation, just as the oculogyral illusion may contribute to the false perception of angular motion produced by semicircular canal stimulation; the oculogravic illusion is no more than a component of the altered perception which occurs when there is a change in the direction and/or magnitude of the force vector.

The oculogravic illusion is the apparent movement and false spatial localization of observed objects produced by changes in the force environment to which the observer is exposed. If we consider again the effect of a linear acceleration acting in the longitudinal axis of the aircraft (Fig. 15), the rotation of the force vector from the vertical in a backward direction evokes a somatogravic illusion of a pitch-up change in attitude which is accompanied by an apparent upward movement of objects within the visual field of the pilot (Fig. 20). If the longitudinal acceleration is sustained, there will be an apparent displacement of the visual scene which is likely to continue until the acceleration stops and the pilot returns to a 1 *g* force environment.

It is known that such changes in the direction and magnitude of the force vector produce compensatory eye movements which, with rapid rotation of the force vector, may be nystagmic and cause transient impairment of vision. These eye movements also accentuate the apparent upward movement of a visual target.

Once steady state conditions are reached, i.e. when the force vector maintains constant direction and magnitude, there is a small compensatory deviation of the eye in the pitch down direction. This causes a displacement of the image of the outside world on the retina and contributes to the apparent displacement of what the pilot sees. However, it is worthy of note that the angle through which the eye deviates is only about one tenth of the angle through which the vector is displaced from the true (gravitational) vertical. Therefore it must be concluded that the apparent movement and displacement of the visual scene brought about by a change in the force environment (i.e. the oculogravic illusion) is not due primarily to eye movement, but to the perceptual mechanism within the brain which integrates the cues provided by otolith organs and other receptors stimulated by linear accelerations.

The apparent movement and displacement of observed objects corresponds with the sensation of altered body orientation (i.e. the somatogravic illusion) evoked by the change in the force environment. The apparent upward movement of the visual scene during longitudinal acceleration is complemented by an apparent pitch-down movement when the aircraft decelerates and the force vector rotates in the forward direction.

Visual illusions also occur when there is a change in the magnitude of the force vector without rotation of the vector. These are given the name of *Elevator illusions* because they were first studied in lifts or elevators, though comparable changes in the force environment occur during flight through an up or down draught. With an increase in the magnitude of the gravity vector, such as occurs during vertical acceleration in the upward direction (updraught), there is a correct sensation of upward movement which is accompanied by an apparent upward motion of the visual scene; in particular, there is apparent movement of objects such as the instrument panel, within the cockpit. Conversely, when the force vector decreases, as during flight through a down-draught, there can be an apparent movement downwards of objects within the pilot's immediate visual scene. These visual illusions are relatively easily suppressed and are rarely noticed when flying with good external visual cues. Even when flying on instruments they present little more than distraction, for associated eye movements are small and there is rarely significant impairment in the pilot's ability to see the instruments clearly.

In conditions where the pilot is exposed to transient alteration in the vertical force vector, disorientation is much more likely to occur because of false perception of the vertical motion than because of the visual (elevator) illusion. It has been shown that even experienced aircrew are unable to make accurate judgement of translational vertical motion, especially when this is of a slowly alternating character (i.e. frequencies below 0.5 Hz). With some individuals the perception of motion is completely out of phase with the actual motion, (i.e. motion downwards is sensed as upwards) and frequently perception leads or lags the stimulus by 90° or more. This explains why helicopter pilots are unable to maintain altitude correctly in the absence of visual cues, and emphasises the need for an accurate altimeter and vertical speed indicator if hovering or precise adjustments of height are to be performed at night or in conditions of poor visibility.

Flicker vertigo

Aircrew have described a number of sensory disturbances which can be attributed to a flickering visual stimulus. Such problems are more common in rotary wing aircraft where the shadow cast by the main rotor blades passes across the cockpit several times a second. Difficulties have also been experienced when light from a rotating anti-collision beacon illuminates the cockpit either directly or by reflection from cloud or snow.

The principal complaint of aircrew when subjected to flicker is irritation and distraction. Less frequently there is a true disorientation in which the visual stimulus gives rise to a sensation of angular motion of the aircraft in the opposite direction to that of the moving shadow. Fortunately there is usually little difficulty in determining the true orientation of the aircraft or helicopter, though there is a conflict to be resolved. An associated problem is one of nausea, which must be regarded as a form of visually induced motion sickness in which visual motion cues are not "matched" by appropriate cues from other sensory receptors.

Finally, mention must be made of flicker epilepsy, as this topic is always raised when there is a flickering visual stimulus at 8 – 10 Hz, a frequency band which coincides with one of the dominant rhythms of the brain waves, as revealed by the electroencephalograph. There are very rare individuals in whom disturbances of consciousness or even fits can be precipitated by visual stimulation at 8 – 10 Hz. Fortunately, susceptibility can be assessed by special tests commonly carried out during the medical examination of aircrew, for such a predisposition is hardly compatible with piloting an aircraft.

The autokinetic illusion

The autokinetic illusion is another visual illusion in which there is apparent motion of an isolated light source, but unlike the oculogyral and oculographic illusions autokinesis occurs without obvious stimulation of the vestibular apparatus. Furthermore, it only occurs when there is no visual frame of reference. Thus it differs from the oculogyral and oculogravic illusions which may be observed when there is some structure to the visual scene, though these illusions are most potent in conditions which would support the autokinetic illusion.

Typically autokinesis (self movement) occurs when a stationary observer looks at a small isolated and stationary target, such as a distant light, on a black night. Commonly, after staring at the target for 10 seconds or so, it may appear to move slowly away from its original position and then drift about in random manner, though rarely moving more than about 10° from its initial position. The illusion comes on sooner and is the more powerful if the target light is not continuously visible, such as a flashing beacon or some other occulting light source. Likewise, the apparent movement is more intense if the light source is very small and dim. The illusion disappears as soon as the visual scene has some overall structure, or if several light sources are visible at any one time.

The autokinetic illusion is caused, in part, by wandering movements of the eye, which is unable to maintain accurate fixation of the observed target on that part of the retina where resolution is highest (the fovea), when presented with a very small target in an otherwise empty structureless visual field. Thus, the image of the isolated light moves slightly on the retina as the eye wanders about. The brain, unaware that the eye is moving, interprets the retinal signal as movement of the observed light. Vestibular responses also contribute to the illusory perception of motion, especially in flight where the observer is commonly exposed to small angular and linear accelerations even when apparently flying straight and level in calm air. Oculogyral and oculogravic effects combine with autokinesis to produce illusory motion of an isolated light on the ground or a lone star.

A further feature of the autokinetic illusion is the ease with which the perception of motion can be modified by suggestion. Laboratory experiments have shown that if an observer is told that a target light is moving in a particular direction, then he is more likely to perceive motion in the manner suggested. Thus, once the aviator thinks that an isolated fixed light moves as if it belongs to another aircraft, the subsequent perceived motion of the light is more likely to be as if it were a light on an aircraft.

An aviator who has autokinesis or other visual illusions of motion is not necessarily disorientated. Problems only occur when he controls his aircraft on the basis of a false interpretation of the illusory motion, as when he alters flight path in order to align his aircraft on to a fixed ground light under the mistaken impression that it is part of another aircraft.

Difficulties also arise when flying in formation at night. If the pilot of an aircraft in the wing position can only see one light on the aircraft upon which he has to formate, then the already near impossible task of judging distance and relative attitude may be made quite impossible by illusory motion of the isolated light. When formation flying at night the aircraft must be equipped with several lights, of which at least two can be seen simultaneously by other aircraft in the formation. A similar problem exists in helicopter landings at night where it has been found necessary to provide the pilot with at least three ground lights if height is to be judged with any accuracy and autokinetic effects eliminated.

CHAPTER 7

OTHER VISUAL ILLUSIONS

About 90% of the incidents of spatial disorientation reported by pilots are associated with false sensations of attitude and motion engendered by inappropriate vestibular cues. The bulk of the remaining 10% of disorientation incidents are attributed to errors of visual perception, most of which occur when the aviator attempts to determine aircraft orientation from external cues, when these cues are essentially inadequate for this task. The errors in perception take a variety of forms and will be discussed under separate headings.

Confusion of lights

A common problem associated with night flying is the confusion of lights on the ground with stars (Fig. 21A). This illusion is especially frequent during flight above sparsely settled territories, where lights are infrequent. On suddenly looking out of the aircraft, the pilot interprets these lights as stars and thinks that his aircraft is upside down. Numerous incidents are recorded in which pilots have put their aircraft into very unusual attitudes in order to keep lights on the ground *above* them, and feelings of complete inversion are not infrequent under these circumstances.

A problem associated with flight at high altitude at night is that the moon and stars may appear below the true horizon (Fig. 21B). The pilot, flying straight and level, looks out and sees the moon below the aircraft. His immediate thought is that he is upside down. He is presented with a conflict, so typical of the disorientation incident, that he can readily resolve by looking at the instruments, though occasionally the pilot forgets to make this obligatory check and makes an immediate change in aircraft attitude.

Cloud leans and related disorientation

The upper surface of cloud formation is usually horizontal and provides the pilot with a useful external visual cue of aircraft attitude. However, certain weather conditions are characterised by cloud decks which slope at an angle of 10° or more from the horizontal (Fig. 21C). If the pilot aligns his aircraft with this false "horizon" he is disorientated, for he is flying in a wing-low attitude, with perhaps associated turn and slip, while under the impression that he is wings-level. On checking instruments, recovery to level flight from the wings-level attitude can bring an attack of the "leans" in the manner described earlier (Chapter 5).

In high latitudes, auroral displays can have convincing "vertical" and "horizontal" components. When flying at night, these present such a strong visual cue that pilots may have considerable difficulty in not aligning their aircraft with such false horizontals. The importance of frequent instrument scans, when using external visual cues at night, cannot be over-emphasised.

Certain topographical features can also provide false "horizons" upon which pilots have been known to align their aircraft. The commonest is probably a range of hills having a gentle and progressive slope. The pilot, being under the impression that the surface over which he is flying is flat, aligns the wings of the aircraft with the surface of the terrain. Another problem of flying in mountainous country at low level is that trees growing on the mountain sides are used as a vertical reference when, in fact, they may be at a considerable angle from the true vertical.

Similarly, lights along a curved seashore have been mistaken for the horizon and pilots are known to have used this false reference while under the impression that they were in straight and level flight. There are stories of pilots who have mistaken certain geometric patterns of light on the ground (such as moving trains, street lamps etc.) for runway and approach lights and have attempted to land using these false cues.

Apart from false visual cues outside the aircraft, errors in the perception of attitude can arise because of difficulties in relating the visual framework of the aircraft to the external visual scene. There is at least one military aircraft in which the edge of the cockpit coaming falls away abruptly to either side of the mid line, there is no vertical division of the canopy and the wings are not readily visible by the pilot. In the absence of any orthogonal aircraft frame of reference, pilots tend to regard the sloping edge of the cockpit as the horizontal of the aircraft, an error which is intensified in some aircraft by the alignment of the instrument dials. Thus, when flying on external visual cues they not infrequently find that they are in a wing-low attitude.

"LEAN ON THE SUN" ILLUSION. There is yet another type of visual illusion, which to date has been given little attention. It occurs when flying through a cloud layer, usually when close to the cloud top. Even though the sun itself is not visible, the cloud is distinctly brighter in the direction towards the sun. Under these circumstances the pilot may have an illusory perception of aircraft attitude in which he develops the "leans" in the direction of the sun.

The "lean on the sun" illusion is thought to be caused by the pilot equating the brightest area of the cloud as "up" and using this as a vertical reference. This error is probably based on a loose perceptual relationship between bright sky "up" and dark earth as "down", even though we know that the sun is but rarely directly overhead. However, if the pilot tries to use external visual cues when flying in cloud, rather than staying on instruments, he will attempt to interpret these cues, inadequate as they are, on the basis of past experience and expectation. If the sun is to the left of the flight path, the pilot of an aircraft in straight and level flight may feel that it is left-wing-low, and conversely when the sun is to the right. During flight towards the sun, the illusion is one of a nose-up attitude of the aircraft.

The lower position of the sun or the closer the pilot flies to the top of the cloud layer, the more intense is the illusory sensation. As the depth of cloud above the aircraft increases, the light of the sun is more diffused, the brightness of the cloud above the aircraft becomes more uniform and the illusion less prevalent. A parallel here exists between aircrew and divers who, in conditions where they have no valid frame of reference, will equate the lightest and brightest area of their field of view with "up" and may swim towards a false "surface".

Flying just below the top of low stratus or through high reaching fog formation is unpleasant and at times dangerous owing to the "lean-on-the-sun" illusion, which may be augmented by the normal "leans". In such weather conditions the illusion may also be encountered during instrument approach, where absolute reliance on the instruments is essential.

False perception of height

During flight in conditions of good visibility over familiar terrain, aircrew learn from experience to estimate the ground clearance of the aircraft with considerable accuracy. However, difficulties arise when the terrain is unfamiliar, and the perceptual task approaches the impossible when the surface below the aircraft lacks visual detail. Commonly the problem is experienced when flying over glassy smooth water, or land uniformly covered by snow or sand. Numerous incidents have been reported where the pilot has allowed his aircraft to come dangerously close to, or has even contacted, the featureless surface, when under the impression that there was adequate ground clearance. The problem is accentuated when attempting to land in these particular visual conditions, for the pilot must always rely on external visual cues at the final stage of an approach and landing. Before attempting to land on smooth water it is common practice to overfly the projected landing area in order to ruffle the water and provide some visual texture to the surface. The need for ground markers on snow covered landing strips is also well recognised.

A somewhat different kind of false perception of height can develop as a sequel to the failure of the pilot to detect an error in aircraft attitude (Fig. 22). This type of illusion occurs when flying at night towards an isolated yet familiar light on the ground. From past experience the pilot knows how the angular depression of the light, observed from the cockpit, changes with height and distance during straight and level flight. Now, if the aircraft has an undetected error in pitch attitude, say for example nose-up, then the angular depression of the light with respect to the longitudinal axis of the aircraft, is the same as that which occurs when the aircraft is in straight and level flight at a higher altitude. In this circumstance, the pilot may have a fallacious impression that the aircraft is higher than its true altitude. Conversely an undetected nose down attitude may give rise to the underestimation of altitude.

CHAPTER 8

BRAIN MECHANISMS AND SPATIAL DISORIENTATION

So far, discussion of the causes of disorientation has been concerned primarily with aspects of the flight environment and features of aircraft motion which aircrew have found to be important. It is now necessary to consider in a more general way factors influencing the way in which the pilot uses the information fed to his brain by visual, vestibular and other receptors.

Coning of attention or fascination

Correct perception of aircraft orientation depends upon the aviator making use of correct sensory information which in turn has to be correctly interpreted by higher centres within the brain. A true appreciation of the behaviour of the aircraft depends as much upon the appropriate selection of information by the pilot as upon the interpretation he puts on the cues selected. It is for this reason that no account of the problems of orientation and disorientation in flight is complete without consideration of the way in which aircrew *attend* to the various sensory cues with which they are provided.

Of particular relevance is the organization of attention when flying on instruments. Here the pilot has to learn to scan the instruments in an orderly manner so that he obtains complete information about the attitude and flight path of his aircraft. During training the student pilot may devote too much of his attention, if not all, to one instrument (say, air speed) and, as a result, fail to perceive correctly aircraft attitude. With experience a proper pattern of scan is established and disorientation due to a *coning of attention*, or *fascination* as it is sometimes called, is a rare event. Nevertheless, even experienced pilots can restrict their attention to a single instrument or just one element of the flying task, especially when this is demanding or difficult, or when an apparently important malfunction occurs. As with other types of disorientation, coning of attention is more common when flying on instruments, though when flying on external cues "fascination" can still occur. Incidents have been described in which the pilot failed to attend to aircraft height or airspeed during an attack manoeuvre when their whole attention was directed towards the alignment of the aircraft on a ground target.

Disorientation caused by "fascination" must be considered as a more dangerous form of disorientation than when the pilot has conflicting sensations, for in the former situation the constriction of attention ensures that the pilot is not aware of any deficiency in his perception of aircraft orientation or in his control of the aircraft.

Behavioural state: arousal

Anecdotal reports as well as laboratory experiments have shown that coning of attention is more likely to occur when individuals are performing a demanding or emotionally stressful task. Indeed, this is but one manifestation of the changes in brain function and behaviour which commonly occurs when man is "aroused" beyond an optimum level by the task he has to perform. "Aroused" in this context is used in a rather special way, to imply a continuum – the arousal continuum – between drowsiness at one extreme, to acute awareness and perhaps even panic at the other. Although this concept is not without criticism, it is a useful framework in which to discuss the effect of physical and mental stress on behaviour and, in the present context, alterations in the way aircrew make use of information about aircraft orientation.

Apart from the coning of attention in high arousal states, performance may also be degraded by an impairment of more recently acquired skills; there is a reversion to more firmly established patterns of behaviour. Thus the highly stressed or anxious pilot tends to accept more readily information from his own vestibular and kinaesthetic receptors, although he has been trained to ignore such sensations in the flight environment. Clearly, this is the more likely to occur in the inexperienced pilot or in one who has not maintained his proficiency.

The particular importance of maintaining a high degree of skill in instrument flight must be emphasised, for this type of flying is not only more demanding than flying with external visual references, hence likely to produce a higher level of arousal, but is also a recently learned complex skill more vulnerable to impairment by high arousal. A potential vicious circle mechanism exists in which high arousal increases susceptibility to disorientation and at the same time reduces the pilot's ability to cope with disorientation (Fig. 23). Appreciation by the pilot that his control of the aircraft is degraded serves only to heighten arousal further, which in turn accentuates the break down of skill. On rare occasions this can be catastrophic, for an individual caught in the vicious circle can become "frozen with fear" and unable to make even a simple control response or initiate an escape procedure. Such an escalation of events is to a large extent preventable by the maintenance of proficiency in the basic flying skills. The recognition by the aviator that he should "keep his cool" will also help, though it must be recognised that in such situations logical thought may not always be possible.

In addition to the disorientation produced by high arousal states, problems also arise when the level of arousal is *below* the optimum. Errors, or more commonly deficiencies, in the perception of aircraft orientation arise because of inattentiveness. During monotonous flights, especially those which involve manual control on instruments, the pilot's scan can become inadequate and changes in aircraft attitude are not perceived (cf. The Leans). Under these conditions of flight the aviator is also more likely to make errors in interpretation, for when he is drowsy the brain mechanisms responsible for perceptual processes are not working at their optimal level.

The break-off phenomenon

Apart from these alterations in "cerebral competence" associated with low arousal there is a particular form of disorientation which commonly occurs during monotonous flights, especially at high altitude (30,000 ft) when the horizon is ill defined. This is an altered perception by the pilot of his relationship to the aircraft, in which he feels detached, remote and isolated from the vehicle he is controlling. About 30% of aircrew who fly at high altitudes experience this type of sensation, which has become known as "the break-off phenomenon" because the aviator feels as if he has "broken-off" from the reality of his immediate environment – his aircraft.

Usually "break-off" is no more than a mild feeling of detachment, though less frequently the dissociative sensation is more dramatic: the pilot may even feel as if he is outside the aircraft watching himself at the controls. Such "outside the body" experiences can be very alarming to an aviator who has never heard of the "break-off phenomenon"; to others, these somewhat unusual sensations are but one of the pleasures of flying. Although "break-off" was first described by pilots of single seat aircraft flying at high altitudes, more recently it has been found that this type of sensory experience is not the prerogative of such aircrew. "Break-off" occurs in helicopter pilots at much lower altitudes (500 – 10,000 ft), particularly when they fly in hazy conditions with an indistinct horizon over featureless terrain or a smooth sea.

The dissociative sensations of "break-off" are only rarely associated with illusory perceptions of aircraft orientation, though an increased awareness of even an exaggerated perception of small changes in attitude may occur. This particular manifestation of disorientation is not a direct threat to flight safety; rather, it can disturb the equanimity of the aviator and lead to apprehension and high arousal states in those aircrew who do not understand or who are unfamiliar with the "break-off phenomenon".

The sensations of "break-off" are usually short lived, and often disappear spontaneously when the aviator directs his attention to some other aspect of the flying task, such as change in heading or an R/T message. Less commonly the pilot has to make a positive effort to redirect his attention in order to dispel the sensations; in rare instances "break-off", like "the leans", may persist until reliable external visual cues appear, such as a clear sight of the ground.

Other factors influencing brain mechanisms

We have seen how the correct interpretation of orientation cues is dependent upon the normal function of higher centres within the brain, and have discussed some of the ways in which these perceptual mechanisms are disturbed by normal alterations in the "level of arousal" of the aviator; but this is far from being the only factor which modifies brain function. The normal functioning of the central nervous system depends upon the physical and chemical environment of the millions of nerve cells which make up a human brain, an environment which has to be controlled within close limits if the brain is to work correctly.

It would be inappropriate here to discuss the great variety of ways in which brain mechanisms can be disordered in flight. However, this manual would be incomplete if mention were not made of anoxia and hyperventilation which can cloud consciousness, impair perception, and disorientate the pilot. The brain is also deprived of oxygen by toxic agents such as carbon monoxide or by a reduction in blood supply caused by a high linear acceleration. The aviator who "blacks out" under high *g* is by definition disorientated, though this perceptual defect is but part of a more global impairment of cerebral function.

Drugs

Cerebral competence is reduced by many drugs, whether these be taken to aid sleep, (e.g. the barbiturates), to treat allergic conditions (e.g. the antihistamines), or to reduce susceptibility to motion sickness (e.g. hyoscine). Many of these drugs stay in the body for long periods (typically longer than 24 hours) and are believed to have a small yet deleterious effect on higher brain function which can persist even though the primary therapeutic action of the drug has ceased. It is for such reasons that drugs and flying do not mix.

Alcohol, whether regarded as a drug or a toxic agent, also has a depressant effect on brain mechanisms, with which most readers are probably familiar. In addition, ethyl alcohol also has specific effects on vestibular mechanisms which can only serve to increase the susceptibility of the aviator to disorientation. As mentioned earlier, alcohol impairs man's ability to suppress vestibular nystagmus and hence his ability to see following prolonged rotation or at other times when the nystagmus response is inappropriate. However, even after alcohol has disappeared from the blood, disordered vestibular function of a different type can be detected in which nystagmus occurs whenever the individual places his head on one side. This *positional nystagmus* may last, for example, for some 20 hours after taking sufficient alcohol to raise the blood level to 100 mg/100 ml and can be evoked at even longer intervals by linear accelerations greater than 1 *g*.

Thus alcohol even in small quantities jeopardizes flight safety on several counts, and is likely to increase the aviator's susceptibility to disorientation long into the "hang-over" period. The restriction, common in most countries of not flying for at least 12 hours after having taken alcohol is probably too lenient, for in some circumstances, especially after heavy drinking, more than 12 hours is required for the blood alcohol to fall to a level where there is no impairment of piloting performance or disturbance of vestibular functions.

CHAPTER 9

PREVENTION AND TREATMENT

Loss of life and damage to aircraft are the most tangible consequences of spatial disorientation. Nevertheless, from an operational standpoint the perceptual conflict, which is a basic feature of most disorientation incidents, impair aircrew efficiency and in a small number of aviators can lead to anxiety and a loss of confidence in their ability to fly. The prevention of orientation error accidents is a primary objective of those concerned with flight safety. Perhaps prevention is too strong a word to use when considering disorders of perception caused by natural limitations of sensory function, yet it is not unrealistic to propose that the incidence of spatial disorientation can at least be reduced by appropriate measures.

The preceding chapters should have made it apparent that many factors influence the incidence of spatial disorientation; the flight path of the aircraft, aircraft instrumentation, cockpit layout, the nature of external visual cues and last, but not least, the sensory mechanisms of the human operator, the aviator. Thus no single preventitive measure, no matter how rigorously pursued, would achieve the desired result; there is no panacea. However, it must be acknowledged that the fallability of man is the most important factor in the aetiology of spatial disorientation, and so it is logical to discuss first how aircrew can be helped to overcome the problem by appropriate training.

Training

One of the aims of training should be to provide flying personnel with adequate understanding of the limitations of man's sensory mechanisms and of the particular flight manoeuvres and conditions where errors in perception of aircraft orientation are most likely to occur. Yet more important than knowledge about the "how and why" of disorientation is an appreciation that errors in perception of orientation are a normal physiological response of all aircrew. For this reason, *personal* experience of illusory vestibular sensations in a demonstration device, such as a simple turntable, can do much to dispel the misconception that "I" never get disorientated although "they" do. Likewise it is important to dispel the hidden anxiety caused by the feeling that "they" never get disorientated but "I" do.

Ground based lectures and demonstrations undoubtedly play a part in the "orientation training" of aircrew, but it is in the flight environment itself that they learn how to cope with the problem of disorientation. We know that illusory perceptions are much more likely to occur and to distract the pilot when he is, or should be, flying by instruments. Hence a high degree of proficiency at this type of flying must be acquired during training. In particular, it is considered to be vital that the pilot learns to interpret and integrate rapidly and reliably the symbolic orientation cues provided by the aircraft instruments, so that even when he is loaded with other tasks the presence of conflicting or distracting sensations will not influence his ability to orientate correctly. Once this state has been acquired it must be maintained by regular practice. In some countries this may be achieved during routine flying duties, but in others where clear weather conditions commonly prevail it should be mandatory that proficiency is maintained by flying "under the hood" at regular intervals.

Commonly, the student pilot receives demonstrations during initial instrument training of how he may be misled by "seat of the pants" sensations and of the necessity to fly only by instrument cues. However, once the rudiments of instrument skill have been acquired he is only rarely given an opportunity to learn how to cope with a disorientating situation. Admittedly this situation does sometimes arise when making a recovery from "unusual attitudes", but more could be done during the later stages of flight training to give the student pilot experience of recovery following disorientating manoeuvres. In this way he may learn how to resolve conflicting cues and in doing so increase his confidence in his ability to fly by instruments.

HABITUATION. One aspect of the maintenance of flying skill achieved by consistent exposure to the flying task is that the level of adaption or habituation to the motions experienced in the flight environment is sustained. Aircrew who are in current flying practice, particularly of high performance aircraft, are in general less aware of vestibular and kinaesthetic sensations and likewise are better able to suppress inappropriate vestibular responses (e.g. nystagmus on spin recovery) than aircrew who have not had recent experience in comparable flight conditions. The ice skater, who spins at high speed (typically 400 – 600°/sec), stops within a fraction of a second and maintains perfect balance, is an unequivocal demonstration of how normal vestibular responses may be modified by experience. But the ice skater has difficulty in performing this feat if it is not practiced regularly. Although the pilot is exposed to a wider variety of motion stimuli than the ice skater, he also loses his habituation if he does not fly regularly and maintain familiarity with the angular and linear acceleration stimuli which are the normal concomitant of flying.

The loss of skill associated with prolonged periods of ground duty is well recognised in Service flying and refresher training with some dual flying is commonly carried out before the pilot returns to operational duties. Yet even after being grounded for only a couple of weeks, some habituation is lost. Surveys have shown that pilots are much more likely to be aware of aircraft motion and to suffer disorientation on the first flight after a period of leave. Such problems can be ameliorated by the gradual introduction of the stressful flight manoeuvres on return to flying duties, and by aircrew recognising their own loss of habituation and increased susceptibility to disorientation after more than a week or so away from flying.

Apart from the need to maintain proficiency at instrument flying it is generally accepted that trained aircrew should periodically have refresher training in aeromedical topics relevant to flight safety. This training should not be confined to the study of oxygen system and safety equipment, but should include revision of the problems of orientation and disorientation in flight, preferably reinforced by movies and demonstrations.

Selection

Selection is the normal precursor to the training of an aviator, yet, despite the relatively long time for which the problem of disorientation has been recognised, little attention has been given to the assessment of a potential aviator's ability to orientate in flight or conversely his susceptibility to disorientation. Certain tests, involving controlled vestibular stimulation, have been carried out on student pilots and on aircrew troubled by spatial disorientation. Statistical differences have been demonstrated in some of these tests, though to date none has proved to be sufficiently precise for use in selection.

Health

Any discussion of the ways of reducing orientation error accidents must put the main emphasis on the training of aircrew. Nevertheless, it must not be forgotten that many other factors influence the function of the nervous system and the aviator's perception of the orientational cues available to him. As a generality it may be stated that any factor which interferes with the physical and mental health of the aviator is also likely to increase his susceptibility to spatial disorientation in flight. Indeed, it is the responsibility of flying personnel to regulate their professional and social activities so as to maintain this desirable state of physical and mental health.

Aircrew should be aware that when fatigued, when intoxicated, when suffering from a cold or when debilitated by illness they should not fly without first consulting a medical adviser. The need to seek such an opinion is usually self apparent when there are physical symptoms. Impairment of mental health is less readily recognised, especially by the individual who is affected. Yet it is no less important that aircrew should seek advice when troubled by undue anxiety, depression, or loss of confidence in flying ability.

Aircraft design

The prevention, or more realistically the reduction, of disorientation incidents is not solely dependent upon improving the skill and fitness of aircrew, for improvements in aircraft design can also be of value in achieving these objectives. Our concern here is not with aerodynamic design and performance, which is usually dictated by operational requirements, but rather with aspects of cockpit layout and instrumentation.

The need to position instruments and controls so that the pilot does not have to make head movements during critical phases of flight has already been discussed in the section dealing with disorientation arising from cross-coupled (Coriolis) stimulation of the vestibular receptors.

In addition to the disposition of instruments and controls, the ease with which the pilot can acquire information from aircraft instruments is of no less importance. Ideally, instruments which provide cues about aircraft orientation should be as easy to interpret as the external cues available to the pilot when flying in clear weather, and ideally, should have the same "visual strength" as these external cues. Unfortunately such instruments do not yet exist; indeed, it is doubtful if cockpit displays can ever be made as compelling as the sight of the real world. Recent advances in avionics and in our understanding of the mechanisms of visual perception should allow improved displays to be developed which will render the pilot less susceptible to disorientation when flying on instruments.

The use of the head-up-display undoubtedly assists in the transfer from external visual to instrument cues, and should reduce disorientation at such times. Likewise this display should reduce perceptual conflict in those flight situations where external visual cues are uncertain, even though the pilot is obliged by operational requirements to look outside the cockpit. However, if the head-up-display is of poor design and lacking in accuracy, clarity or reliability it may contribute to disorientation by increasing arousal or by adding to conflicts.

Living with spatial disorientation

Minor spatial disorientation, where characteristically the aviator has little difficulty in resolving the conflict between his own sensations and instrument cues, is relatively common in normal flying. Such incidents rarely provide a serious hazard though they may be an irritation and distraction to the pilot, especially when the illusory sensations persists.

Aircrew have found that persistent minor disorientation may be dispelled by making a positive effort to re-direct their attention. A call over the R/T, the re-adjustment of seat harness or the performance of routine cockpit checks have all been employed to divert attention from a distracting yet clearly false sensation such as the "leans" Other pilots have found that a quick shake of the head "topples the internal gyros" or more accurately provides a new sensory input which is sufficient to interrupt the perceptual conflict. Laboratory experiments have shown that on shaking the head the sensory threshold for inappropriate sensations of turning is raised, though it must be emphasised that head shaking is not a universal cure for disorientation. Indeed, if such head movements are made when there is angular motion of the aircraft or when under increased *g* forces, new false sensations can be engendered which are more likely to intensify than reduce disorientation.

Severe spatial disorientation where the aviator is alarmed by sensations, which are unusual either in character or intensity, are fortunately less common. When suddenly confronted with strong illusory sensations, or where difficulties are experienced in establishing orientation and appropriate control of the aircraft, the advice to the pilot is:

(1) Get on to instruments; check and cross check.
(2) Stick on instruments; do not attempt to mix flight by external visual references with instrument flight until external visual cues are unambiguous.
(3) Maintain correct instrument scan; do not omit altimeter.
(4) Seek help if severe disorientation persists. Hand over to co-pilot (if present), call ground controller and other aircraft, check altimeter.
(5) If control cannot be regained, abandon aircraft.

The last item of the list is in some respects an admission of defeat, but in fixed or rotating wing aircraft where escape is feasible, any attempt to regain control should not be prolonged to such an extent that safe escape becomes impossible. It is for this reason that due attention should always be paid to the altimeter in those situations where difficulties are experienced due to spatial disorientation.

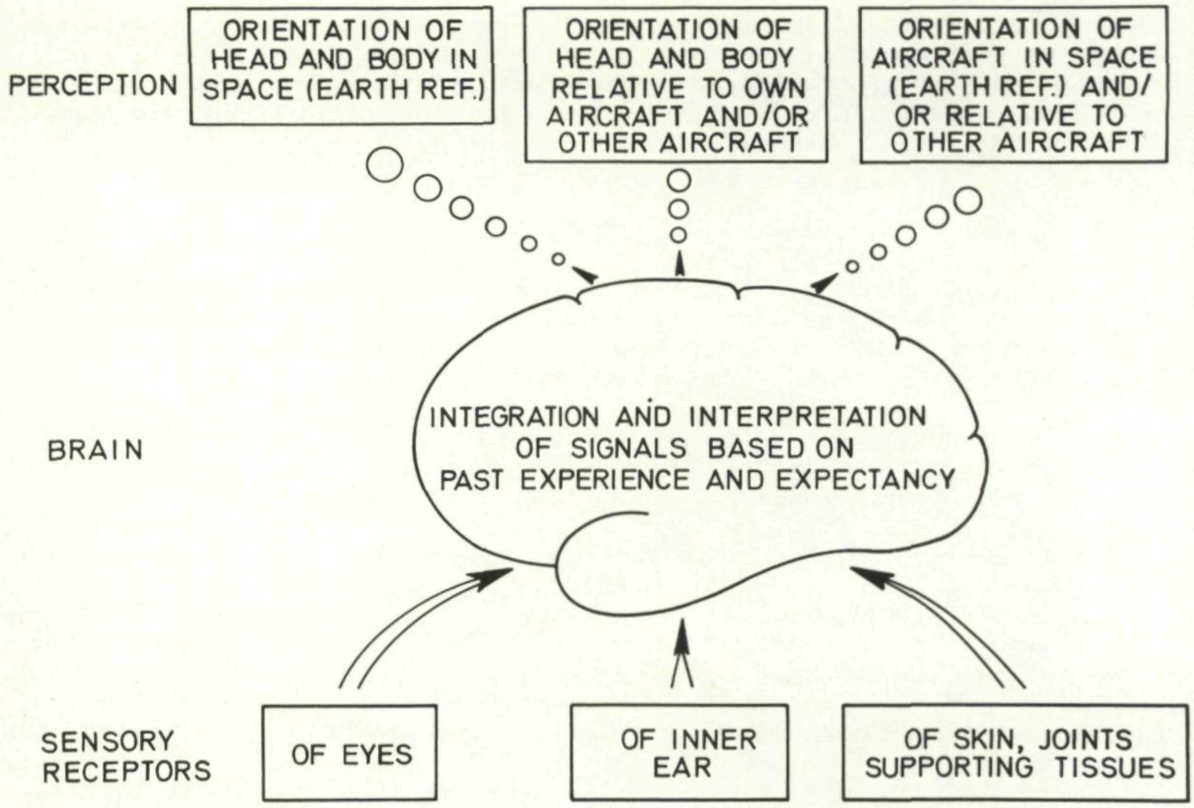


Fig.1 Diagram to show the sense organs used by man to determine his spatial orientation and components of his perception of spatial orientation in the flight environment

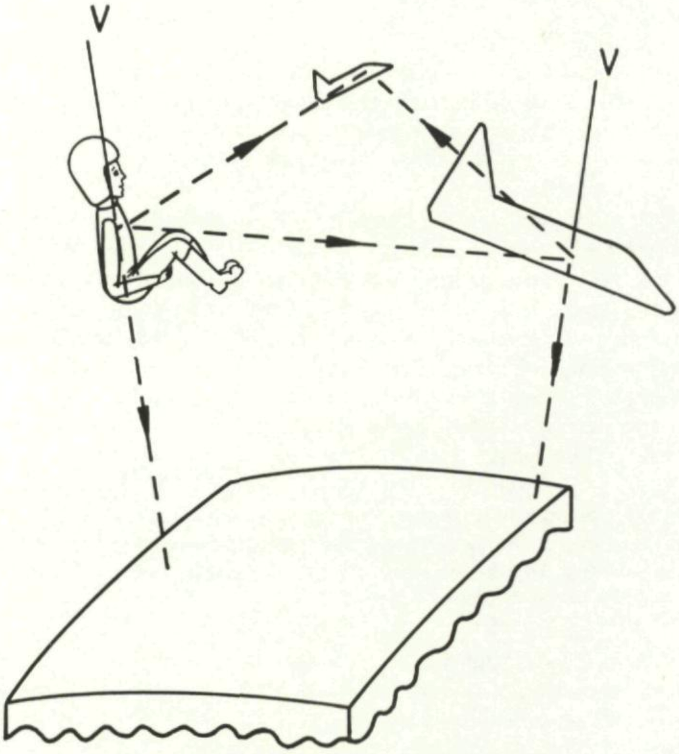


Fig.2 Spatial references used during orientation in flight. The pilot has been separated from his aircraft in order to emphasise the fact that his perception of the attitude of the aircraft relative to the gravitational vertical is determined by the aviator's perception of his own attitude relative to the vertical and the orientation of his body with respect to the aircraft. Correct orientation also depends upon the correct perception of the height of the aircraft above the surface of the earth, of the heading of the aircraft and of the projected position of the aircraft on the surface of the earth with respect to known co-ordinates.

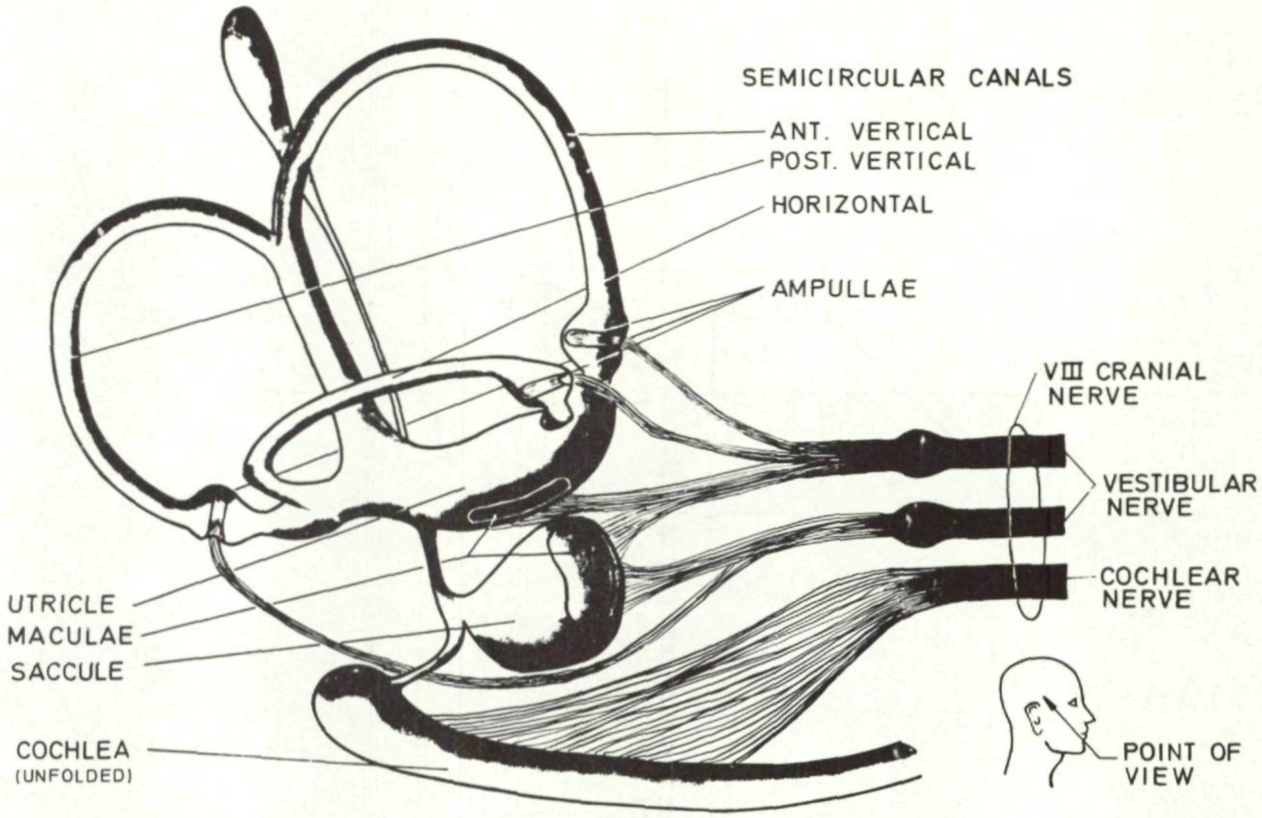


Fig.3 Diagramatic representation of the inner ear on the right side to show the relative positions of the three semicircular canals and the sac-like structures, the utricle and saccule, which house the otolith organs. The organ of hearing, the cochlea, has been unfolded and simplified. *(Crown Copyright, from Benson (1965))*

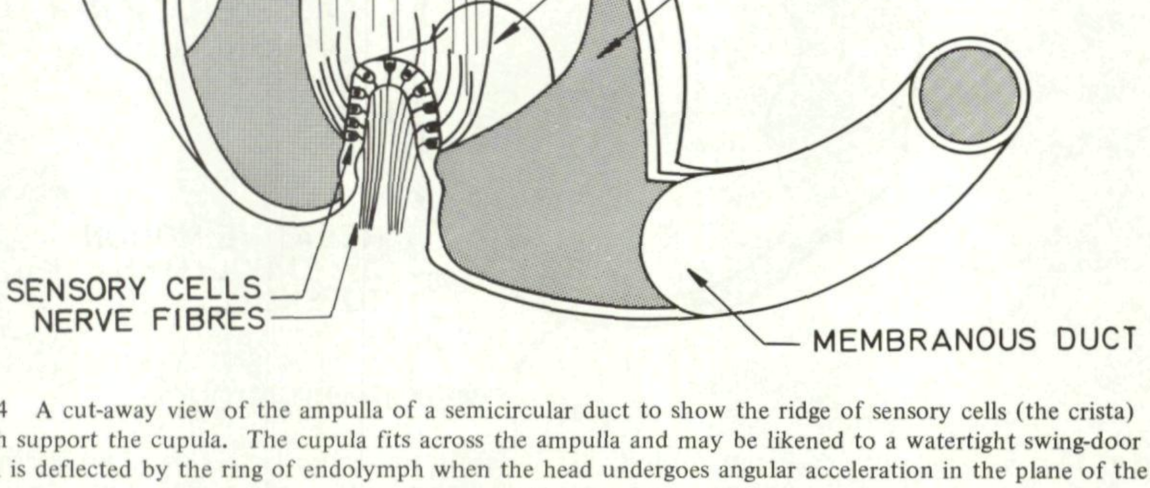


Fig.4 A cut-away view of the ampulla of a semicircular duct to show the ridge of sensory cells (the crista) which support the cupula. The cupula fits across the ampulla and may be likened to a watertight swing-door which is deflected by the ring of endolymph when the head undergoes angular acceleration in the plane of the semicircular canal (After Lindeman, 1969)

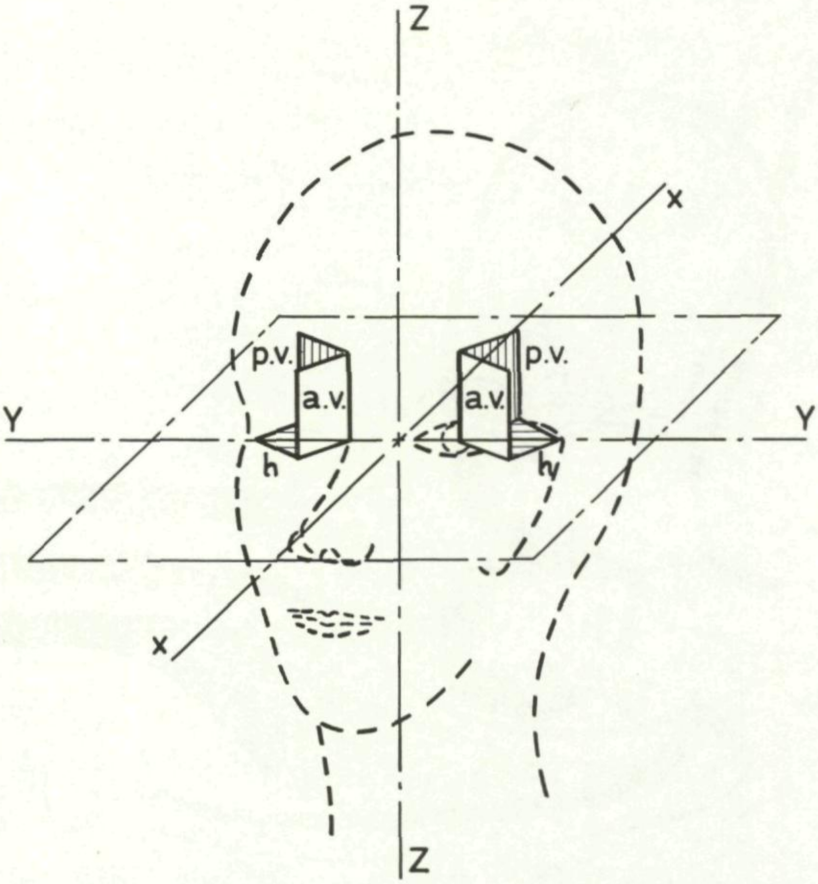


Fig.5 Diagram to show the approximate planes of the semicircular canals; *h* represents the horizontal canals, *a.v.* the anterior vertical canals and *p.v.* the posterior vertical canals. *X* , *Y* and *Z* are the principal axes of the head, the *XY* plane is horizontal when *Z* is vertical.

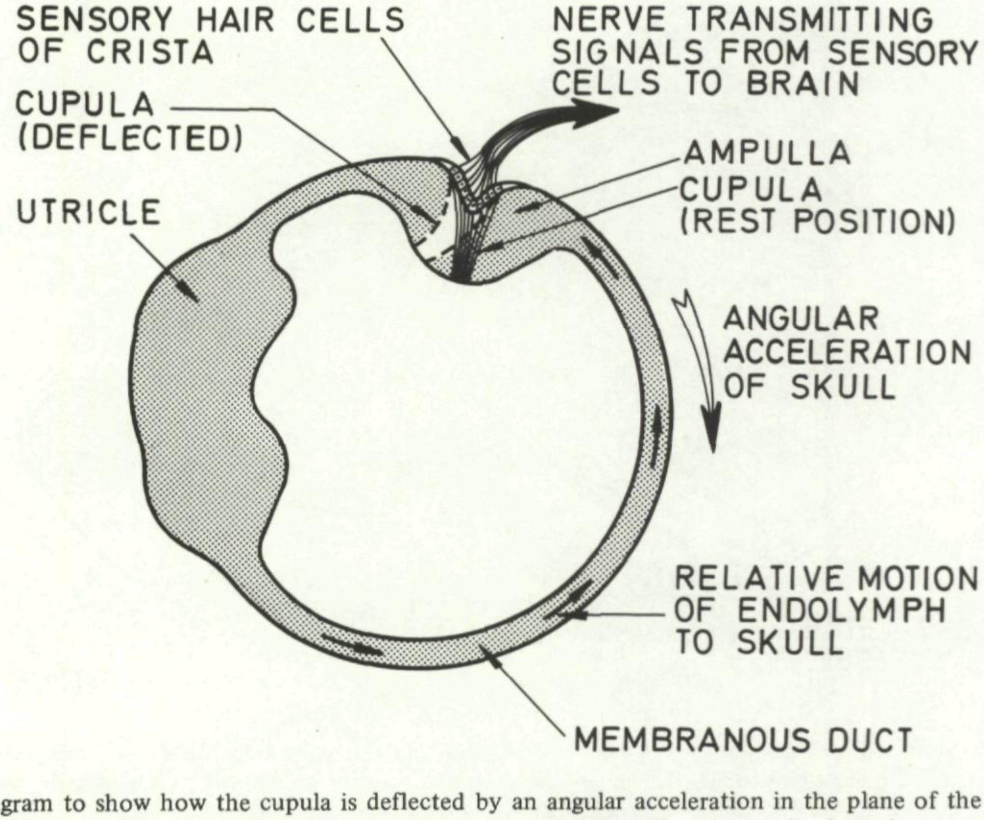


Fig.6 Diagram to show how the cupula is deflected by an angular acceleration in the plane of the semicircular duct. The ring of fluid, because of its inertia, resists angular acceleration and a force is exerted on the flexible cupula which is deflected

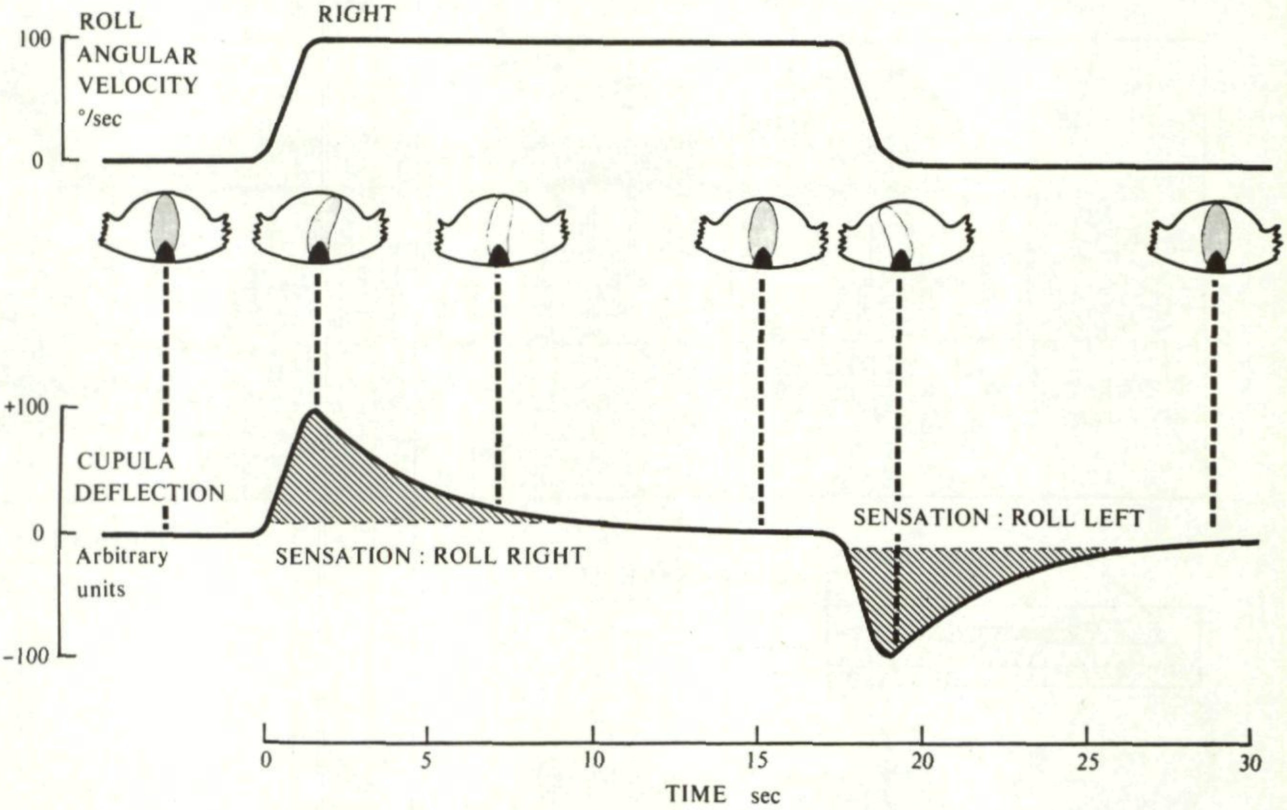


Fig.7 Response of the semicircular canal and sensations of turning during prolonged rotation. The upper graph shows the angular velocity during a sustained rolling manoeuvre. The lower graph shows the deflection of the cupula of a vertical semicircular canal stimulated by the angular motion. Note: (1) How the cupula deflection and associated sensation of turning follow the *change* in angular velocity at the beginning and end of the roll. (2) How the sensation and cupula deflection decay during rotation at constant speed and following the stimulus at the end of the rolling manoeuvre. (3) That the deflection of the cupula must exceed a threshold level before a sensation of turning is evoked.

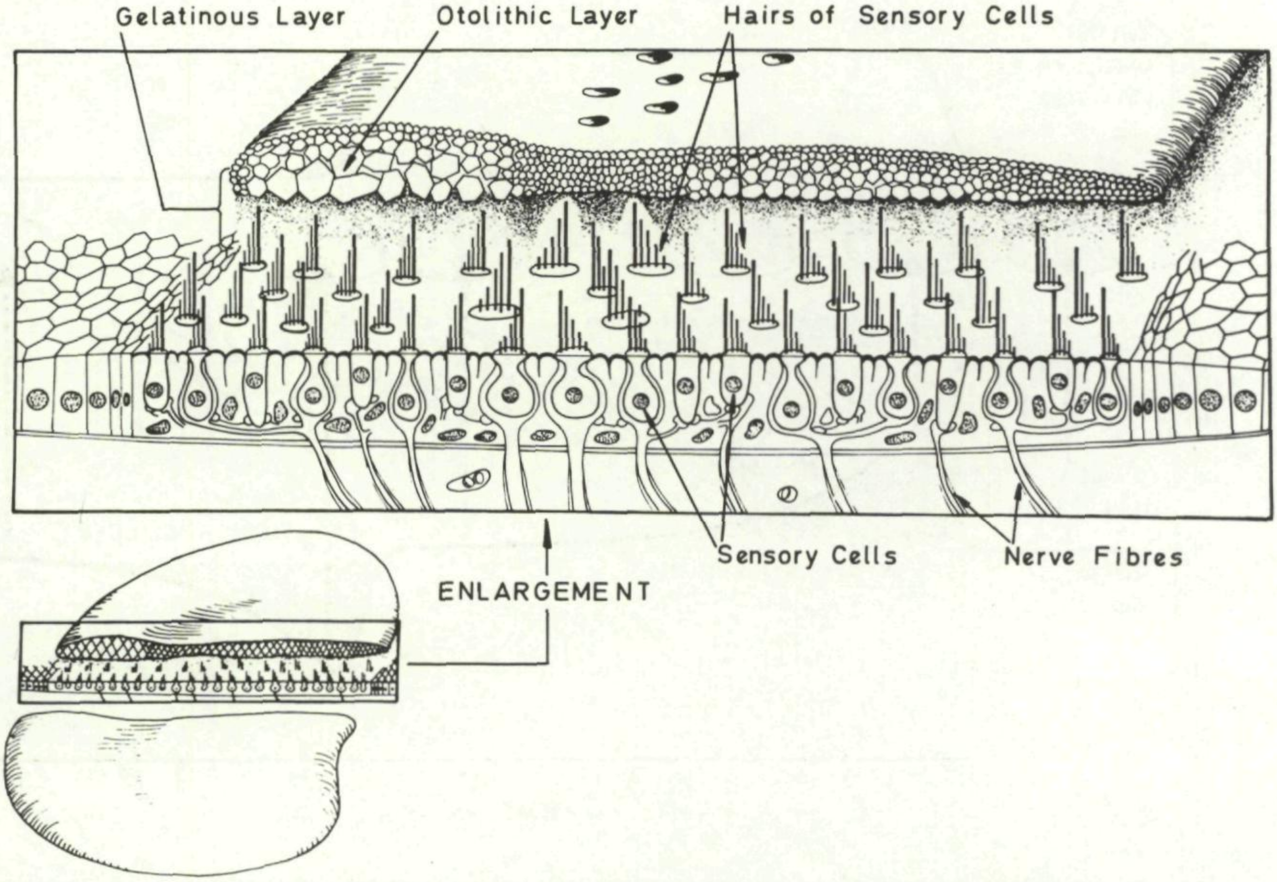


Fig.8 Diagram to show the structure of the utricular otolith organ. The lower part of the figure is a general view of the surface of the organ, the upper part of the figure shows details of the sensory cells and the irregular crystalline structure of the otolithic membrane. The saccular otolith differs in structure only in shape and in the grouping of the crystals of the otolithic membrane. (From Lineman, 1969)

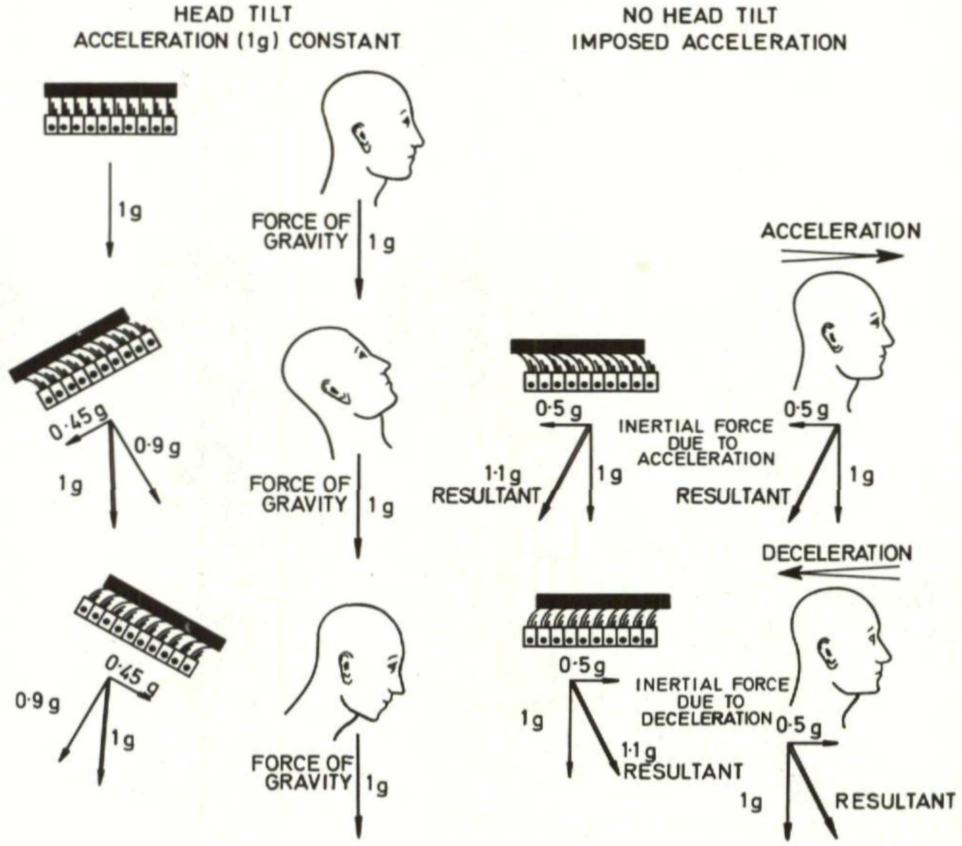


Fig.9 Diagramatic representation of the utricular otolith organ to show how the sensory cells are stimulated by displacement of the otolithic membrane (solid black) when the head is tilted in a fore-aft plane (left side of figure) and under the influence of linear accelerations in the fore-aft direction (right side of figure). Note the similarity between the deflection of the hair cells when the head is tilted backwards and during forward acceleration.

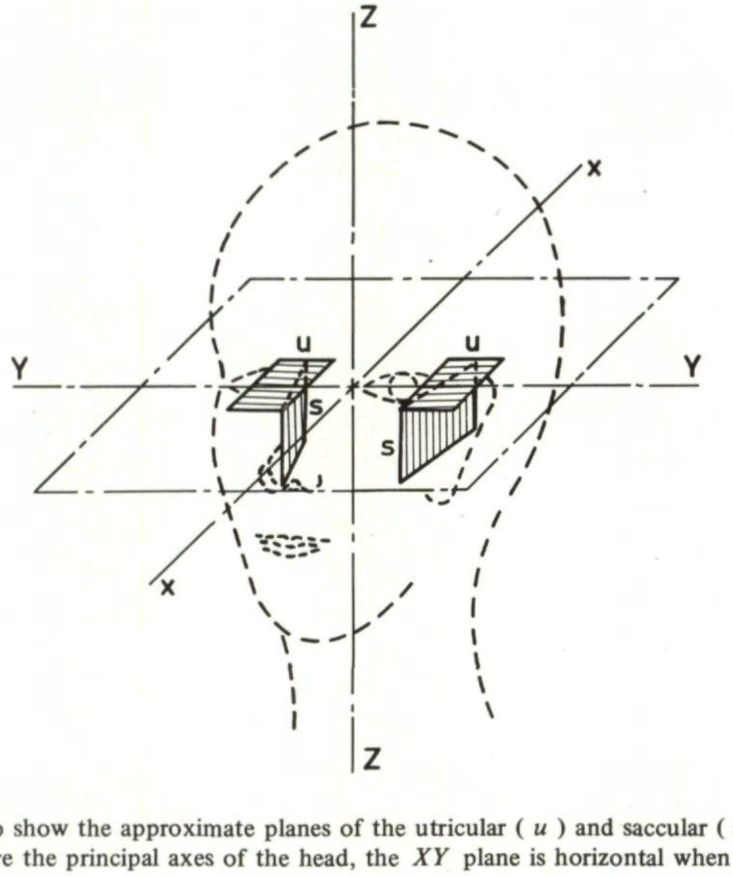


Fig.10 Diagram to show the approximate planes of the utricular (*u*) and saccular (*s*) otolith organs. *X* , *Y* and *Z* are the principal axes of the head, the *XY* plane is horizontal when *Z* is vertical.

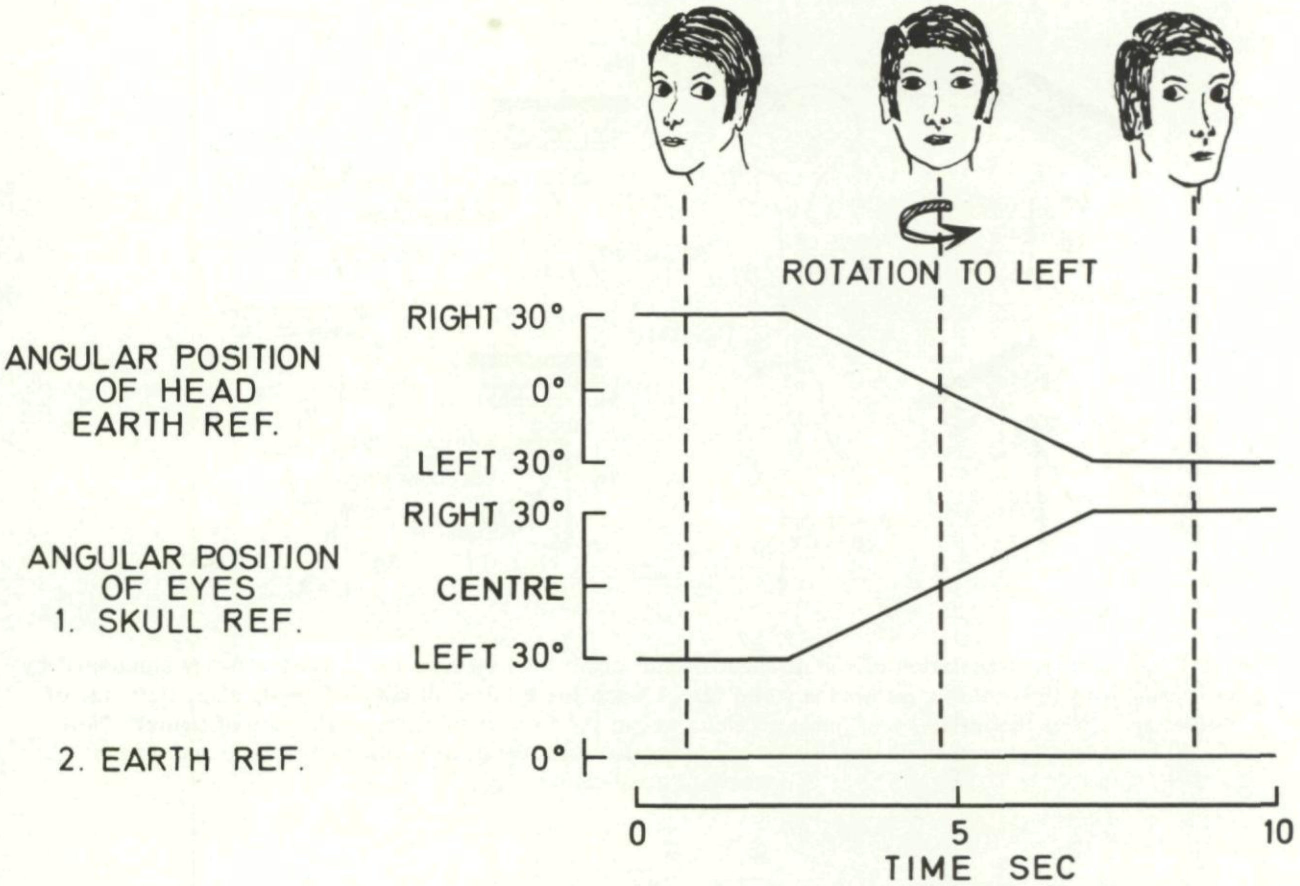


Fig.11 Stabilization of eye position during a turn of the head through 60°. The man looks at a stationary object; as the head is turned (upper graph) the eye moves relative to the head (middle graph) so that angular position of the eye relative to the target and hence the image of the object on the retina is stabilized (lower graph)

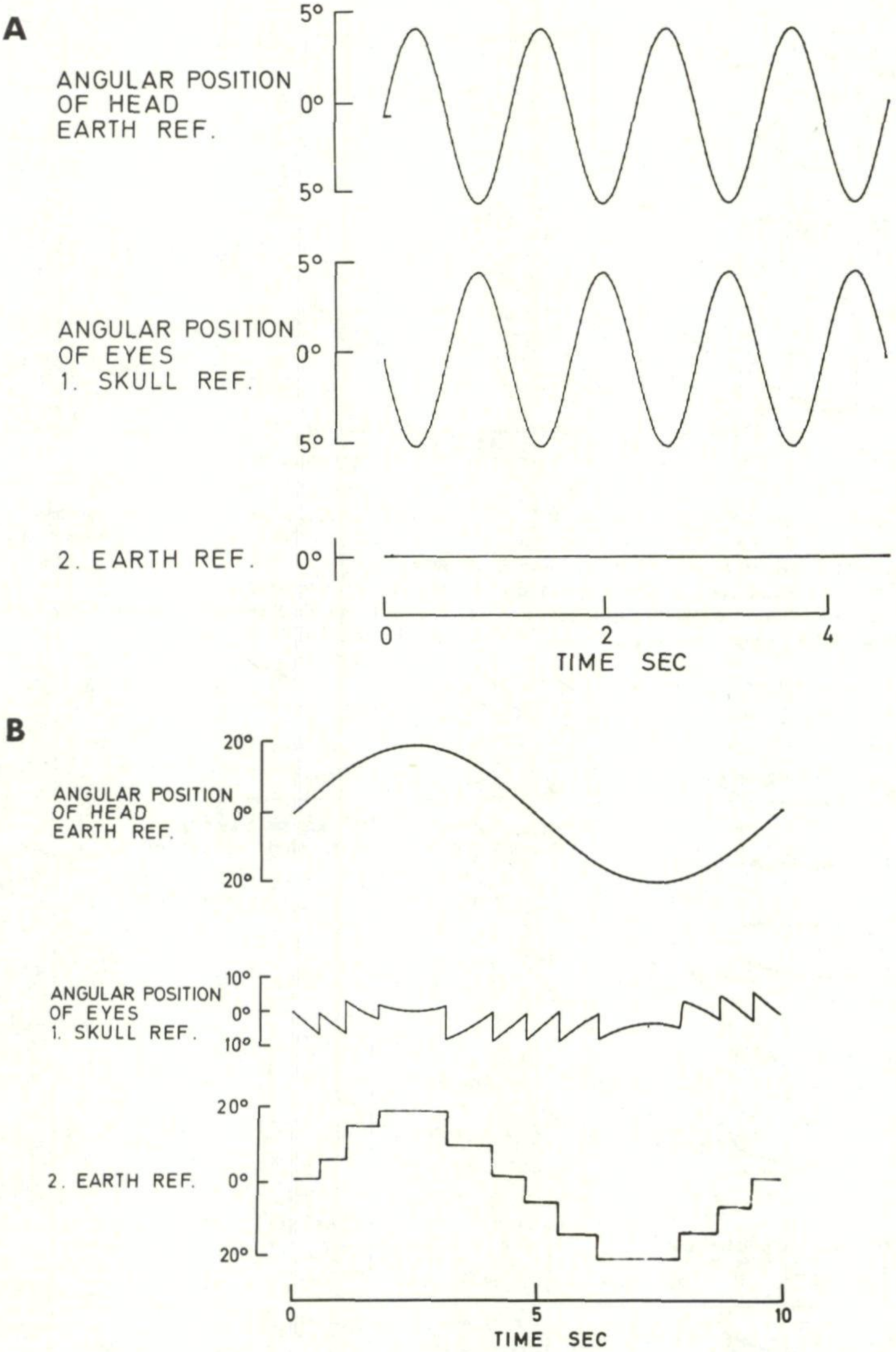


Fig.12 Eye stabilization during cyclical angular movements of the head.

A. When the head is oscillated through a small arc (10°) at high frequency (1 Hz) stabilization of the eye, with respect to a stationary object, is achieved by compensatory eye movements which precisely match the angular movement of the head.

B. When the head is moved through a larger arc (40°) at a lower frequency (0.1 Hz) the compensatory eye movement is interrupted by rapid (saccadic) beats to give the characteristic nystagmus. In this way the eye is stabilized for short periods in several spatial positions.

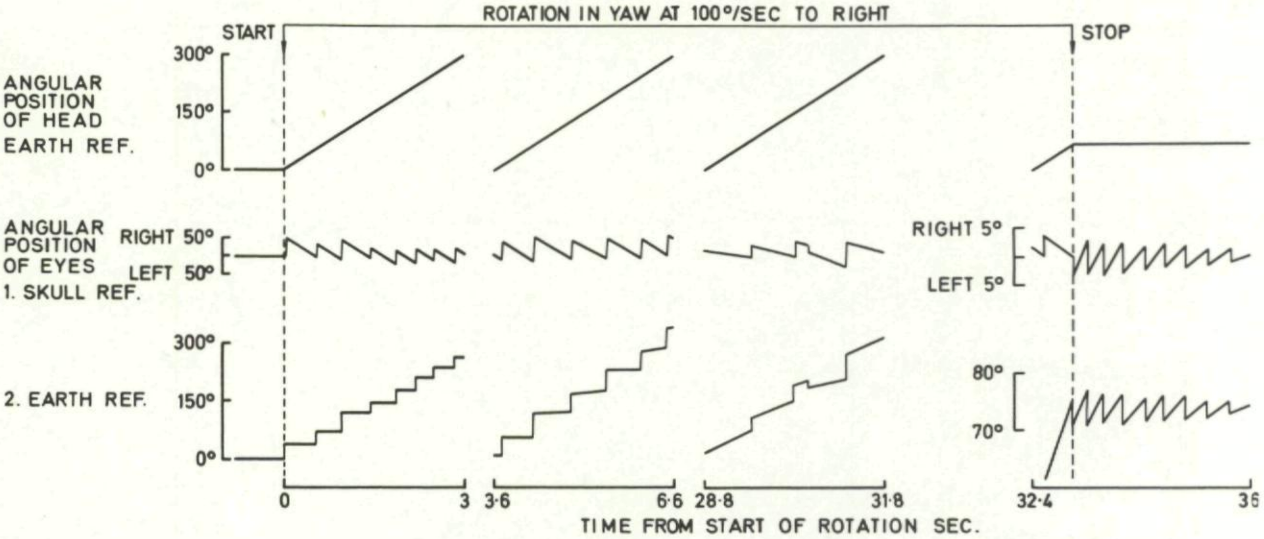
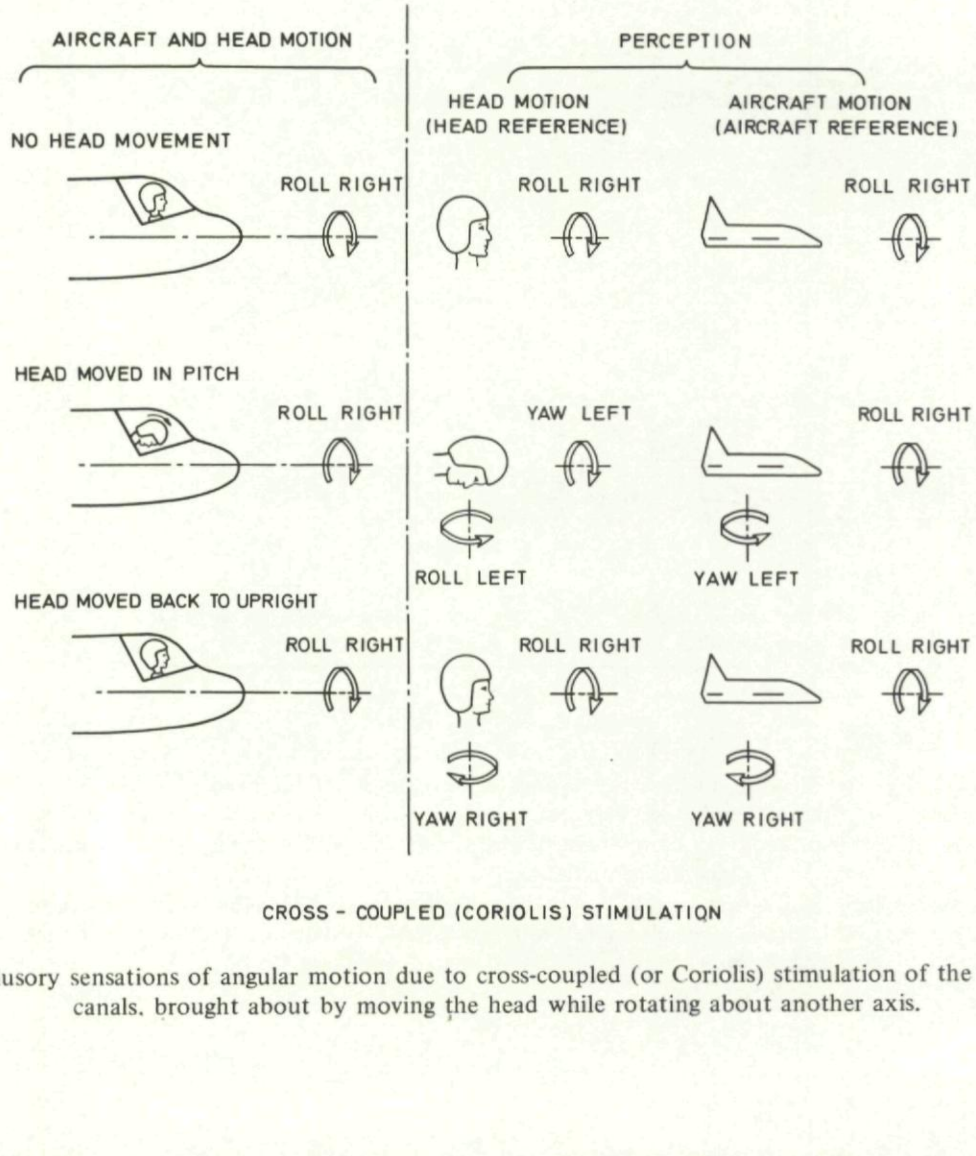


Fig.13 Eye movements during prolonged rotation (cf. Fig. 7). At the beginning of rotation the eye movements accurately compensate for the angular motion of the head; after a few seconds the signal from the semicircular canals no longer matches the stimulus and eye stabilization is impaired; after 30 seconds semicircular canal information is all but absent, the eye is not stabilized and there may be impairment of vision for objects outside the aircraft. When rotation stops, nystagmus in the opposite direction develops which though of low velocity (note change in scale) can degrade the aviator's vision for objects both inside and outside the aircraft.



CROSS - COUPLED (CORIOLIS) STIMULATION

Fig.14 Illusory sensations of angular motion due to cross-coupled (or Coriolis) stimulation of the semicircular canals, brought about by moving the head while rotating about another axis.

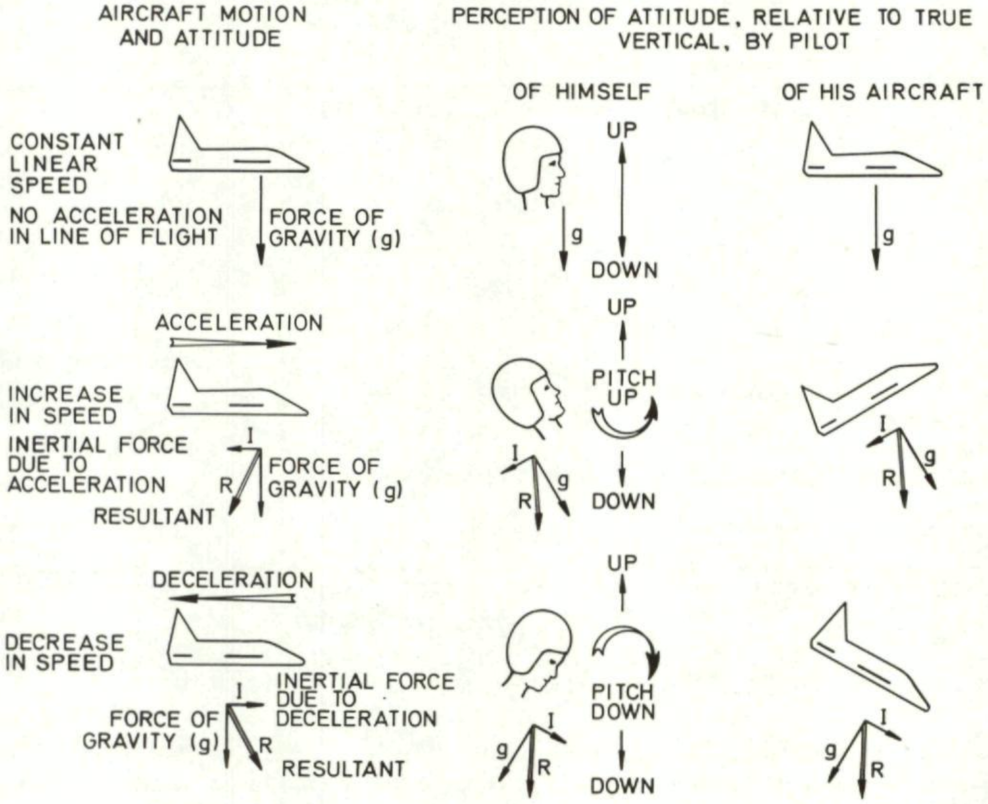
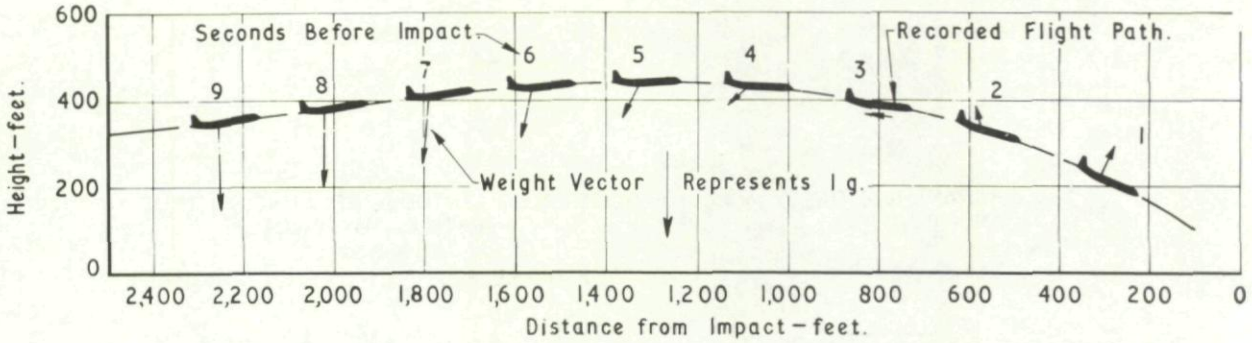
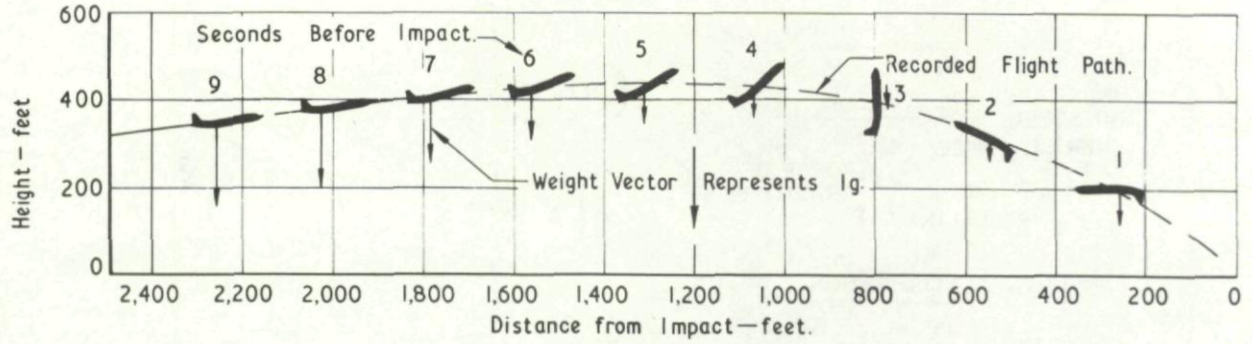


Fig.15 False perception of attitude – the somatogravic illusion – during linear acceleration, or deceleration, in the line of flight. The aviator tends to regard the resultant force vector (R) as the vertical and hence has a false perception of the pitch attitude of his aircraft.



Recorded Attitude and Flight Path.



Illusory Attitude

Fig.16 Recorded flight path and calculated force (weight) vector of an aircraft which crashed after initiating an overshoot. The initial change in the direction of the force vector was caused by acceleration in the line of flight, later the curved flight path introduced a radial acceleration and was responsible for large changes in the direction and magnitude of the force vector. Over the relatively short time scale in which changes in the force environment occurred it is unlikely that the illusory perception of attitude was as erroneous as indicated in the lower half of the figure, but illusions of the form shown have been reported during comparable bunt manoeuvres.

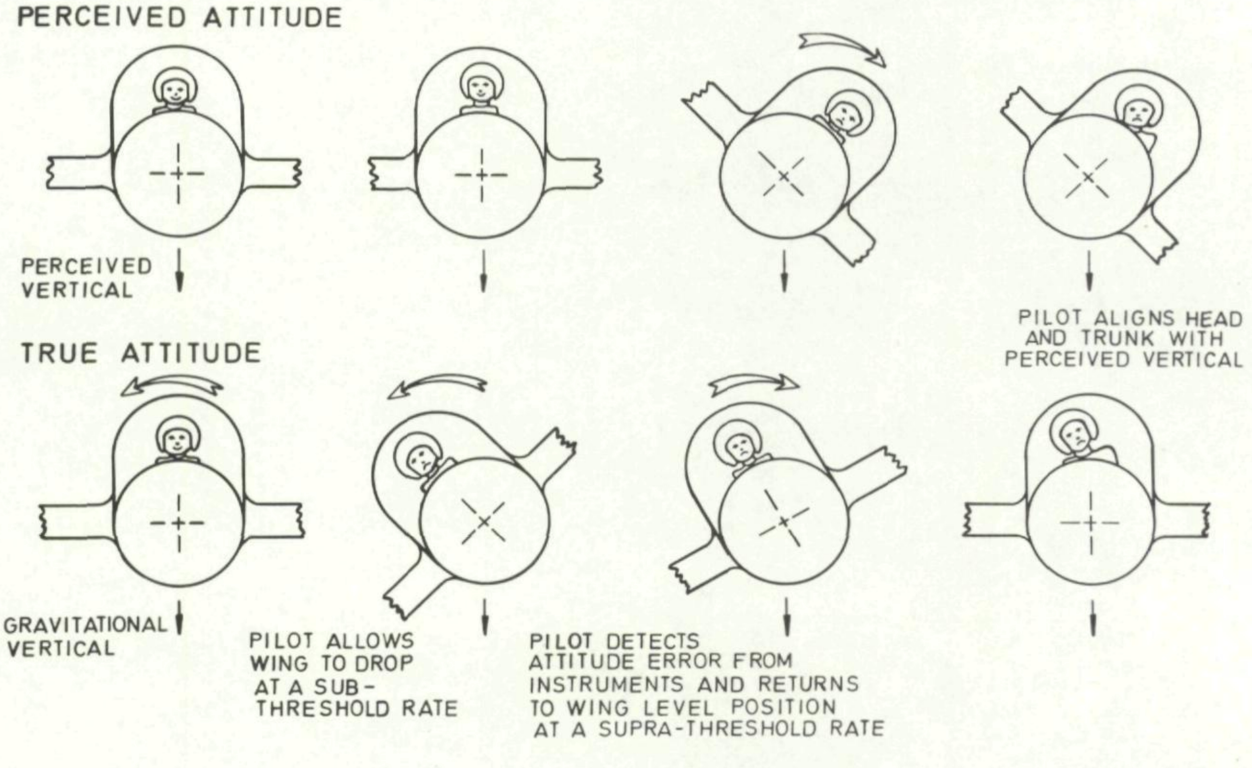


Fig.17 The leans. A diagramatic representation of one of the causes of this common illusion.

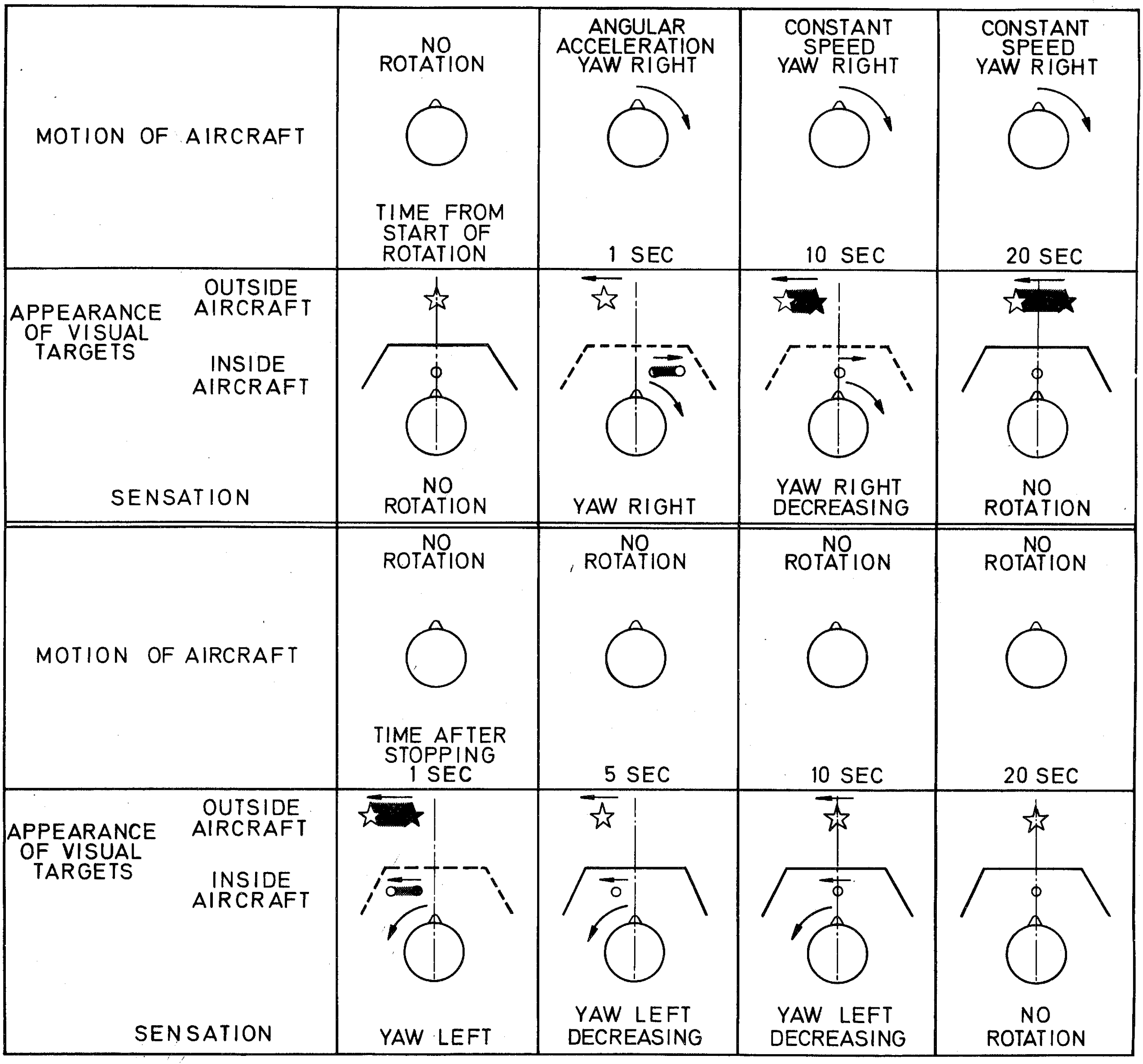


Fig.18 Visual perception during prolonged rotation at 100 – 150°/sec and on stopping. The diagram attempts to show the blurring of vision, indicated by shaded zones, of an isolated object (star) outside the aircraft and of a cockpit instrument (small circle) which rotates with the observer. The perceived motion of these targets is shown by the straight arrows and their apparent position with respect to the observer is indicated.

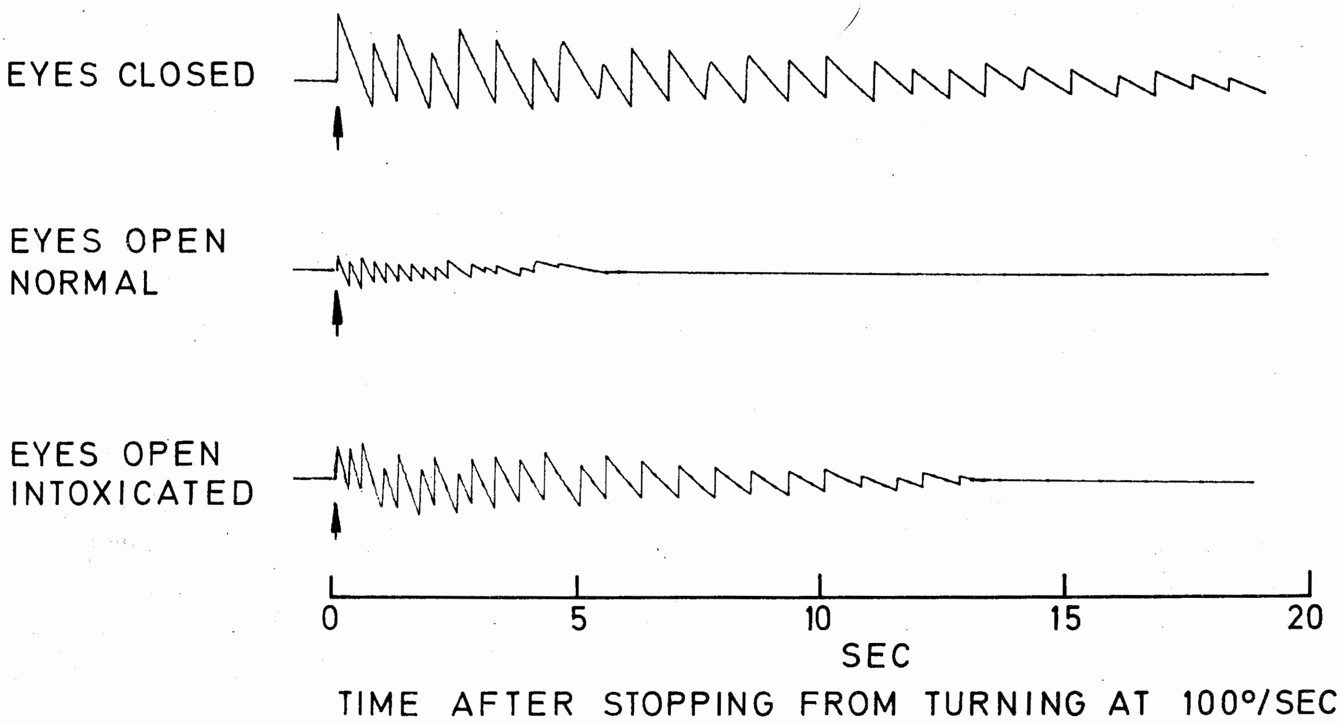


Fig.19 Alteration of post-rotational eye movements by alcohol. The graphs show the nystagmus produced by recovery from sustained rotation at 100°/sec. In the dark, or with eyes closed, the eye movements last for 30 seconds or more, but when the pilot tries to see – to fixate on – objects inside or outside the aircraft the nystagmus is suppressed, though not abolished until about 5 seconds after the stimulus. Intoxication with ethyl alcohol reduces the effectiveness of the suppressive mechanism and hence prolongs the time vision is impaired by inappropriate nystagmus.

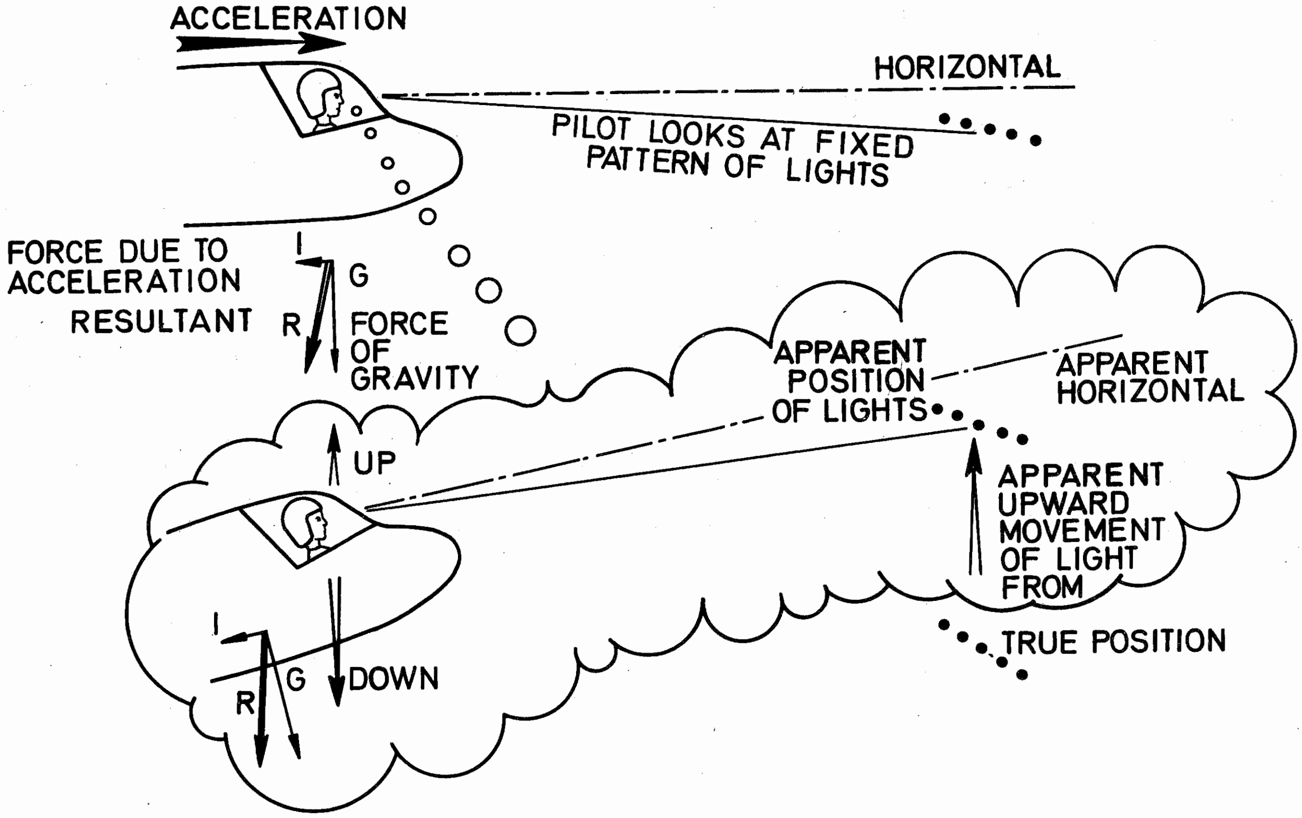


Fig.20 The oculogravic illusion. This is the visual component of the somatogravic illusion (Fig. 15) in which a change in the force environment causes apparent movement and false localization of observed objects.

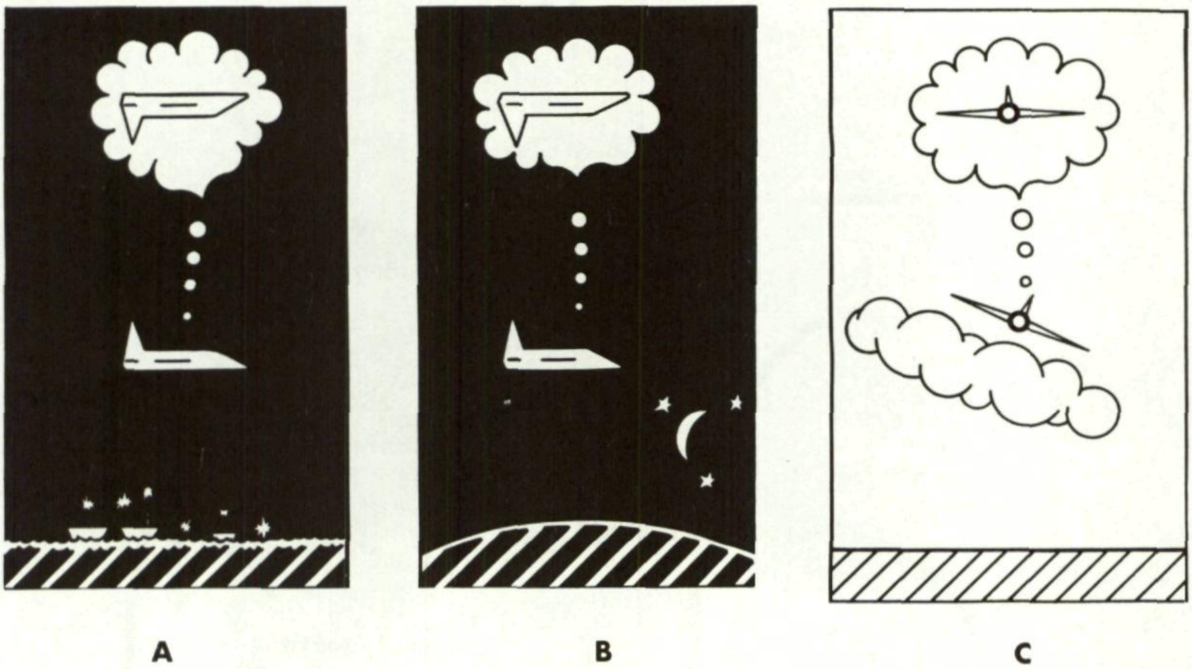


Fig.21 Diagramatic representation of illusions caused by the false interpretation of visual information.
A: Lights on the ground or on ships are thought to be stars and the pilot thinks he is inverted.
B: At high altitudes an inversion illusion can occur when the pilot sees objects, which he expects to be above him, below the horizontal.
C: The upper surface of a sloping cloud bank is used as a false reference.

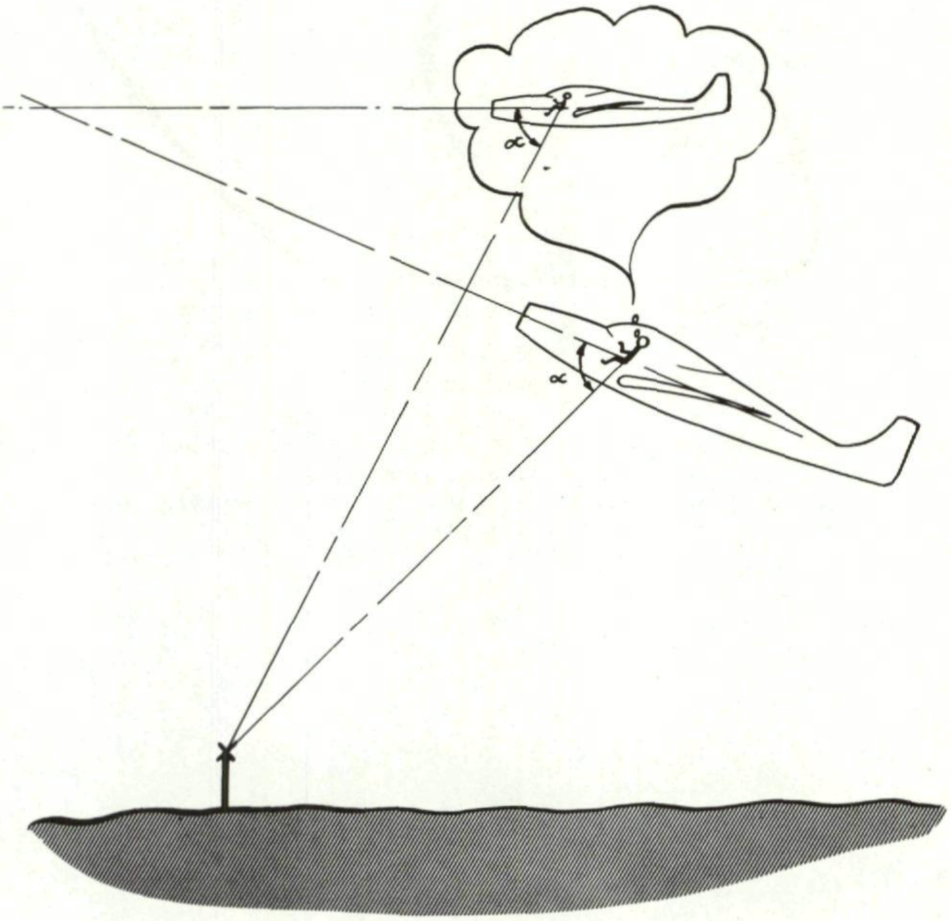


Fig.22 False perception of altitude which can occur on sighting a familiar object on the ground when there is an undetected error in attitude.
(Crown Copyright, from Benson (1965))

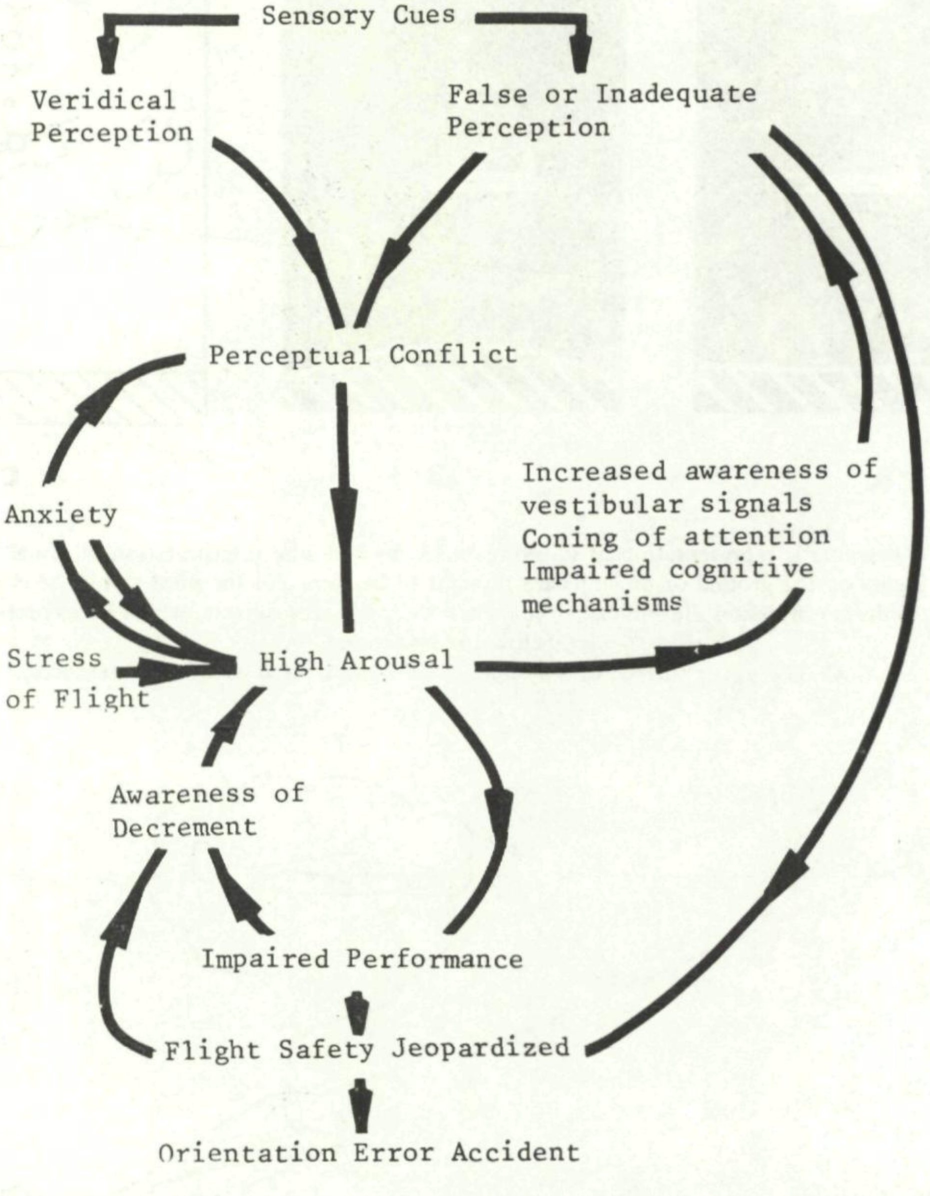


Fig.23 A conceptual scheme to show some of the vicious circle mechanisms by which spatial disorientation is potentiated.
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