CHAPTER 4

SPECIAL SENSES

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VISION

General

1. The ability to see well is a most necessary requirement in flying. The aviator relies on his eyes completely at every stage in order to see the ground, the instruments and other objects. Vision is more than just an act of seeing however, it depends on the proper utilization of the eyes and then the correct interpretation of the visual picture by the brain.

The Eye

2. The eye receives rays of light directly from luminous sources or reflected from objects and focuses them on to the retina at the back of the eyeball by means of the

cornea at the front and the lens within the eye. The impulses received on the retina are transmitted by the optic nerve to the brain where they are interpreted as a picture.

3. Each eyeball is roughly spherical, approximately 2.5 cm in diameter and lies within the bony orbit suspended in fat. It is protected against damage from all directions except at the front where protection is limited to that provided by the eyelids.

4. The eyeball is hollow and depends on its own internal pressure to maintain its shape and integrity. It is composed of three skins which are modified at the front to admit light (Fig 1). The outermost skin, the sclera, is tough, supportive and relatively free from blood vessels. It has a transparent region at the front called the cornea. The middle skin or uvea contains many blood vessels and its prime function is nutritive. At the front this middle skin becomes the ciliary body and iris, while at the rear it forms the choroid. The innermost skin is the retina which is light sensitive and in its extent corresponds to the choroid. The globe of the eyeball is divided into two main compartments by the lens iris diaphragm; a large rear compartment filled with a clear jelly called the vitreous and a smaller front chamber filled with a clear liquid called the aqueous.

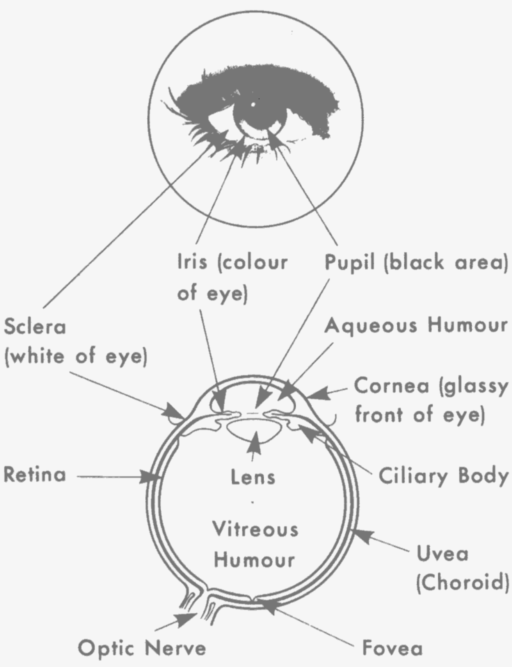

Fig 1 The Human Eye

5. It is conventional to compare the human eye with a camera, but this analogy is too simple. The eye is self-focusing; it can adjust over an enormous range of brightnesses; it is capable of fine hue discrimination; and it can distinguish detail which subtends visual angles of less than 30 seconds of arc.

6. The optical system of the eye is, however, relatively crude and its sophisticated performance is principally due to the coordination between eye and brain. The brain and the neural retina process visual information, adding and subtracting as necessary, to improve the image falling upon the retina.

Visual Function

7. It is convenient to separate visual function into its three component senses, light, form and colour.

8. The eye is capable of functioning over a wide range of luminances. The luminance of an object is a measure of its brightness: it is the product of the illumination falling on an object and its reflectance. The threshold stimulus of the eys is as low as faint starlight, and the maximum limit, where discomfort is evident, as high as bright sunlight on snow. Two mechanisms function over this range. Scotopic or rod vision operates over the lowest quarter of luminance and over this range the ability to see form is poor and vision is monochromatic. Over the remainder of the range, photopic or cone vision takes over progressively giving, with increasing luminance, the advantages of good form sharpness and the ability to discriminate colours. The transitional stage, when both rods and cones are functioning, is known as mesopic vision and corresponds roughly to full moonlight.

9. The eye requires time to adjust to varying luminances because the control is a photochemical reaction. When it adapts from dark to light the adjustment is rapid, but in adapting from light to dark the adjustment is slow. As can be seen from the dark adaption curve (Fig 2), there is not a steady increase in sensitivity. The curve is in

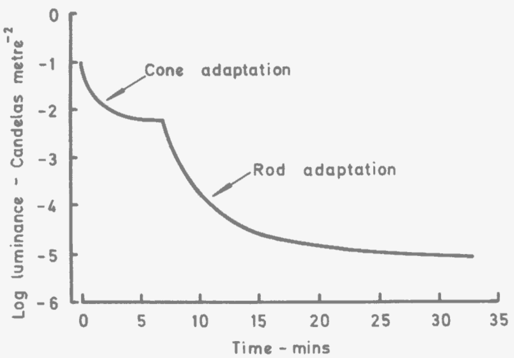

Fig 2 Dark Adaptation Curve

two portions, the initial rapid adaptation being that of the cones and the slower adaptation that of the rods. A further feature of rod and cone vision is their different colour sensitivity. Rods are most sensitive to blue/green light and cones to yellow/green light (Fig 3). This differing colour sensitivity is evident at dusk when red objects appear relatively darker and

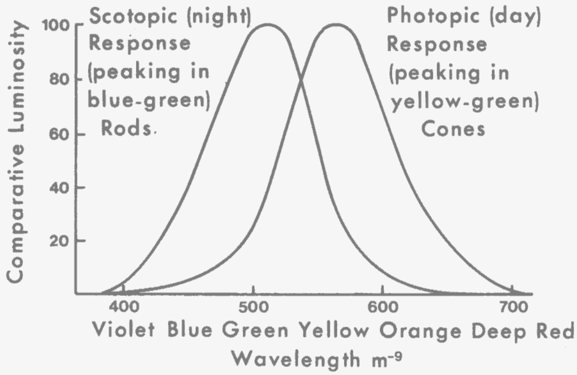

Fig 3 Rod and Cone Colour Sensitivity

blue objects retain their subjective brightness.

10. When one looks at an object it is imaged on the fovea and the surrounding macula. The fovea is a specialised region of the retina composed entirely of cones. It is where vision is sharpest and colours are most readily seen. Peripheral to the fovea the retina is composed of both rods and cones, the ratio of rods to cones increasing and visual sharpness decreasing with distance from the fovea.

11. A result of this double mechanism for light appreciation is that to detect dim lights one must look off centre. It also used to be customary to wear red goggles in lighted crew rooms and to use red cockpit lighting since rods, unlike cones, are insensitive to the longer red wavelengths. The advantage of preserving rod adaptation, is however, to a large extent illusory as few flight tasks can be performed with rod vision. In most cases the sharpness of vision given by the cones is imperative and the disadvantages involved with red cockpit lighting systems in colour discrimination, the increased focusing effort required and the distortion in the relative luminance of coloured objects outweigh any theoretical advantage.

12. A valuable feature of rod vision is its ability to detect movement as an image traverses the retina. It is useful, therefore, in search procedures at night, not to allow the rod image to stabilise within the range of involuntary eye movements but to scan the area of search in small arcs, inducing on the retina a moving image of a stationary object.

13. Under good conditions the eye can resolve detail which subtends a visual angle of 30 seconds of arc. However, under some special circumstances much finer resolution is possible. A single line may be differentiated against a plain background when it subtends a visual angle as small as 0.5 seconds of arc. This is more a measure of

contrast than of resolution, but it is important in aviation, as aircraft or wires may first be sensed by their contrast against the sky.

14. Factors which may influence the resolution of the eye are, atmospheric conditions, the optical quality and cleanliness of interposed transparencies, the requirement for spectacles and eye disease. The large pupillary diameters which occur in near darkness reduce the depth of field of the eye, rendering more evident the decrement caused by the need for corrective spectacles.

15. Recognition of targets is profoundly influenced by the inductive state of the retina. One part of the retina modifies the function of another part. This is known as spatial induction. In aviation, spatial induction will enhance the recognition of aircraft against the sky. The bright sky diminishes retinal sensitivity and a grey aircraft therefore appears darker, with a consequent increase of the contrast between the target and the sky. However, a stimulus on a portion of retina will also affect function of that portion to a subsequent stimulus. This is known as temporal induction and may reduce target recognition. If a bright object such as the sun forms an image on a portion of the retina, the sensitivity of that portion will be depressed for a considerable period of time. This may cause low contrast targets to remain unseen.

16. Visual sharpness is to a large extent influenced by contrast between target and background and by the prevailing brightness of the target. Sharpness improves with increasing luminance up to a moderate level beyond which no further increase occurs, and, at very high luminances, may be impaired. The best resolution is achieved when the luminance of the target and the ambient lighting are similar. If an aviator is placed in a dark cockpit with only a small window on the world, the resolution of bright external targets will suffer. When cockpit illumination is increased resolution improves. The converse of a bright cockpit and a dim target also impairs resolution.

17. Colour sense is a function of cones and therefore of photopic (day) vision. According to the generally accepted theory of colour vision, there are three classes of cones present at the macula, in the ratio of 1:10:10. These cones have absorption peaks at blue, green and red in the colour spectrum. A combination of these three primary colours in the correct proportions is seen as white light, and by varying the proportions and saturation (subtraction of white light) any other colour can be matched. However, at the centre of the macula there is a region called the fovea, approximately 0.5 mm in diameter, which is rod free and does not possess blue cones. As a result, if signal lights may only be seen as point sources, it is important to exclude blue as this colour may be seen as white.

Visual Function in Flight

18. There are a number of visual problems which are specific to aviation. These are outlined below.

a. *Empty Field Myopia.* During flight, particularly at night or in cloud, the external scene is often featureless. Without visual cues to attract attention the eye frequently comes to focus at a point in space perhaps 1–2 metres away, making the aviator functionally short-sighted. Should another aircraft enter his visual field it may not be seen, as objects at infinity will be blurred. It is important therefore that aircrew look periodically at objects at virtual infinity, such as wing tips, in order to relax their focus.

b. *Perception Time in High Speed Flight.* Large distances may be travelled during the time taken to perceive and react to objects appearing in the visual field. This problem may become critical in the high-speed, low-level role, especially when vibration may increase pilot stress. Table 1 lists the estimated times required for the various operations from an image falling on the peripheral retina to perception, reaction and the finish of aircraft manoeuvre.

Stage in avoidance of an object	Distance travelled in nautical miles by an aircraft flying at:		
	500 kt	1000 kt	1500 kt
(1) Time taken from image first falling on periphal retina to focused central fixation and recognition = 1.0 second.	0.14	0.28	0.42
(2) Time taken for decision and subsequent action = 2.5 seconds.	0.35	0.70	1.04
(3) Time taken for aircraft to change heading = 1.5 seconds.	0.21	0.42	0.62
Total time elapsed = 5.0 seconds.	0.70	1.40	2.08

Note: The above distances must be doubled when two aircraft, travelling at the same speed, are on a head-on collision course.

Table 1 Distance Travelled by an Aircraft whilst the Pilot is Perceiving and Reacting to an Object Approaching in his Visual Field

It is not possible to reduce these periods and indeed they may be extended under adverse conditions. When a pilot transfers his attention from scanning the external field to reading an instrument and returns to the external field, there is a time interval of up to 2.5 seconds, during which time the aircraft covers a considerable distance. This is why vital information is often presented by head up display in order that all attention need not be removed from the external scene. Less important instruments are designed, sited and lighted so that the information they give may be extracted rapidly.

c. *Dynamic Visual Sharpness*. In the previous paragraphs, where form sense was discussed, it was assumed that the object of interest was stationary. Where a target moves across the visual field the eye must track it in order to maintain its image on the part of the retina which will give the sharpest picture (the fovea). The ocular pursuit mechanism is capable of maintaining steady fixation where the angular velocity does not exceed a value of about 30° per second. At an angular velocity of about 40° per second, visual sharpness may drop to half its static value, the decrement increasing further as angular velocity increases.

d. *Depth Perception*. Both binocular and monocular cues are used to assess depth. The binocular cues of accommodation and convergence have a limited value at the visual ranges important in aviation. This limitation is largely due to the small distance between the two eyes of about 6 cm making the base of the 'rangefinder' too short. These binocular cues will only provide depth information at short ranges of up to one kilometre. Stereoscopic vision which is produced by the slightly different images of the object falling on the fovea of the two eyes, due to the separation of the eyes, also gives some depth perception out to a distance of one kilometre. Monocular cues to depth perception are:

(1) *Parallax.* Head movements cause targets which are at different distances from the observer to move in opposite directions relative to each other. The nearer target moves in the reverse direction to the head movement.

(2) *Perspective.* Converging parallels such as runways and railway lines show the recedence of these terrain features.

(3) *Relative Size.* Objects, the size of which are known, are able, by virtue of the angle they subtend, to provide information as to their distance from the observer.

(4) *Overlapping Contours.* Objects which overlap others must be closer.

(5) *Aerial Perspective.* Objects at great distances appear bluer due to the scattering of light. White lights may appear more red when seen at a distance because the red component is less subject to scatter than the blue component. This is a further reason to exclude blue signal lights in aviation.

Visual Illusions

19. The most important illusions in flight are those associated with the vestibular apparatus and these are dealt with later in this chapter. Only those illusions which are purely visual are included here.

20. **Autokinesis.** A light, such as a star or aircraft tail-light, seen against a black background, will, after a short time lapse, appear to wander in different directions. These apparent movements occur because the background does not provide sufficient information about the involuntary eye movements which are occurring. These eye movements are then interpreted as movements of the light. In modern aircraft, some degree of general lighting is usually provided which gives a visual reference.

21. **Flicker.** The flicker produced by helicopter rotors or by strobe lighting systems has been found to cause epileptiform episodes. The problem arises when the frequency is between 5 and 20 Hz, being worst at 12 Hz. Modern strobe lighting systems, which are favoured for their conspicuity, have a flash frequency of around 100 flashes per minute and are harmless.

Vision Protection Devices in Military Aviation

22. In military aviation, vision has to be protected from several possible hazards. These are given below.

23. **Solar Glare.** Glare from direct, reflected or scattered sunlight causes discomfort and reduction in visual sharpness. In transport aircraft spectacles suffice to overcome the problem but in high performance aircraft, where crews wear protective helmets, an adjustable tinted visor, integral with the helmet, provides protection against external glare and gives an undiminished view of the flight instruments. In the fully lowered position the visor is capable of cutting out all unfiltered light. The tint density of the spectacles or visor provides a reasonable compromise in attenuating high luminances without producing a significant visual decrement. The tint is neutral in order to avoid affecting colour discrimination, particularly the recognition of red warning signals. As discomfort from glare is eliminated, it is also necessary to attenuate infra-red and ultra-violet radiation in order to avoid the possibility of retinal damage. The field of view is as wide as possible and the optical and physical properties conform to carefully calculated specifications. Unapproved sunglasses may not satisfy the foregoing requirements.

24. **Protection of the Face against Birdstrike.** The hazard of birdstrike is always present during flight (both day and night) at low level. Approximately 85% of

incidents in the UK occur at altitudes below 500 ft agl, whilst only 7% occur at altitudes above 1,000 ft agl. The incidence of birdstrikes in low-level, high-speed flight is such that a strike in the cockpit area is not an uncommon emergency. Ideally cockpit transparencies should be strong enough to withstand bird impact, but the cost in weight may be prohibitive. In the absence of other forms of protection, a helmet-mounted visor made of a strong transparent material, such as polycarbonate, is essential. The visor protects all the uncovered area of the face as well as the eyes. Tinted and clear visors are incorporated in the new dual visor helmets to provide day and night protection against glare and birdstrike.

25. **Blast Protection.** During a high-speed ejection, the head is exposed to very high aerodynamic forces. These may damage the face and eyes. With the visor lowered the helmet, visor and mask are so integrated that they remain in place throughout the ejection and provide the necessary protection.

26. **Canopy Fragmentation Devices.** Where there is no reasonable certainty that the canopy can be clear of the aircraft before the ejection seat moves, explosive devices are fitted to shatter the transparencies and permit the seat and occupant to pass safely through. There have been a number of occasions in which lead spatter from the explosive charges has caused superficial damage to the face and the eyes. It is most unlikely that any damage will result if the visor is lowered and/or the eyes closed at the time of ejection.

27. **Lasers.** Lasers are devices which produce beams of monochromatic light, usually of small diameter, intense and highly collimated. The energy density within the beam only decreases slowly with increasing distance from the laser. The eye has the ability to focus the collimated beam of some lasers and to concentrate the energy into small image sizes on the retina. Thus, lasers can damage eyes at a considerable distance from the source. The applications of lasers in military aviation include ranging and target illumination. Protection is best provided by distance. Codes of practice, such as DCI BSI 4803 and STANAG 3606, give guidance on the method of calculating the Nominal Ocular Hazard Distance (NOHD) – the distance within which the laser may be hazardous. The calculation is based upon knowledge of the maximum safe corneal energy or power density for the particular laser system together with the beam divergence and maximum output of that system. The necessity for protection of a pilot from his own laser is debatable. The likelihood of a specular reflector in the range area orientated normal to the beam must be small; the probability being less than one in a million. Should a reflector be present, its reflectivity at the laser wavelength is not likely to be high. Where it is considered necessary, protection may be provided by goggles or visors with the requisite optical density at the laser wavelength.

28. **Nuclear Flash.** The fireball resulting from a nuclear explosion is capable of producing direct and indirect flash blindness and indeed may cause eye damage. By day, the small pupillary diameter and the optical blink reflex should prevent retinal burns from direct flash at distances at which survival is possible. Similarly, indirect flash blindness from scattered light within the atmosphere and the globe itself does not pose a problem. Temporary blindness from the image of the fireball is difficult to avoid, but again, at survival distances, the irradiated area is likely to be small. Even in the worst case, where the fireball is imaged on the macula, para-macula vision should allow all vital flight procedures to continue. At night, when the pupil is dilated, the situation is much worse and indirect flash blindness may deprive the aviator of all useful vision for an unacceptably long time. In short, protection against nuclear flash is only desirable by day but is vital at night. Protection devices are being developed for this purpose.

HEARING

General

29. A good standard of hearing is important to the aviator because the recognition of auditory signals is an integral part of his tasks. Audition is more than the act of passive listening and involves the interpretation by the brain of signals often embedded in background noise. The ear receives pressure variations or sound waves normally through the air and converts these into neural impulses. For the normal adult the range of vibrations within the audible spectrum is 20 Hz to 10,000 Hz although the frequency limits of the ear can vary between 2 Hz and 20,000 Hz. Within the audible range the ear is most sensitive to sounds between 750 Hz and 3,000 Hz.

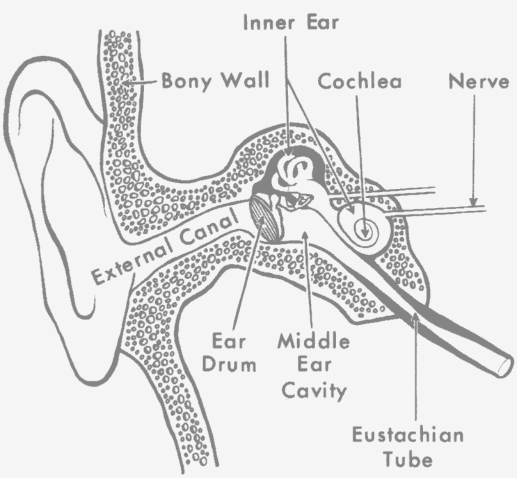

Fig 4 The Human Ear

30. The function of the hearing apparatus is to collect sound waves and convert them into nerve impulses. It consists of three main parts, the outer ear, the middle ear and the inner ear, and is shown in Fig 4. The ear drum is in the outer wall of the middle ear cavity, separating it from the outer ear. Sound waves are collected by the external ear and directed onto the ear drum which vibrates. Attached to the inner surface of the ear drum is a system of three small bones, lying in the air-filled cavity of the middle ear, which condition the vibrations and transfers them to the fluid-filled inner ear. The air-filled cavity of the middle ear is vented via the Eustachian tube and temporary hearing loss can occur when there is pressure difference between the middle and outer ear, as may be caused by descent from altitude. *See* Chap 2, para 37 *et seq.* A common cold or respiratory infection can cause the Eustachian tube to become blocked. A climb or descent in this condition can result in rupture of the ear drum. This is one reason for not flying with a cold. It is the part of the inner ear known as the cochlea which transduces vibrations into nerve impulses, essentially performing a frequency analysis of the sounds.

31. One percent or more of the total power output of a jet engine is in the form of noise, ranging from the lower limits of audibility to ultrasonic oscillations. Sound intensity is measured in decibels (dB) (a logarithmic measure of the ratio of the measured sound intensity to a reference sound intensity). A logarithmic formula is used to avoid an excessively large scale since the range of responsiveness of the human is very large. The noise levels in decibels of certain familiar sounds are given in Table 1. An increase of 3 dB represents a doubling of sound intensity.

32. Intense sounds or noise can induce temporary hearing loss and produce ringing in the ears when the noise ceases although recovery from this is fairly rapid. The extent of temporary loss is related to the frequency of the sounds, their intensity and duration. In temporary hearing loss the reduction of sensitivity is at frequencies higher than those of the stimulating noise. A noise at one intensity will produce the same temporary loss of hearing as another noise at double the intensity if the duration of the former sound is double that of the latter. Noise-induced loss is not normally induced by sounds below 90 dB. If noise levels that induce temporary loss are experienced reg-

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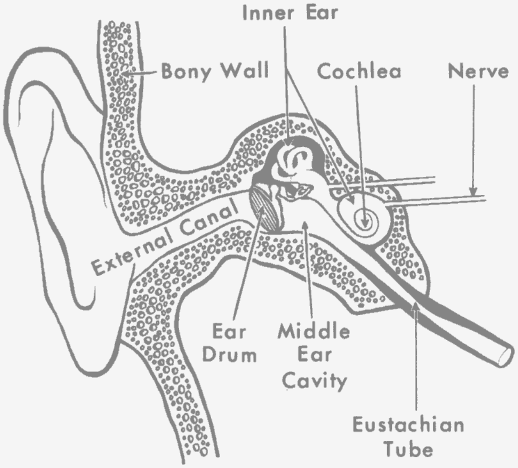

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Intensity in Decibels	
140	Turbojet at 50ft.
	Jet takeoff at 50ft.
120	Inside low level fighter
	Large jet landing at 50ft.
	Inside helicopter
100	
	Pneumatic drill
80	
	Street corner traffic
	Normal speech at 3ft.
60	Office
	Living room
40	Library
20	
	Broadcasting studio
0	Reference value

Table 2 Noise Levels of Familiar Sounds

ularly over a period of years, then permanent loss of hearing is likely. Permanent loss is observed at the higher frequencies with a pronounced loss at 4,000 Hz. Permanent loss of hearing can be allayed by keeping the noise dose within specific limits. Very intense sounds can invoke special responses even in a short time. At 120 dB localized discomfort in the ear is experienced, 140 dB produces pain in the ear and the ear drum may be ruptured at levels of 160 dB.

33. Sounds and voices are normally perceived within a background of unwanted noise. Sounds of similar frequencies interfere and make hearing difficult. To offset the effects of this masking it is necessary to have the signal at a greater intensity than the background noise: a difference of 15 dB will ensure accurate recognition and as the difference increases so will recognition accuracy. The rate of decrease of recognition with the difference between signal and background noise can be minimized by the use of familiar, meaningful or predictable signals.

34. The noise inside a jet aircraft is generated by four sources: the jet efflux, boundary layer noise, subsidiary systems like cabin conditioning and communications, and special sources such as armament discharge. These four sources combine to produce different noise pictures for different aircraft types. The fast jet will show a flat noise spectrum with a high proportion of boundary-layer noise whereas a rotary-wing will show high noise at the low frequencies because of the rotor and blade mechanisms. The wearing of properly fitting headgear is very important because helmets can attenuate the impinging noise considerably. Minimizing noise levels not only safeguards hearing but it also reduces the stress caused by high noise levels. Work in high noise levels produces fatigue, irritation and an accompanying risk of accident, though there are wide individual differences in the stress reaction to noise. People not directly involved in aviation are most likely to be disrupted by aircraft noise and so it is important that as much as possible of the ground running of aircraft is done away from buildings housing such personnel. Additionally it is valuable to protect buildings in aircraft movement areas by such means as double glazing of windows. Individuals who, by nature of their work, are required to be in high noise fields must be suitably protected by means of personal noise-excluding ear protectors.

THE SENSE OF BALANCE

General

35. Unlike vision and hearing, man is usually not aware of the constant barrage of information coming from the specialised

organs of balance in the inner ear which signal movement of the head and its orientation (attitude) to the earth's gravitational force. It is only when these sense organs are stimulated by unusual patterns of linear or angular motion, as in flight, or when their function is disturbed by disease, that the signals from these receptors give rise to disturbing sensations.

The Vestibular Apparatus

36. The inner ear is made up of the cochlea (the organ of hearing) and the vestibular apparatus (the organ of balance). The labyrinthine structure of the vestibular apparatus is shown diagrammatically in Fig 5. It consists of three thin walled tubes – the semicircular canals – disposed in planes approximately at right angles to each other. These communicate with sac-like structures called the otolith organs (utricle and saccule). The whole system is filled with fluid and is tethered within a bony cavity at the base of the skull. The vestibular apparatus on one side of the head is a mirror image of that on the other side.

a. *Semicircular Canals – Transduction of Angular Motion.* In each semicircular canal there is a swelling where the sensory cells are located. Sensory hairs from these cells pass into the substance of a gelatinous flap (the cupula) which lies across the bulge (or ampulla) of the canal (Fig 6). An angular acceleration in the plane of the canal causes a deflection of the flap, because its motion is resisted by the inertia of the ring of fluid. Deflection of the flap bends the sensory hairs and produces a corresponding alteration of the neural signal which is transmitted to

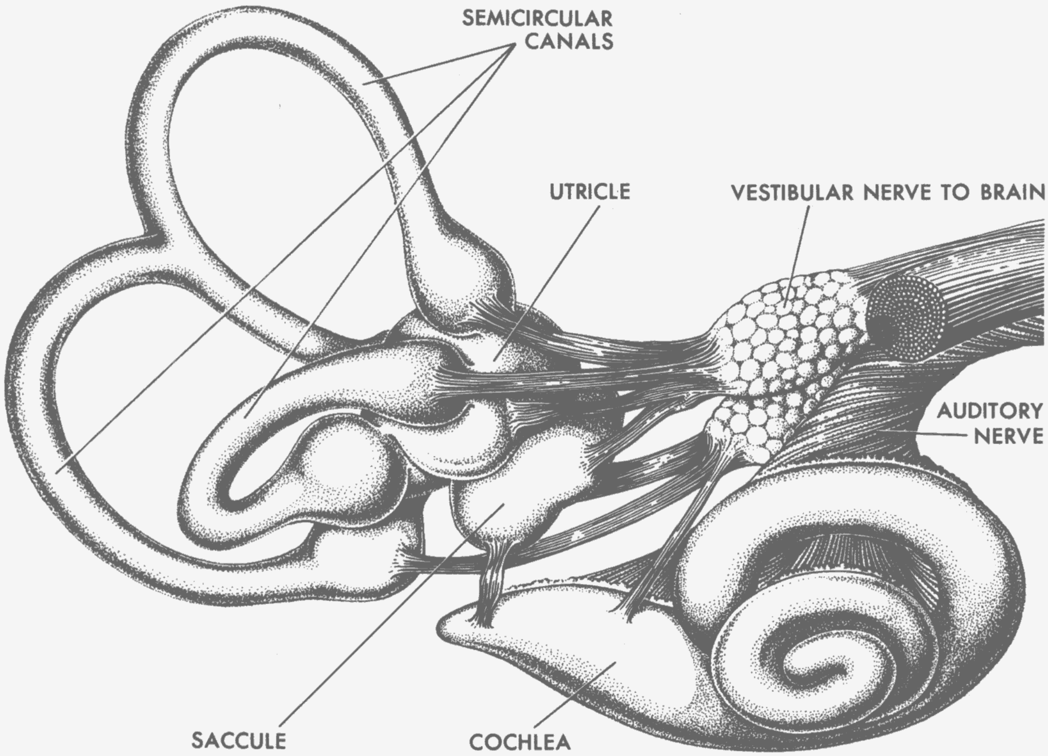

Fig 5 The Vestibular Apparatus

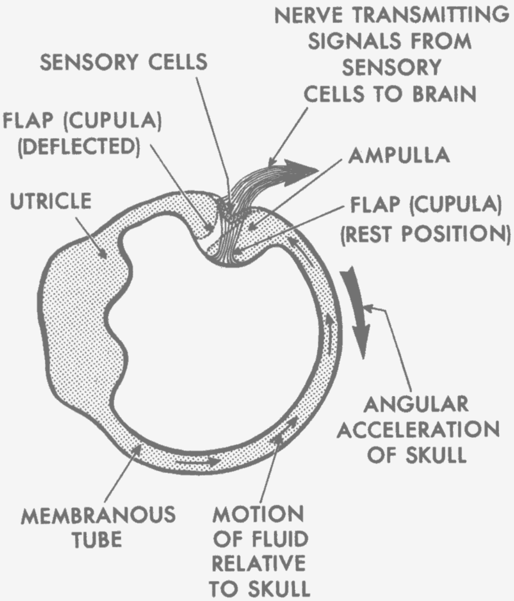

Fig 6 Section of Semicircular Canal

the brain. Although the receptors of each semicircular canal are stimulated by an angular acceleration, in the normal course of events the signal transmitted is more closely related to head angular velocity (ie rate of turn) than angular acceleration, because the dynamics of the organ are such that it acts like a leaky integrator of angular acceleration. The flap has the same density as the fluid in the canal and so it is not deflected by linear accelerations.

b. *Otolith Organs – Transduction of Linear Motion*. The otolith organs (Utricle and Saccule) each house a plate-like congregation of sensory hair cells covered by a gelatinous layer that carries in its free surface a 'frosting' of calcium carbonate crystals (Fig 7). The density of this mineral is more than twice that of the fluid which fills the system so it behaves as an inertial mass restrained and supported by the hairs of the sensory cells. Accordingly, a linear acceleration acting in the plane of the otolithic plate deflects the hairs and alters the neural signal from the sensory cells. The otolithic plate, unlike the cupula of the semicircular canal, is not heavily damped so it conveys information to the brain about the magnitude and direction of linear accelerations and rate of change acceleration (jerk), experienced by the head. Like any man-made linear accelerometer, the otolith organs are influenced both by their orientation to the Earth's gravitational acceleration (the gravitational vertical) and by applied linear accelerations, and like the ball in the turn and slip indicator, they indicate the direc-

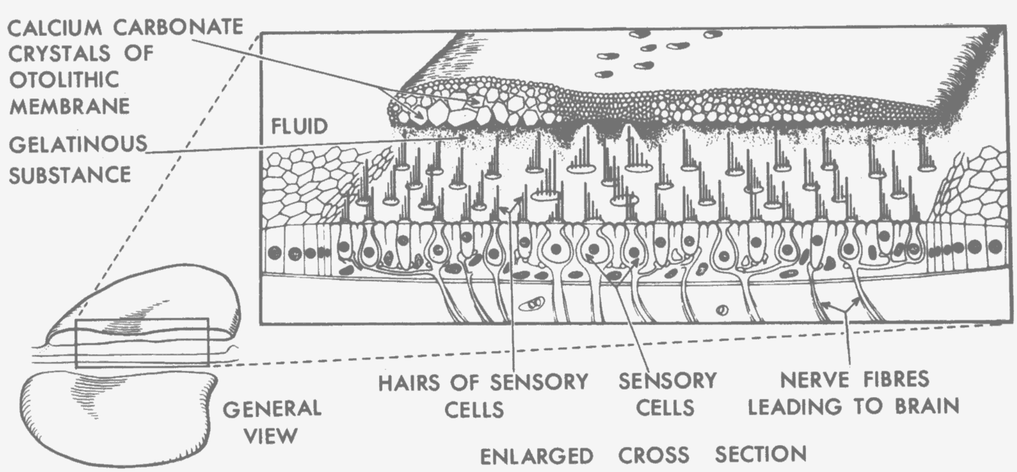

Fig 7 Section of an Otolith Organ

tion of the resultant force vector. The configuration of the four otolith organs allows man to sense the direction and magnitude of a resultant linear acceleration in any axis.

Orientation on the Ground and in the Air

37. Man's ability to determine his position, attitude and motion (ie his spatial orientation), with respect to a reference system provided by the Earth's surface and the gravitational vertical, is dependent upon sensory information provided by the eyes, by the organs of balance and by other receptors in the skin, joints and muscles which are stimulated by forces acting upon them (Fig 8).

a. *The Eyes*. Both on the ground and in the air the visual sense is pre-eminent, for it provides a wealth of information about position, attitude and movement of the head in relation to the fixed external environment. Even when external visual references are absent, as when flying in cloud, the only reliable information is visual and comes in symbolic form from the flight instruments.

b. *Other Sensory Systems*. On the ground man can maintain his balance and his orientation to gravity in the absence of vision because of information provided by the vestibular apparatus and by the more widely distributed pressure and movement receptors located in the skin, muscles, capsules of joints and supporting tissues. The dynamic range (sensitivity and frequency response) of these receptor systems is nicely matched to the angular and linear motion stimuli which occur during normal activities, (like walking and running) in a stable normogravic *(1g)* environment. However, in the flight environment man can be exposed to patterns of angular and linear motion which are outside the functional range of these non-visual sensory systems. Consequently, they may either fail to give adequate information or they may give erroneous information and lead to disorientation. Without visual cues, sustained manual control of the attitude and flight path of an aircraft is impossible.

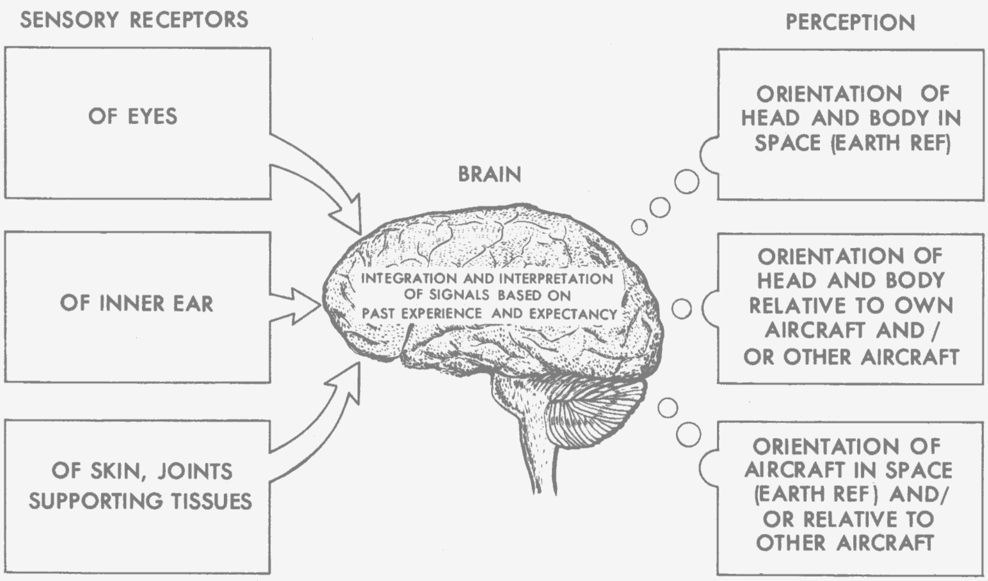

Fig 8 Orientation

Despite these inadequacies, the vestibular and other acceleration sensitive receptors do provide the aviator with information about the onset of motion that can aid aircraft control, because the movement is sensed with less delay than the change of position of an external visual reference or an instrument display.

Spatial Disorientation in Flight

38. There are several reasons why the task of maintaining correct spatial orientation in flight is more difficult than when on the ground. These may be summarised:

a. In flight, angular and linear motions differ in intensity and duration from that to which man is functionally adapted.

b. The aircraft operates and has to be controlled in 6 degrees of freedom (3 linear and 3 angular), while on the ground man generally operates only in 5 degrees of freedom and is in contact with a stable reference.

c. The appearance of the external visual world can be difficult to interpret especially when visual cues are sparse or unfamiliar.

d. When instrument references are employed, the cues are symbolic and separate; integration and interpretation of such information is more demanding than when unambiguous visual references are employed. For example, a glance at the visual horizon frequently enables a pilot to assess the attitude of the aircraft in all three planes but he needs to look at two separate instruments, the attitude indicator and the heading indicator, to obtain the same information when the visual horizon is obscured.

39. False sensations (or perceptions) of attitude, position or motion are a common experience of flying personnel and are a quite normal manifestation of the limitations of sensory function and information processing. Usually the aviator is aware that the sensation he is experiencing is false (ie it is illusory) because it is contradicted by correct information about aircraft orientation provided by the flight instruments. More rare, though much more serious, are those incidents in which the pilot is not aware that his sensations are incorrect and bases his control of the aircraft on a false perception. This implies that control is lost, or at least is inappropriate, and so flight safety is jeopardised.

40. Many different kinds of erroneous sensations and perceptions, falling within the broad definition of spatial disorientation, have been reported and there are a variety of causes. Some of the more common types of disorientation are described and explained below.

a. *Failure to Sense Changes in Aircraft Orientation.* Changes in aircraft attitude and flight path can occur which are below the threshold detection level of the non-visual sensory systems. Thresholds are dependent upon the intensity and duration of the motion stimulus. When it is prolonged, ie, more than 20 sec, then acceleration is the important variable. Average figures are $0.3°/sec^2$ for an angular movement and $0.1\ m/sec^2$ (0.01g) for a linear movement. When the movement is more transient, ie 10 sec or less, detection is determined by the change in velocity that occurs; typical values are 1.5°/sec for angular and 0.3 m/sec for linear motion. These figures come from laboratory studies in which the subject's task was only to detect motion. In flight, many other factors and sensory stimuli compete for the aviator's attention, and so changes in attitude or velocity substantially greater than these 'threshold' values can occur without being detected. In the absence of a visual reference, aircrew can, on occasion, be quite unaware of an extreme change in attitude.

b. *False Sensations of Angular Motion.* These are caused by:

(1) *Sustained Rotation.* In general, misleading sensations of angular motion are due to dynamic limitations of the semicircular canals which, as noted earlier, are imperfect transducers of angular velocity. The time constant of the leaky integration of angular acceleration is about 5–10 sec, thus at the beginning of a rotational movement (such as a turn or a spin) the change in angular velocity is correctly transduced, provided it exceeds the threshold value. However, once a steady rate of turn is achieved, and there is no longer any angular acceleration, the deflected flaps of the canals in the plane of the motion slowly return to their rest position and the associated sensation of turn dies away (Fig 9). Provided there is no appreciable change in angular velocity, the turn can continue without any sensation of turn being evoked. Recovery from the turn is associated with an angular acceleration in the opposite direction to that on entering the turn. The cupulae are deflected from their rest position and will erroneously signal rotation in the opposite direction, at a rate commensurate with the change in velocity that has occurred. This false sensation decays somewhat more quickly than the decay of the correct sensation during the initial phase of the turn, but whilst this is happening the presence of inappropriate eye movements induced by the vestibular stimulus can degrade vision and impair the pilot's only reliable source of information. The intensity of these post-rotational effects is a function of the duration of the rotational manoeuvre and of the angular velocity achieved; accordingly, disorientation is most likely to be a problem on recovery from prolonged, high-rate rolling or spinning manoeuvres.

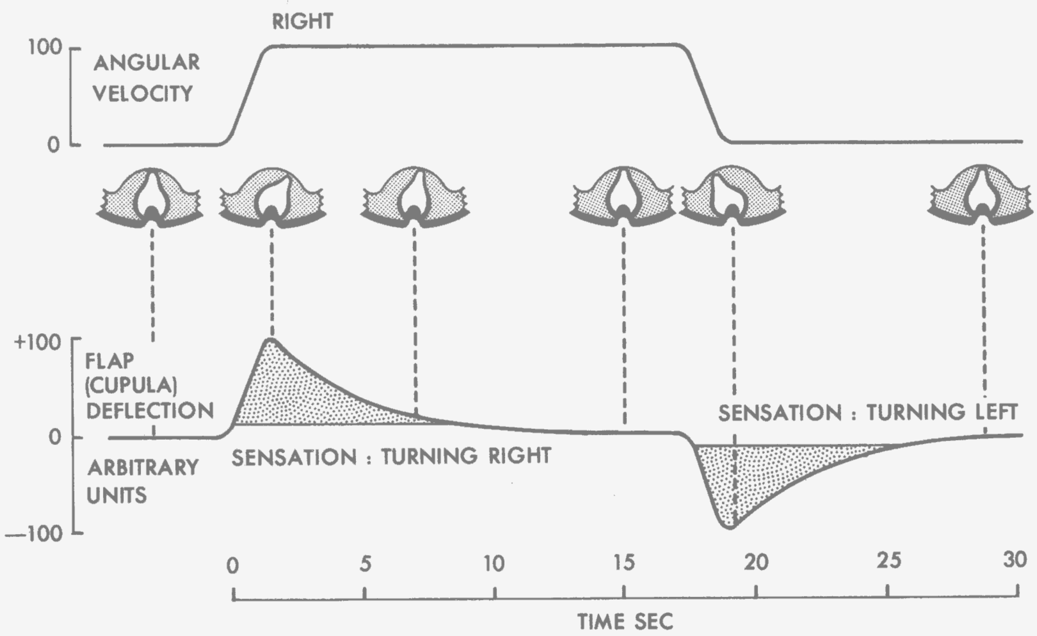

Fig 9 False Sensations of Angular Motion

(2) *Cross-coupled Stimulation.* Cross-coupled stimulation of the semicircular canals occurs whenever an angular movement of the head is made while rotating about another axis. However, disorientating sensations are evoked only when rotation is prolonged and semicircular canals do not signal correctly the sustained turn. For example, if the pilot moves his head in pitch at the beginning of a prolonged spin his sensation of both head and aircraft motion will be correct, but if the same head movement is made 15–20 sec into the spin the head movement will elicit an entirely illusory sensation of rotation in roll. Head movements made during the recovery phase cause even stronger and more bizarre sensations. As a general rule: a head movement made in one axis, after rotating for some time about an orthogonal axis, produces an illusory sensation in the third orthogonal axis.

(3) *Middle Ear Pressure Change (Pressure Vertigo).* The semicircular canals may also be stimulated by changes of pressure in the middle ear. Characteristically, on the first rapid ascent of a sortie, there is a sudden onset of a false sensation of turning (ie vertigo) which is associated with the venting of air from the middle ear. This disorientating sensation usually dies away within 15–20 sec, although initially it can be quite intense, and be accompanied by blurring of vision and apparent movement of the visual scene. The same symptoms may also be produced if an over-pressure in a middle ear is achieved when the ears are 'cleared' by a too forceful 'Valsalva' manoeuvre. Usually the disability is associated with impaired middle ear ventilation due to a common cold or other respiratory tract infection, and it is another reason for not flying when affected by these common ailments.

(4) *Effect of Alcohol.* Alcohol modifies vestibular function and increases the likelihood of disorientation. The vertigo which accompanies a change in position of the head with respect to gravity, is the best known effect of alcohol. However, it is not generally appreciated that such a 'positional vertigo' can be induced many hours after the blood alcohol level has returned to zero, while in the presence of high g forces the abnormal response may be elicited for up to two days after the consumption of alcohol. Alcohol and certain other drugs also tend to increase the visual disturbances produced by erroneous semicircular canal signals, as, for example, on recovery from a prolonged spin. Normally, these inappropriate eye movements are suppressed within a few (2–5) seconds, but when intoxicated the ability to suppress the movements is impaired, so vision may be blurred for a substantially longer time (15–20 sec). This increase of eye movement occurs at quite low blood alcohol levels (10–20mg/100ml) though, unlike the positional vertigo, it does not persist after the blood alcohol has returned to zero.

c. *Misleading Attitude Sensations.* These are caused by:

(1) *Sustained Linear accelerations.* In the presence of the constant acceleration of Earth's gravity the otolith organs and the other gravitational indicators, provide information which allows the orientation of the head and body to be sensed with accuracy. Furthermore, the brain is able to distinguish changes of attitude from transient linear accelerations. However, perceptual errors arise when the imposed linear acceleration or deceleration is sustained, as in an aircraft when power is applied or dive-brakes are operated (Fig 10 a–c). In such circumstances, the resultant of the imposed acceleration

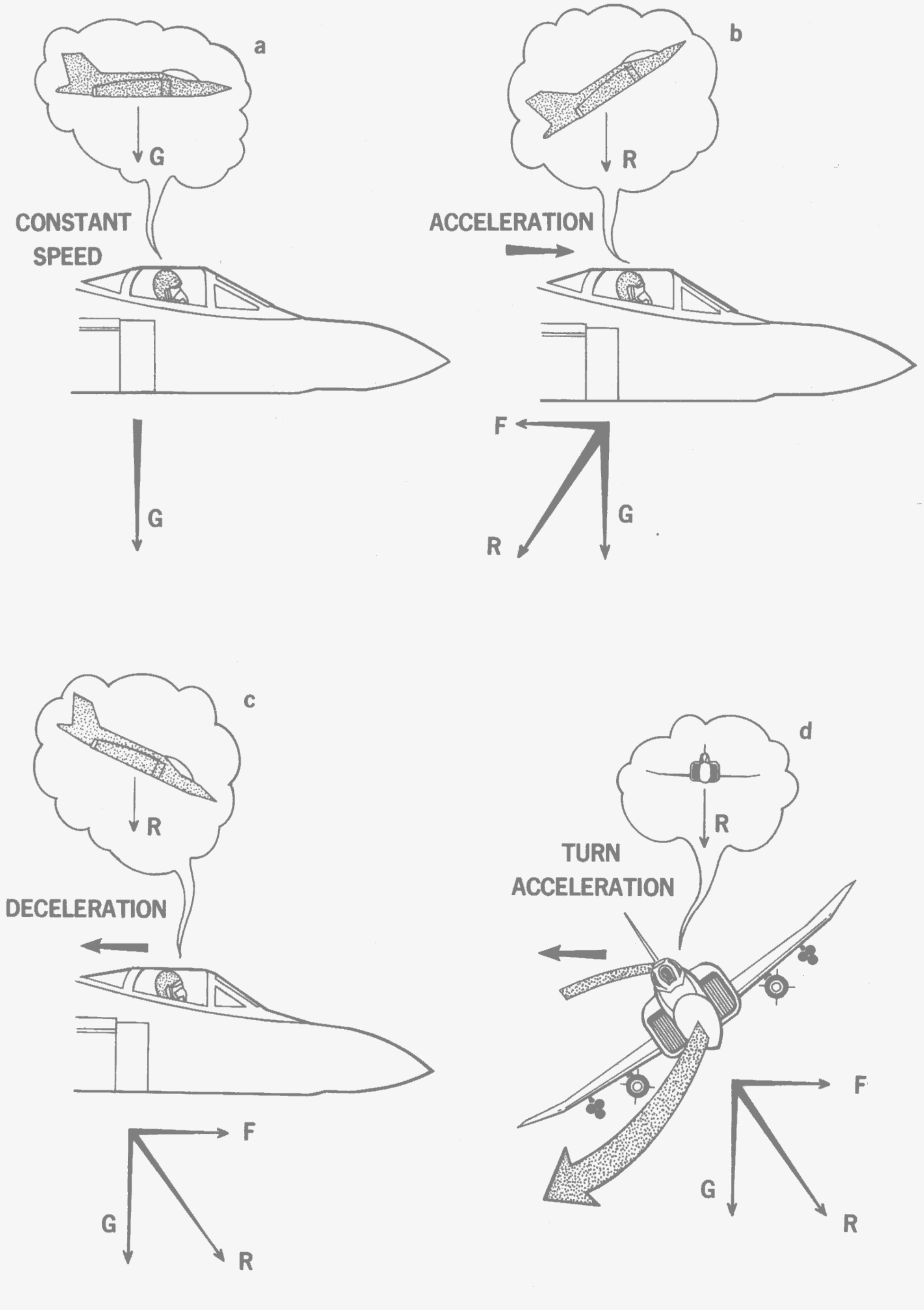

Fig 10 Misleading Attitude Sensations

and gravity is accepted as the vertical reference, so there is an erroneous perception of attitude which increases the longer the acceleration is sustained. The false sensation of pitch-up on accelerating is the more serious, for if a pitch-down corrective response is made, the radial acceleration of the induced bunt causes a larger deviation of the resultant vector and the illusion is intensified. Likewise, the failure to sense accurately the angle of bank during a turn is also due to the resultant of the radial and gravitational accelerations being accepted as the vertical, for in a co-ordinated turn the resultant vector remains normal to the aircraft's longitudinal axis and aligned with the long axis of the pilot's head and body (Fig 10d).

(2) *The Leans.* A false sensation of roll attitude is one of the commonest illusions experienced by aircrew. It usually occurs on recovery from a prolonged turn or from a previously undetected banked attitude to straight and level flight. In both of these conditions the aviator feels that he is straight and level before he rolls out. The change in bank on roll out is made within a few seconds and is sensed by the semicircular canals. This vestibular information is interpreted as roll from the wing-level attitude to one of bank in a direction opposite to that which existed before recovery was initiated. The curious feature of 'the leans' is that it may persist for many minutes even though instruments indicate level flight, though characteristically the illusion disappears as soon as an unambiguous external visual reference is present.

(3) *Effect of Head Movement.* The disorientating sensations produced when head movements are made in a turning aircraft are not solely due to a cross-coupled stimulation of the semicircular canals. The presence of a linear acceleration greater than 1g means that the otoliths will also be stimulated in an atypical manner when the head is moved. The principal effect on moving the head under high *g* is to generate an otolithic signal which corresponds to a greater change in attitude, relative to the acceleration vector, than has actually occurred. The semicircular canals and receptors in the neck signal the angular movement of the head with little error, and so there is a mismatch which is interpreted as a change of attitude of the aircraft in the plane and direction of the head movement. At higher accelerations (eg 5–6*g*) a sensation of tumbling, as well as of a change in attitude, can accompany the head movement. In high performance aircraft appreciable '*g*' forces are developed at low rates of turn. As the angular rates are close to threshold for the semicircular canals the intensity of the cross-couples stimulus accompanying the head movement is insignificant, and so any disorientating sensations are most probably caused by otolithic mechanisms.

d. *Errors in the Perception of Visual Cues.* Although many of the disorientating sensations experienced by aircrew are caused by inadequate vestibular signals, spatial disorientation may also arise because of errors or deficiences in the aviator's perception of visual cues.

(1) *External Visual Cues.* Disorientation is likely to occur when the pilot attempts to use external visual cues, rather than instrument reference, in those conditions where visibility is impaired or where there is a paucity of external cues. During flight over featureless terrain, such as sand or snow, or over a waveless sea, the judgement of height is likely to be erroneous. Similar difficulties arise when attempting to maintain hover or to land on terrain which is poorly illuminated or indicated by an inadequate array of lights. In addition, 'the

leans' are often experienced when formation flying in cloud or in hazy conditions. Even when visual cues are apparently unambiguous these may be misinterpreted because they differ from those which the aviator 'expects' to be present. One example is the use of a cloud top as a horizontal reference: cloud tops are commonly horizontal but on the rare occasion when they are not, this visual cue is erroneous and the pilot who accepts it will have a false perception of aircraft attitude. Errors in the perception of height and distance also occur when ground features are not of the expected size. These range from gross features, like the aspect ratio of a runway, to finer detail, such as the size of trees and shrubs or even surface texture. Less commonly, there is gross misinterpretation of external visual cues; the acceptance that the lights of a fishing fleet are stars and that the aircraft is in an inverted attitude, is but one example.

(2) *Instrument Cues*. Errors in the perception of the symbolic cues displayed by the aircraft instruments are occasionally responsible for disorientation, and instruments can fail, albeit rarely, without an indication of failure being represented or detected by the aviator. More common is the situation in which there is a breakdown of the normal visual scan and perceptual integration of the separate elements of the head-up or head-down display. Attention is focused on one instrument to the exclusion of the others and the pilot fails to obtain a comprehensive perception of the attitude and flight path of his aircraft. This 'coning of attention' is the more likely to occur at times of high workload and arousal, such as are engendered by aircraft system malfunction.

Prevention of Disorientation

41. Knowledge about the causes of spatial disorientation and of the flight conditions in which it is likely to occur, should lead either to the avoidance of provocative flight environments and manoeuvres, or, when this is impracticable, to the exercise of special care in such situations.

42. Illusory sensations are much more likely to be experienced and to distract when visual cues are inadequate, so a high degree of proficiency at instrument flying is important if the aviator is to resolve correctly conflicting sensory cues and maintain proper control of the aircraft. Proficiency, in this context, implies both a high standard of instrument flying, being in current practice, and having an intimate knowledge of the specific aircraft and relevant instrument procedures.

43. Any prolonged period of ground duty leads to a loss of skill and a heightened susceptibility to disorientating sensations. Aircrew should, therefore, be particularly vigilant on return to flying duties after a ground tour, when a properly planned and supervised period of refresher training is essential. Yet even after a week or two on the ground there is some loss of habituation to the motion stimuli of flight, accordingly on return from leave, it is desirable that the first flight should not be a demanding IMC sortie.

44. Advice on preventative measures may be summarised as follows:

a. Remain convinced that you cannot fly by the 'seat of the pants'.

b. Do not allow control of the aircraft to be based at any time on 'seat of the pants' sensations even when you are temporarily deprived of visual cues.

c. Do not unnecessarily mix flying by instruments with flying by external visual cues.

d. Aim to make an early transition to instruments in poor visibility; once on instruments, stay on instruments until external cues are unambiguous.

e. Maintain a high proficiency and be in practice at flight in IMC.

f. Avoid unnecessary manoeuvres of aircraft or head movements which are known to induce disorientation.

g. Be particularly vigilant in high risk situations, such as at night and in poor visibility, in order to maintain intellectual command of the orientation and position of the aircraft.

h. Do not fly:

(1) With an upper respiratory tract infection.

(2) When under the influence of drugs or alcohol.

(3) When mentally or physically debilitated.

i. Make your first flight after a period off flying a simple day VMC sortie.

j. Remember: experience does not make you immune.

Coping with Disorientation

45. When confronted by a minor, but persistent, disorientating sensation (eg the Leans) this may be dispelled by a redirection of attention to other aspects of the flying task, provided the correct orientation of the aircraft has been established and instrument references have been cross-checked. Some aircrew find that a quick shake of the head is effective, though it is important that such head manoeuvres should be made only when the aircraft is established in straight and level flight.

46. Should there be strong illusory sensations and difficulties experienced in establishing orientation and control of aircraft, the following procedures are recommended:

a. Go on to instruments; check and cross-check. Ensure good instrument illumination.

b. Maintain instrument reference and correct scan pattern; watch your height at all times.

c. Control the aircraft in such a way as to make the instruments display the desired flight configuration.

d. Do not attempt to mix flight by external visual reference with instrument flight until external visual reference cues are unambiguous.

e. Seek help if severe disorientation persists. Hand over to co-pilot (if present); call ground controller or other aircraft; check altimeter.

f. If control cannot be regained, abandon aircraft with safe ground clearance. Do not leave it too late.

Conclusion

47. Remember: nearly all disorientation is a normal response to the unnatural environment of flight. If you have been alarmed by a flight incident, discuss it with colleagues including your Station Medical Officer. Your experience will probably be not as unusual as you think.

AIR SICKNESS

General

48. Air sickness, like other forms of motion sickness (eg car sickness, sea sickness, space sickness) is not a pathological condition but is the normal response of man to certain motion stimuli. Typically, on exposure to provocative motion there is first a slight feeling of malaise, then nausea of increasing severity and eventually vomiting. These symptoms are commonly accompanied by a feeling of warmth, sweating and pallor, and more variably, by headache, dizziness, increased salivation, drowsiness, apathy and depression. This collection of signs and symptoms constitutes the motion sickness syndrome and if evoked in flight by motion of the aircraft is called air sickness.

Causal Mechanisms

49. Why man reacts in this curious way on being exposed to particular motion stimuli is not known; there is, however, a reasonable understanding of what makes him motion sick, and why certain types of motion induce sickness and others do not. The current concept is that individuals develop motion sickness when the various sense organs that signal body motion provide discordant information. The essential feature of this discord is a mismatch between the motion information provided by the eyes and inner ear and the information that is 'expected' by the central nervous system (Fig 11).

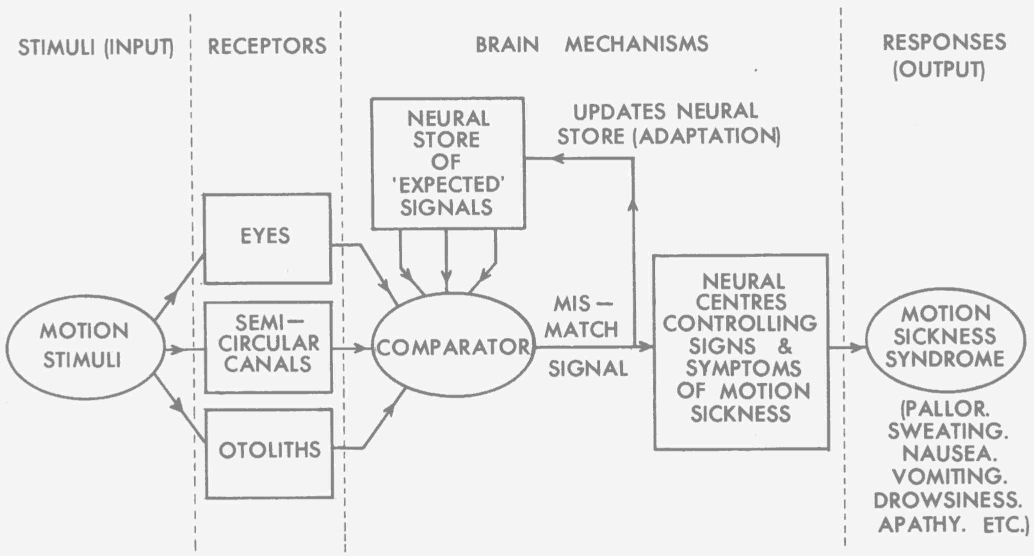

Fig 11 Mismatch

50. Various types of 'mismatch' can be identified. Most important is the mismatch of signals from the vestibular apparatus of the inner ear in which the semicircular canals and the otoliths do not provde concordant information. For example, when head movements are made in an aircraft which is turning, both the semicircular canals and the otoliths can provide erroneous and incompatible signals which are likely to differ substantially from those generated by the same head movement in a normal 1*g* environment. Likewise, low frequency (below 0.5 Hz) linear accelerations (such as occur in flight through turbulence, repeated high rate turns and aerobatic manoeuvres) can also generate conflicting vestibular signals and hence be a potent cause of motion sickness.

51. The mismatch of visual and vestibular information can also be an important causal factor. For example, flying personnel who cannot see out of the aircraft are more likely to suffer from air sickness than those with a good external visual reference, because in the former the motion sensed by the inertial receptors of the vestibular apparatus is not accompanied by any visual motion cues. Sickness can also be induced by purely visual motion in the absence of any motion of the man, as in some simulators which have a convincing external visual world

display but no motion of the simulator cockpit.

52. Anxiety and the presence of environmental features, such as the smell of the aircraft or manoeuvres which have previously caused sickness, may increase susceptibility to motion sickness in some individuals, but in general these factors are of secondary importance.

Factors Affecting Susceptibility

53. There are very large differences between individuals in their response to provocative motion stimuli. Some are never sick, others succumb within minutes on exposure to mild turbulence. However, only those without a functioning vestibular system are truly immune. There are also considerable differences in the way people adapt to repeated, or prolonged, exposure to provocative motion as well as differences in the retention of adaptation following exposure.

54. Air sickness is most likely to occur on initial exposure to an unfamiliar motion; thus it is seen most frequently in student aircrew during the initial phases of flying training with recurrence on first experiencing the more provocative flight manoeuvres such as spinning, high rate turns and aerobatics. With continuing flight experience the majority of students adapt and air sickness is no longer a problem, but a few do not develop protective adaptation, or are very slow to adapt and training is impaired by continuing sickness.

55. The retention of adaptation is also highly variable. In a few individuals it is lost within days; more commonly, the decay of adaptation is relatively slow. On return to flying (which can be from a fortnight's leave to a ground tour lasting years) many aircrew find that their tolerance to provocative motion has decreased. Fortunately readaptation usually proceeds more rapidly than the initial adaptation. Adaptation can be highly specific. Thus it is not uncommon for flying personnel, who have have adapted to the motion of one type of aircraft, to suffer from air sickness on transfer to another type having different motion characteristics. Pilots may also experience malaise when flying as a passenger but not when they are in control of the aircraft.

Prevention

56. Air sickness can be prevented, or at least the onset of symptoms delayed, by a number of methods though those available to aircrew, but not to passengers, are limited by operational constraints. Head movement should be reduced to a minimum and good restraint of the body ensured. Provision of a good external visual reference is advantageous, as is involvement in a task, provided this does not involve additional head movements or introduce conflicting visual cues (eg as when reading a book or map in turbulence).

57. A number of drugs increase tolerance to provocative motion, though there are considerable differences between individuals in the efficacy of a particular drug and the incidence of side effects. Unfortunately, all these drugs are sedative and can impair performance, so it is mandatory that they should not be taken by pilots when flying solo or by other aircrew who have a critical role to play in flight. They are, however, valuable in allaying symptoms in passengers and a short course of anti-motion sickness drugs can help student aircrew to tolerate aircraft motion whilst acquiring protective adaptation – Nature's own cure.

Printed in England for Her Majesty's Stationery Office by Nelson Brothers of Chorley
27.1.82 (14276) 8225775 4/82 3347


CPL V WOOTON
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