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ARMSTRONG LABORATORY

SPATIAL ORIENTATION IN FLIGHT

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Human spatial orientational mechanisms, and how those mechanisms fail in flight, are discussed in detail in this comprehensive review. Specific topics include: mechanics and associated physiologic nomenclature; visual orientation; vestibular function and information processing; other orientational senses, spatial disorientation, including definitions, types, causes, examples, statistics, and methods of preventing spatial disorientation mishaps; and the significance, etiology, and therapy of motion sickness. Forty-four figures are included, many illustrating vestibular anatomy and physiology, and others depicting the more common visual and vestibular illusions in flight.

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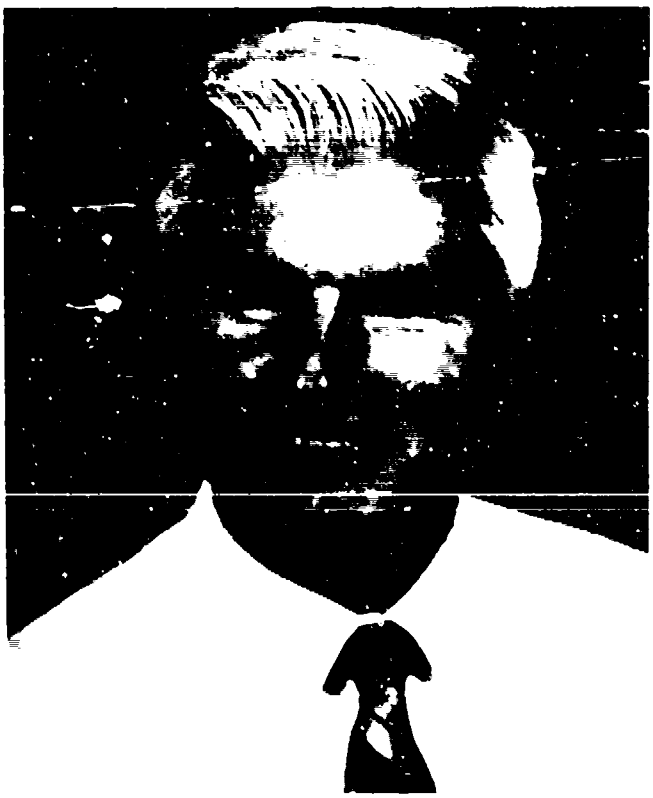
FOREWORD

This volume is dedicated to the memory of Dr. Kent K. Gillingham, who died tragically in a plane crash at the age of 55 at 5:20 PM on 27 Sep 93. This report, which overwhelmingly reflects the ideas and efforts of Dr. Gillingham, was essentially completed just prior to his untimely death.

Dr. Gillingham was the acknowledged USAF expert and a leading international authority in both spatial disorientation and acceleration physiology. He had a similar command of the scientific and applied aspects of spatial disorientation which stemmed from his unique scientific/medical background and his longstanding experience as a pilot. He graduated from the University of Michigan with a B.S. degree in 1959 and an M.D. degree in 1963. After serving a 3-year tenure as an Air Force medical officer at Brooks AFB from 1964 to 1967, Dr. Gillingham later returned to graduate school and received a Ph.D. in cerebellar physiology from the University of Iowa in 1973. Upon receiving his doctorate, he returned to the USAF School of Aerospace Medicine and later to the Armstrong Laboratory to serve as a medical officer in the civil service until his death. Throughout his career, Dr. Gillingham authored over 75 articles, chapters, and other reports, mostly in acceleration physiology and spatial disorientation.



This volume, in highlighting Dr. Gillingham's 30-year commitment to understand the often fatal consequences of spatial disorientation and to teach pilots and flight surgeons to recognize its symptoms and quickly respond with appropriate aircraft control countermeasures, will be valued as an important reference source by scientists, flight surgeons, aerospace physiologists, students, writers, and other professionals for many years to come. In applying the knowledge and insight thoughtfully presented in these pages, all of us will sustain the legacy of Dr. Kent K. Gillingham.

SPATIAL ORIENTATION IN FLIGHT

MECHANICS

Operators of today's and tomorrow's air and space vehicles must understand clearly the terminology and physical principles relating to the motions of their craft so they can fly with precision and effectiveness. These crewmembers also must have a working knowledge of the structure and function of the various mechanical and electrical systems of which their craft is comprised to help them understand the performance limits of their machines and to facilitate trouble-shooting and promote safe recovery when the machines fail in flight. So, too, must practitioners of aerospace medicine understand certain basic definitions and laws of mechanics so that they can analyze and describe the motional environment to which the flyer is exposed. In addition, the aeromedical professional must be familiar with the physiologic bases and operational limitations of the flyer's orientational mechanisms. This understanding is necessary to enable the physician or physiologist to speak intelligently and credibly with aircrew about spatial disorientation and to enable him or her to contribute significantly to investigations of aircraft mishaps in which spatial disorientation may be implicated.

Motion

We shall discuss two types of physical motion: linear motion or motion of translation, and angular motion or motion of rotation. Linear motion can be further categorized as rectilinear, meaning motion in a straight line, or curvilinear, meaning motion in a curved path. Both linear motion and angular motion are composed of an infinite variety of subtypes, or motion parameters, based on successive derivatives of linear or angular position with respect to time. The most basic of these motion parameters, and the most useful, are displacement, velocity, acceleration, and jerk. Table 1 classifies linear and angular motion parameters and their symbols and units, and serves as an outline for the following discussions of linear and angular motion.

Linear Motion

The basic parameter of linear motion is linear displacement. The other parameters--velocity, acceleration, jerk--are derived from the concept of displacement. Linear displacement, x, is the distance and direction of the object under consideration from some reference point; as such, it is a vector quantity, having both magnitude and direction. The position of an aircraft located at 25 nautical miles on the 150° radial of the San Antonio vortac, for example, describes completely the linear displacement of the aircraft from the navigational facility serving as the reference point. The meter (m), however, is the unit of linear displacement in the International System of Units (SI) and will eventually replace other units of linear displacement such as feet, nautical miles, and statute miles.

TABLE 1. LINEAR AND ANGULAR MOTION--SYMBOLS AND UNITS

Motion Parameter	Linear		Angular	
	Symbols	Units	Symbols	Units
Displacement	x	meter (m) nautical mile (=1852 m)	θ	degree (°) radian (rad) (=360/2π°)
Velocity	v, $\dot{x}$	m/sec knot (≈0.514 m/sec)	ω, $\dot{\theta}$	°/sec rad/sec
Acceleration	a, $\dot{v}$, $\ddot{x}$	m/sec^2; g (≈9.81 m/sec^2)	α, $\dot{\omega}$, $\ddot{\theta}$	°/sec^2 rad/sec^2
Jerk	j, $\dot{a}$, $\ddot{v}$, $\dddot{x}$	m/sec^3 g/sec	Υ, $\dot{\alpha}$, $\ddot{\omega}$, $\dddot{\theta}$	°/sec^3 rad/sec^3

When linear displacement is changed during a period of time, another vector quantity, linear velocity, occurs. The formula for calculating the mean linear velocity, v, during a time interval, Δt, is as follows:

$$v = \frac{x_2 - x_1}{\Delta t} \tag{1}$$

where x_1 is the initial linear displacement and x_2 is the final linear displacement. An aircraft that travels from San Antonio, Texas, to New Orleans, Louisiana, in 1 hour, for example, moves with a mean linear velocity of 434 knots (nautical miles per hour) on a true bearing of 086°. Statute miles per hour and feet per second are other commonly used units of linear speed, the magnitude of linear velocity; meters per second (m/sec), however, is the SI unit and is preferred. Frequently, it is important to describe linear velocity at a particular instant in time, that is, as t approaches zero. In this situation, one speaks of instantaneous linear velocity, $\dot{x}$ (pronounced "x dot"), which is the first derivative of displacement with respect to time, $\frac{dx}{dt}$.

When the linear velocity of an object changes over time, the difference in velocity, divided by the time required for the moving object to make the change, gives its mean linear acceleration, a. The following formula:

$$a = \frac{v_2 - v_1}{\Delta t} \tag{2}$$

where v_1 is the initial velocity, v_2 is the final velocity, and Δt is the elapsed time, is used to calculate the mean linear acceleration, which, like displacement and velocity, is a vector quantity with magnitude and direction. Acceleration is thus the rate of change of velocity, just as velocity is the rate of change of displacement. The SI unit for the magnitude of linear acceleration is meters per second squared (m/sec^2). Consider, for example, an aircraft that accelerates from a dead stop to a velocity of 100 m/sec in 5 seconds; the mean linear acceleration is 100 m/sec - 0 m/sec ÷ 5 seconds, or 20 m/sec^2. The instantaneous linear acceleration, $\ddot{x}$ ("x double dot") or $\dot{v}$, is the second derivative of displacement or the first derivative of velocity, $\frac{d^2x}{dt^2}$ or $\frac{dv}{dt}$, respectively.

A very useful unit of acceleration is g, which for our purposes is equal to the constant g_o, the amount of acceleration exhibited by a free-falling body near the surface of the earth--9.81 m/sec^2. To convert values of linear acceleration given in m/sec^2 into g units, simply divide by 9.81. In the above example in which an aircraft accelerates at a mean rate of 20 m/sec^2, one divides 20 m/sec^2 by 9.81 m/sec^2 per g to obtain 2.04 g.

A special type of linear acceleration--radial or centripetal acceleration--results in curvilinear, usually circular, motion. The acceleration acts along the line represented by the radius of the curve and is directed toward the center of the curvature. Its effect is a continuous redirection of the linear velocity, in this case called tangential velocity, of the object subjected to the acceleration. Examples of this type of linear acceleration are when an aircraft pulls out of a dive after firing on a ground target or flies a circular path during aerobatic maneuvering. The value of the centripetal acceleration, a_c, can be calculated if one knows the tangential velocity, v_t, and the radius, r, of the curved path followed:

$$a_c = \frac{v_t^2}{r} \tag{3}$$

For example, the centripetal acceleration of an aircraft traveling at 300 m/sec (approximately 600 knots) and having a radius of turn of 1500 m can be calculated. Dividing $(300 \text{ m/sec})^2$ by 1500 m gives a value of 60 m/sec^2, which, when divided by 9.81 m/sec^2 per g, comes out to 6.12 g.

One can go another step in derivation of linear motion parameters by obtaining the rate of change of acceleration. This quantity, j, is known as linear jerk. Mean linear jerk is calculated as follows:

$$j = \frac{a_2 - a_1}{\Delta t} \qquad (4)$$

where a_1 is the initial acceleration, a_2 is the final acceleration, and t is the elapsed time. Instantaneous linear jerk, $\dddot{x}$, or $\dot{a}$, is the third derivative of linear displacement or the first derivative of linear acceleration with respect to time, $\frac{d^3x}{dt^3}$ or $\frac{da}{dt}$, respectively. Although the SI unit for jerk is m/sec^3, it is generally more useful to speak in terms of g-onset rate, measured in g's per second (g/sec).

Angular Motion

The derivation of the parameters of angular motion follows in a parallel fashion the scheme used to derive the parameters of linear motion. The basic parameter of angular motion is angular displacement. For an object to be able to undergo angular displacement it must be polarized; that is, it must have a front and back, so that it can face or be pointed in a particular direction. A simple example of angular displacement is seen in a person facing east. In this case, the individual's angular displacement is 90° clockwise from the reference direction, which is north. Angular displacement, symbolized by θ, is generally measured in degrees, revolutions (1 revolution = 360°), or radians (1 radian = 1 revolution ÷ 2π, approximately 57.3°). The radian is a particularly convenient unit to use when dealing with circular motion (e.g., motion of a centrifuge) because it is necessary only to multiply the angular displacement of the system, in radians, by the length of the radius to find the value of the linear displacement along the circular path. The radian is the angle subtended by a circular arc the same length as the radius of the circle.

Angular velocity, ω, is the rate of change of angular displacement. The mean angular velocity occurring in a time interval, Δt, is calculated as follows:

$$\omega = \frac{\theta_2 - \theta_1}{\Delta t} \qquad (5)$$

where θ_1 is the initial angular displacement and θ_2 is the final angular displacement. Instantaneous angular velocity is $\dot{\theta}$ or $\frac{d\theta}{dt}$. As an example of angular velocity, consider the standard-rate turn of instrument flying, in which a heading change of 180° is made in 1 minute. Then $\omega = (180° - 0°) + 60$ seconds, or 3 degrees per second (°/sec). This angular velocity also can be described as 0.5 revolutions per minute (rpm) or as 0.052 radians per second (rad/sec) (3°/sec divided by 57.3°/rad). The fact that an object may be undergoing curvilinear motion during a turn in no way affects the calculation of its angular velocity: an aircraft being rotated on the ground on a turntable at a rate of half a turn per minute has the same angular velocity as one flying a standard-rate instrument turn (3°/sec) in the air at 300 knots.

Because radial or centripetal linear acceleration results when rotation is associated with a radius from the axis of rotation, a formula for calculating the centripetal acceleration, a_c, from the angular velocity, ω, and the radius, r, is often useful:

$$a_c = \omega^2 r \tag{6}$$

where ω is the angular velocity in radians per second. One can convert readily to the formula for centripetal acceleration in terms of tangential velocity (Equation 3) if one remembers the following:

$$v_t = \omega r \tag{7}$$

To calculate the centripetal acceleration generated by a centrifuge having a 10-m arm and turning at 30 rpm, Equation 6 is used after first converting 30 rpm to π rad/sec. Squaring the angular velocity and multiplying by the 10-m radius, a centripetal acceleration of $10\ \pi^2$ m/sec^2, or 10.1 g, is obtained.

The rate of change of angular velocity is angular acceleration, α. The mean angular acceleration is calculated as follows:

$$\alpha = \frac{\omega_2 - \omega_1}{\Delta t} \tag{8}$$

where ω_1 is the initial angular velocity, ω_2 is the final angular velocity, and Δt is the time interval over which angular velocity changes.

$\ddot{\theta}$, $\dot{\omega}$, $\frac{d^2\theta}{dt^2}$, and $\frac{d\omega}{dt}$ all can be used to symbolize instantaneous angular acceleration, the second derivative of angular displacement or the first derivative of angular velocity with respect to time. If a figure skater is spinning at 6 revolutions per second (2160°/sec, or 37.7 rad/sec) and then comes to a complete stop in 2 seconds, the rate of change of angular velocity, or angular acceleration, is (0 rad/sec - 37.7 rad/sec) ÷ 2 seconds, or -18.9 rad/sec^2. One cannot express angular acceleration in g units, which measure magnitude of linear acceleration only.

Although not commonly used in aerospace medicine, another parameter derived from angular displacement is angular jerk, the rate of change of angular acceleration. Its description is completely analogous to that for linear jerk, but angular rather than linear symbols and units are used.

Force, Inertia, and Momentum

Generally speaking, the linear and angular motions, by themselves, are not of physiologic importance. Forces and torques that result in, or appear to result from, linear and angular velocity changes are the entities that stimulate or compromise the crewmember's physiologic mechanisms.

Force and Torque

Force is an influence that produces, or tends to produce, linear motion or changes in linear motion; it is a pushing or pulling action. Torque produces, or tends to produce, angular motion or changes in angular motion; it is a twisting or turning action. The SI unit of force is the newton (N). Torque has dimensions of force and length because torque is applied as a force at a certain distance from the center of rotation. The newton meter (N m) is the SI unit of torque.

Mass and Rotational Inertia

Newton's Law of Acceleration states the following:

$$F=ma \qquad (9)$$

where F is the unbalanced force applied to an object, m is the mass of the object, and a is linear acceleration.

To describe the analogous situation pertaining to angular motion, the following equation is used:

$$M=J\alpha \qquad (10)$$

where M is unbalanced torque (or moment) applied to the rotating object, J is rotational inertia (moment of inertia) of the object, and α is angular acceleration.

The mass of an object is thus the ratio of the force acting on the object to the acceleration resulting from that force. Mass, therefore, is a measure of the inertia of an object--its resistance to being accelerated. Similarly, rotational inertia is the ratio of the torque acting on an object to the angular acceleration resulting from that torque--again, a measure of resistance to acceleration. The kilogram (kg) is the SI unit of mass and is equivalent to 1 N/(m/sec^2). The SI unit of rotational inertia is merely the N m/(radian/sec^2).

Because F = ma, the centripetal force, F_c, needed to produce a centripetal acceleration, a_c, of a mass, m, can be calculated as follows:

$$F_c = ma_c \tag{11}$$

Thus, from Equation 3:

$$F_c = \frac{mv_t^2}{r} \tag{12}$$

or from Equation 6:

$$F_c = m\omega^2 r \tag{13}$$

where v_t is tangential velocity and ω is angular velocity.

Newton's Law of Action and Reaction, which states that for every force applied to an object there is an equal and opposite reactive force exerted by that object, provides the basis for the concept of inertial force. Inertial force is an apparent force opposite in direction to an accelerating force and equal to the mass of the object times the acceleration. An aircraft exerting an accelerating forward thrust on its pilot causes an inertial force, the product of the pilot's mass and the acceleration, to be exerted on the back of the seat by the pilot's body. Similarly, an aircraft undergoing positive centripetal acceleration as a result of lift generated in a turn causes the pilot's body to exert inertial force on the bottom of the seat. More important, however, are the inertial forces exerted on the pilot's blood and organs of equilibrium because physiologic effects result directly from such forces.

At this point it is appropriate to introduce G, which is used to measure the strength of the gravitoinertial force environment. (Note: G should not be confused with G, the symbol for the universal gravitational constant, which is equal to 6.70×10^{-11} N m^2/kg^2.) Strictly speaking, G is a measure of relative weight:

$$G = \frac{w}{w_o} \tag{14}$$

where w is the weight observed in the environment under consideration and w_o is the normal weight on the surface of the earth. In the physical definition of weight,

$$w = ma \tag{15}$$

and

$$w_o = mg_o \tag{16}$$

where m is mass, a is the acceleratory field (vector sum of actual linear acceleration plus an imaginary acceleration opposite the force of gravity), and g_o is the standard value of the acceleration of gravity (9.81 m/sec^2). Thus, a person having a mass of 100 kg would weigh 100 kg times 9.81 m/sec^2 or 981 N on earth (although conventional scales would read "100 kg"). At some other location or under some other acceleratory condition, the same person could weigh twice as much--1962 N--and the scale would read "200 kg." Our subject would then be in a 2-G environment, or in an aircraft, would be "pulling" 2 G. Consider also that since

$$G = \frac{w}{w_o} = \frac{ma}{mg_o}$$

then

$$G = \frac{a}{g_o} \tag{17}$$

Thus, the ratio between the ambient acceleratory field (a) and the standard acceleration (g_o) also can be represented in terms of G.

Therefore, g is used as a unit of acceleration (e.g., a_c = 8 g), and the dimensionless ratio of weights, G, is reserved for describing the resulting gravitoinertial force environment (e.g., a force of 8 G, or an 8-G load). When in the vicinity of the surface of the earth, one feels a G force equal to 1 G in magnitude directed toward the center of the earth. If one also sustains a G force resulting from linear acceleration, the magnitude and direction of the resultant gravitoinertial force can be calculated by adding vectorially the 1-G gravitational force and the inertial G force. An aircraft pulling out of a dive with a centripetal acceleration of 3 g, for example, would exert 3 G of centrifugal force. At the bottom of the dive, the pilot would experience the 3-G centrifugal force in line with the 1-G gravitational force, for a total of 4 G directed toward the floor of the aircraft. If the pilot could continue his circular flight path at a constant airspeed, the G force experienced at the top of the loop would be 2 G because the 1-G gravitational force would subtract from the 3-G inertial force. Another common example of the addition of gravitational G force and inertial G force occurs during the application of power on takeoff or on a missed approach. If the forward acceleration is 1 g, the inertial force is 1 G directed backward. The inertial force adds vectorially to the 1-G force of gravity, directed downward, to provide a resultant gravitoinertial force of 1.414 G pointing 45° down from the aft direction, if the aircraft is traveling horizontally.

Just as inertial forces oppose acceleratory forces, so do inertial torques oppose acceleratory torques. No convenient derived unit exists, however, for measuring inertial torque; specifically, there is no such thing as angular G.

Momentum

To complete this discussion of linear and angular motion, the concepts of momentum and impulse must be introduced. Linear momentum is the product of mass and linear velocity--mv. Angular momentum is the product of rotational inertia and angular velocity--$J\omega$. Momentum is a quantity that a translating or rotating body conserves; that is, an object cannot gain or lose momentum unless it is acted on by a force or torque. A translational impulse is the product of force, F, and the time over which the force acts on an object, Δt, and is equal to the change in linear momentum imparted to the object. Thus:

$$F\Delta t = mv_2 - mv_1 \tag{18}$$

where v_1 is the initial linear velocity and v_2 is the final linear velocity.

When dealing with angular motion, a rotational impulse is defined as the product of torque, M, and the time over which it acts, Δt. A rotational impulse is equal to the change in angular momentum. Thus:

$$M\Delta t = J\omega_2 - J\omega_1 \tag{19}$$

where ω_1 is the initial angular velocity and ω_2 is the final angular velocity.

The above relations are derived from the Law of Acceleration, as follows:

$$F = ma$$

$$M = J\alpha$$

since

$$a = \frac{v_2 - v_1}{\Delta t}$$

and

$$\alpha = \frac{\omega_2 - \omega_1}{\Delta t}$$

Directions of Action and Reaction

A number of conventions have been used in aerospace medicine to describe the directions of linear and angular displacement, velocity, and acceleration, and of reactive forces and torques. The more commonly used of those conventions will be discussed in the following sections.

Vehicular Motions

Because space is three-dimensional, linear motions in space are described by reference to three linear axes and angular motions by three angular axes. In aviation, it is customary to speak of the longitudinal (fore-aft), lateral (right-left), and vertical (up-down) linear axes, and the roll, pitch, and yaw angular axes, as shown in Figure 1.

Most linear accelerations in aircraft occur in the vertical plane defined by the longitudinal and vertical axes because thrust is usually developed along the former axis and lift is usually developed along the latter axis. Aircraft capable of vectored thrust are now operational, however, and vectored-lift aircraft are currently being flight-tested. Most angular accelerations in fixed-wing aircraft occur in the roll plane (perpendicular to the roll axis) and, to a lesser extent, in the pitch plane. Angular motion in the yaw plane is common in rotating-wing aircraft, and it occurs during spins and several other aerobatic maneuvers in fixed-wing aircraft. Certainly, aircraft and space vehicles of the future can be expected to operate with considerably more freedom of both linear and angular motion than do those of the present.

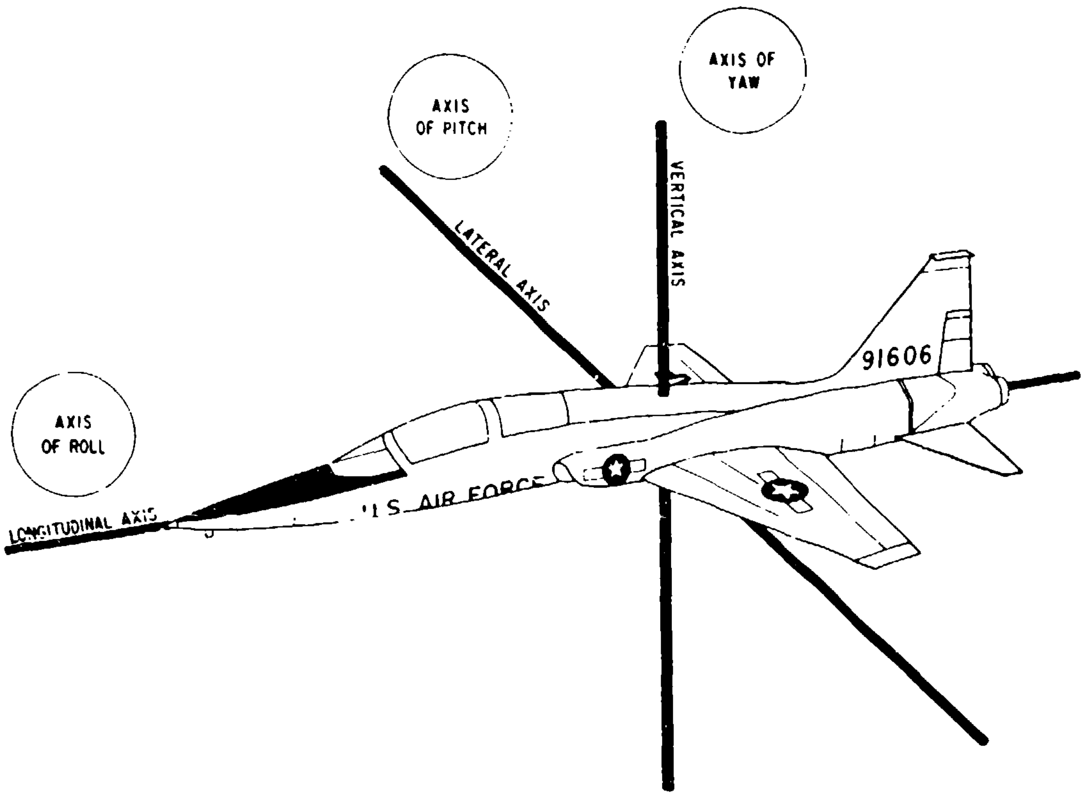


Figure 1. **Axes of linear and angular aircraft motions.** Linear motions are longitudinal, lateral, and vertical; angular motions are roll, pitch, and yaw.

Physiologic Acceleration and Reaction Nomenclature

Figure 2 depicts a practical system for describing linear and angular accelerations acting on man.[1] This system is used extensively in aeromedical scientific writing. In this system, a linear acceleration of the type associated with a conventional takeoff roll is in the $+a_x$ direction; that is, it is a $+a_x$ acceleration. Braking to a stop during a landing roll results in $-a_x$ acceleration. Radial acceleration of the type usually developed during air combat maneuvering is $+a_z$ acceleration--foot-to-head. The right-hand rule for describing the relationships among three orthogonal axes aids recall of the positive directions of a_x, a_y, and a_z accelerations in this particular system: if one lets the forward-pointing index finger of the right hand represent the positive x-axis, and the left-pointing middle finger of the right hand represent the positive y-axis, the positive z-axis is represented by the upward-pointing thumb of the right hand. A different right-hand rule, however, is used in another convention, one for describing vehicular coordinates. In that system, $+a_x$ is noseward acceleration, $+a_y$ is to the right, and $+a_z$ is floorward; an inverted right hand illustrates that set of axes.

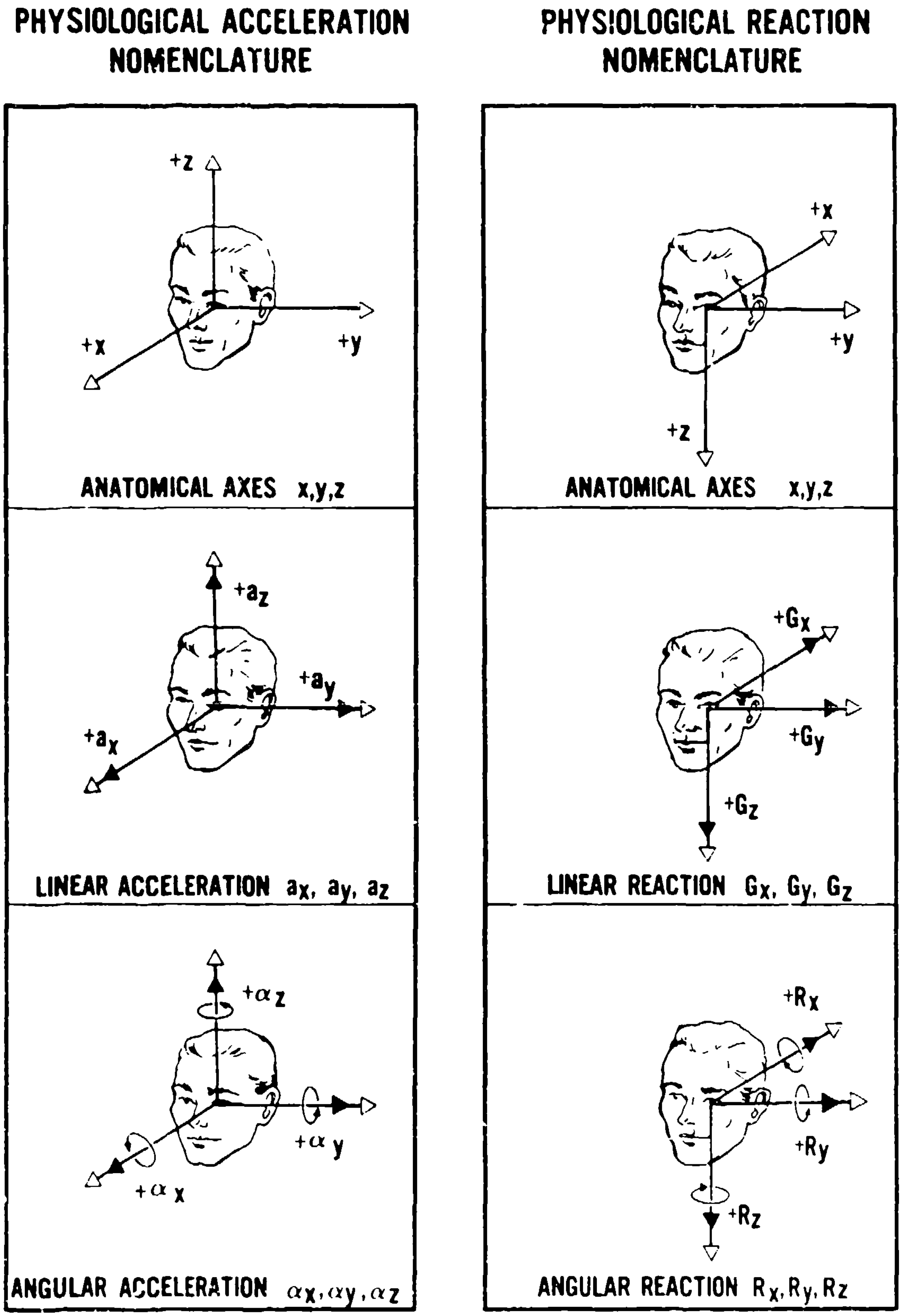


Figure 2. **System for describing accelerations and inertial reactions in humans.** (Adapted from Hixson et al.[1])

The angular accelerations, α_x, α_y, and α_z, are roll, pitch, and yaw accelerations, respectively, in the system shown in Figure 2. Note that the relations among the positive x-axis, y-axis, and z-axis are identical to those for linear accelerations. The direction of positive angular displacement, velocity, or acceleration is described by another right-hand rule, wherein the flexed fingers of the right hand indicate the direction of angular motion corresponding to the vector represented by the extended, abducted right thumb. Thus, in this system, a right roll results from $+\alpha_x$ acceleration, a pitch down results from $+\alpha_y$ acceleration, and a left yaw results from $+\alpha_z$ acceleration. Again, it is important to be aware of the inverted right-hand coordinate system commonly used to describe angular motions of vehicles. In that convention, a positive roll acceleration is to the right, positive pitch is upward, and positive yaw is to the right.

The nomenclature for the directions of gravitoinertial (G) forces acting on humans is also illustrated in Figure 2. Note that the relation of these axes to each other follows a backward, inverted, right-hand rule. In the illustrated convention, $+a_x$ acceleration results in $+G_x$ inertial force, and $+a_z$ acceleration results in $+G_z$ force. This correspondence of polarity is not achieved on the y-axis, however, because $+a_y$ acceleration results in $-G_y$ force. If the $+G_y$ direction were reversed, full polarity correspondence could be achieved between all linear accelerations and all reactive forces, and that convention has been used by some authors. An example of the usage of the symbolic reaction terminology is: "An F-16 pilot must be able to sustain +9.0 G_z without losing vision or consciousness."

The "eyeballs" nomenclature is another useful set of terms for describing gravitoinertial forces. In this system, the direction of the inertial reaction of the eyeballs when the head is subjected to an acceleration is used to describe the direction of the inertial force. The equivalent expressions, "eyeballs-in acceleration" and "eyeballs-in G force," leave little room for confusion about either the direction of the applied acceleratory field or the resulting gravitoinertial force environment.

Inertial torques can be described conveniently by means of the system shown in Figure 2, in which the angular reaction axes are the same as the linear reaction axes. The inertial reactive torque resulting from $+\alpha_x$ (right roll) angular acceleration is $+R_x$ and $+\alpha_z$ (left yaw) results in $+R_z$; however, $+\alpha_y$ (downward pitch) results in $-R_y$. This incomplete correspondence between acceleration and reaction coordinate polarities again results from the mathematical tradition of using right-handed coordinate systems.

It should be apparent from this discussion that the potential for confusing the audience when speaking or writing about accelerations and inertial reactions is great, and it may be necessary to describe the coordinate system being used. For most applications, the "eyeballs" convention is perfectly adequate.

VISUAL ORIENTATION

Vision is by far the most important sensory modality subserving spatial orientation, especially so in moving vehicles such as aircraft. Without it, flight as we know it would be impossible, whereas this would not necessarily be the case in the absence of the vestibular or other sensory systems that provide orientation information. For the most part, the function of vision in spatial orientation is obvious, so a discussion proportional in size to the importance of that function in orientation will not be presented here. Certain special features of visual orientation deserve mention, however. First, there are actually two separate visual systems, and they have two distinct functions: object recognition and spatial orientation. A knowledge of these systems is extremely important, both to help in understanding visual illusions in flight and to appreciate the difficulties inherent in using flight instruments for spatial orientation. Second, visual and vestibular orientation information are integrated at very basic neural levels. For that reason, spatial disorientation frequently is not amenable to correction by higher-level neural processing.

Anatomy of the Visual System

General

The retina, an evaginated portion of the embryonic brain, consists of an outer layer of pigmented epithelium and an inner layer of neural tissue. Contained within the latter layer are the sensory rod and cone cells, the bipolar and horizontal cells that comprise the intraretinal afferent pathway from the rods and cones, and the multipolar ganglion cells, the axons of which are the fibers of the optic nerve. The cones, which number approximately 7 million in the human eye, have a relatively high threshold to light energy. They are responsible for sharp visual discrimination and color vision. The rods, of which there are over 100 million, are much more sensitive to light than the cones; they provide the ability to see in twilight and at night. In the retinal macula, near the posterior pole of the eye, the cone population achieves its greatest density; within the macula, the fovea centralis--a small pit totally comprised of tightly packed slender cones--provides the sharpest visual acuity and is the anatomic basis for foveal, or central, vision. The remainder of the eye is capable of far less visual acuity and subserves paracentral and peripheral vision.

Having dendritic connections with the rods and cones, the bipolar cells provide axons that synapse with the dendrites or cell bodies of the multipolar ganglion cells, whose axons in turn course parallel to the retinal surface and converge at the optic disc. Emerging from the eye as the optic nerve, they meet their counterparts from the opposite eye in the optic chiasm and then continue in one of the optic tracts, most likely to terminate in a lateral geniculate body, but possibly in a superior colliculus or the pretectal area. Second order neurons from the lateral geniculate body comprise the geniculocalcarine tract, which becomes the optic radiation and terminates in the primary visual cortex, the striate area of the occipital cerebral cortex (Area 17). In the visual cortex, the retinal image is represented as a more or less point-to-point projection from the lateral geniculate body, which receives a similarly topographically structured projection from both retinas. The lateral geniculate body and the primary visual cortex are thus structurally and functionally suited for the recognition and analysis of visual images. The superior colliculi project to the visual association areas (Areas 18 and 19) of the cerebral cortex via the pulvinar, and also eventually to the motor nuclei of the extraocular muscles and muscles of the neck, and appear to provide a pathway for certain gross ocular reflexes of visual origin. Fibers entering the pretectal area are involved in pupillary reflexes. In addition, most anatomic and physiologic evidence indicates that information from the occipital visual association areas, parietal cerebral cortex, and frontal eye movement area (Area 8) is relayed through the paramedian pontine reticular formation to the nuclei of the cranial nerves innervating the extraocular muscles. Via this pathway and perhaps others involving the superior colliculi, saccadic (fast) and pursuit (slow) eye movements are initiated and controlled.

Visual-Vestibular Convergence

Vision in humans and other primates is highly dependent on cerebral cortical structure and function, whereas vestibular orientation primarily involves more primitive anatomic structures. Yet visual and vestibular orientational processes are by no means independent. We know that visually perceived motion information and probably other visual orientational data reach the vestibular nuclei in the brain stem[2,3], but it appears that the integration of visual and vestibular information is to a large extent accomplished in the cerebral cortex of humans.

The geniculostriate projection system is divided both anatomically and functionally into two parts: that incorporating the parvocellular layers of the lateral geniculate body (the "parvo" system) and that incorporating the magnocellular layers (the "magno" system). These systems are largely segregated in the primary visual cortex, undergo further segregation in the visual association cortex, and ultimately terminate in the temporal and parietal lobes, respectively. The parvo system neurons have smaller, more centrally located receptive fields that exhibit high spatial resolution (acuity), and they respond well to color; they do not, however, respond well to rapid motion or high flicker rates. The magno cells, by comparison, have larger receptive fields and respond better to motion and flicker, but are relatively insensitive to color differences. Magno neurons generally exhibit poorer spatial resolution, although they seem to respond better than parvo neurons at low luminance contrasts. In general, the parvo system is better at detecting small, slowly moving, colored targets located near the center of the visual field, while the magno system is more capable of processing rapidly moving and optically degraded stimuli across larger regions of the visual field.

What is important about these two components of the geniculostriate system is that the parvo system projects ventrally to the inferior temporal areas, which are involved in visual search, pattern recognition, and visual object memory, while the magno system projects dorsally to the posterior parietal and superior temporal areas, which are specialized for motion information processing. The cerebral cortical areas to which the parvo system projects receive virtually no vestibular afferents; the areas to which the magno system projects, on the other hand, receive significant vestibular and other sensory inputs, and are believed to be highly involved with maintaining spatial orientation.

The posterior parietal region projects heavily to cells of the pontine nuclei, which in turn provide the mossy-fiber visual input to the cerebellar cortex. Via the accessory optic and central tegmental tracts, visual information also reaches the inferior olives, which provide climbing fiber input to the cerebellar cortex. The cerebellar cortex, specifically its flocculonodular lobe and vermis, also receives direct mossy-fiber input from its vestibular system. Thus, the cerebellum is another area of very strong visual-vestibular convergence. Furthermore, the cerebellar Purkinje cells have inhibitory connections in the vestibular nuclei and possibly even in the vestibular end-organs; so visual-vestibular interactions mediated by the cerebellum also occur at the level of the brain stem, and maybe even peripherally.

Finally, there is a confluence of visual and vestibular pathways in the paramedian pontine reticular formation. Integration of visual and vestibular information in the cerebellum and brain stem appears to allow visual control of basic equilibratory reflexes of vestibular origin. As might be expected there also are afferent vestibular influences on visual system nuclei; these influences have been demonstrated in the lateral geniculate body and especially the superior colliculus.

Visual Information Processing

Primary control of the human ability to move and orient oneself in three-dimensional space is mediated by the visual system, as exemplified by the fact that individuals without functioning vestibular systems ("labyrinthine defectives") have virtually no problems with spatial orientation unless they are deprived of vision. The underlying mechanisms of visual orientation-information processing are revealed by receptive field studies, which have been accomplished for the peripheral retina, nuclear relays, and primary visual cortex. Basically, these studies show that there are several types of movement-detecting neurons and that these neurons respond differently to the direction of movement, velocity of movement, size of the stimulus, its orientation in space, and the level of illumination. (For an excellent review of this fascinating topic, see Grüsser and Grüsser-Cornehls.[4])

As evidenced by the division of the primate geniculostriate system into two separate functional entities, however, vision must be considered as two separate processes. Some researchers emphasize the role of the ventral (parvo) system in object recognition (the "what" system) and that of the dorsal (magno) system in spatial orientation (the "where" system); others categorize the difference in terms of form (occipito-temporal) versus motion (occipito-parietal) processing. A recent theory suggests that the dorsal system is primarily involved in processing information in peripersonal (near) space during reaching and other visuomotor activity, whereas the ventral system is principally engaged in visual scanning in extrapersonal (far) visual space.[5] In the present discussion, we shall refer to the two systems as the "focal" and "ambient" visual systems, respectively, subserving the focal and ambient modes of visual processing. Certain aspects of yet another visual process, the one responsible for generating eye movements, will also be described.

Focal Vision

Liebowitz and Dichgans[6] have provided a very useful summary of the characteristics of focal vision:

> [The focal visual mode] is concerned with object recognition and identification and in general answers the question of "what." Focal vision involves relatively fine detail (high spatial frequencies) and is correspondingly best represented in the central visual fields. Information processed by focal vision is ordinarily well represented in consciousness and is critically related to physical parameters such as stimulus energy and refractive error.

Focal vision uses the central 30 degrees or so of the visual field. While it is not primarily involved with orienting the individual in the environment, it certainly contributes to conscious percepts of orientation, such as those derived from judgments of distance and depth and those obtained from reading flight instruments.

Tredici[7] categorized the visual cues to distance and depth as monocular or binocular. The monocular cues are (1) size constancy, the size of the retinal image in relation to known and comparative sizes of objects; (2) shape constancy, the shape of the retinal image in relation to the known shape of the object (e.g., the foreshortening of the image of a known circle into an ellipsoid shape means one part of the circle is farther away than another); (3) motion parallax (also called optical flow), the greater displacement of retinal images of nearer objects when an individual is moving linearly in the environment; (4) interposition, the partial obstruction from view of more distant objects by nearer ones; (5) texture or gradient, the apparent loss of detail with greater distance; (6) linear perspective, the convergence of parallel lines at a distance; (7) illumination perspective, which results from the tendency to perceive the light source to be above an object and from the association of more deeply shaded parts of an object with being farther from the light source; and (8) aerial perspective, the perception of objects to be more distant when the image is relatively bluish or hazy.

The binocular cues to depth and distance are (1) stereopsis, the visual appreciation of three-dimensional space that results from the fusion of slightly dissimilar retinal images of an object; (2) vergence, the medial rotation of the eyes and the resulting direction of their gaze along more or less converging lines, depending on whether the viewed object is closer or farther, respectively; and (3) accommodation, or focusing of the image by changing the curvature of the lens of the eye. Of all the cues listed, size and shape constancy and motion parallax appear to be most important for deriving distance information in flying, and they are available at and well beyond the distances at which binocular cues are useful. Stereopsis can provide orientation information at distances up to only about 200 m; it is, however, more important in orientation than vergence and accommodation, which are useless beyond about 6 m.

Ambient Vision

Liebowitz and Dichgans[6] have also provided a summary of ambient vision:

> The ambient visual mode subserves spatial localization and orientation and is in general concerned with the question of "where." Ambient vision is mediated by relatively large stimulus patterns so that it typically involves stimulation of the peripheral visual field and relatively coarse detail (low spatial frequencies). Unlike focal vision, ambient vision is not systematically related to either stimulus energy or optical image quality. Rather, provided the stimulus is visible, orientation responses appear to be elicited on an "all or none" basis....The conscious concomitant of ambient stimulation is low or frequently completely absent.

Ambient vision, therefore, is primarily involved with orienting the individual in the environment. Furthermore, this function is largely independent of the function of focal vision. This becomes evident in view of the fact that one can fully occupy central vision with the task of reading while simultaneously obtaining sufficient orientation cues with peripheral vision to walk or ride a bicycle. It is also evidenced by the ability of certain patients with cerebral cortical lesions to maintain visual orientation responses even though their ability to discriminate objects is lost.

While we commonly think of ambient vision as dependent on stimulation of peripheral visual fields, it is more accurate to consider ambient vision as involving large areas of the total visual field, which of course must include the visual periphery. In other words, ambient vision is not so much location-dependent as it is area-dependent. Moreover, ambient vision is stimulated much more effectively by large images or groups of images perceived to be at a distance than by those appearing to be close.

The function of ambient vision in orientation can be thought of as two processes, one providing motion cues and the other providing position cues. Large, coherently moving contrasts detected over a large area of the visual field result in vection, i.e., a visually induced percept of self-motion. If the moving contrasts revolve relative to the subject, he or she perceives rotational self-motion or angular vection (also called circular vection), which can be in the pitch, roll, yaw, or any intermediate plane. If the moving contrasts enlarge and diverge from a distant point, become smaller and converge in the distance, or otherwise indicate linear motion, the percept of self-motion that results is linear vection, which also can be in any direction. Vection can, of course, be veridical or illusory, depending on whether actual or merely apparent motion of the subject is occurring. One can appreciate the importance of ambient vision in orientation by recalling the powerful sensations of self-motion generated by certain scenes in wide-screen motion pictures (e.g., flying through the Grand Canyon in an IMAX theater).

Position cues provided by ambient vision are readily evidenced in the stabilization of posture that vision affords patients with defective vestibular or spinal proprioceptive systems. The essential visual parameter contributing to postural stability appears to be the motion of the retinal image that results from minor deviations from one's desired postural position. Visual effects on posture also can be seen in the phenomenon of height vertigo. As the distance from (height above) a stable visual environment increases, the amount of body sway necessary for the retinal image movement to be above threshold increases. Above a certain height, the ability of this visual mechanism to contribute to postural stability is exceeded, and vision indicates posture to be stable despite large body sways. The conflict between visual orientation information, indicating relative stability, and the vestibular and somatosensory data, indicating large body sways, results in the unsettling experience of vertigo.

One more distinction between focal and ambient visual function should be emphasized. In general, focal vision serves to orient the perceived object relative to the individual, whereas ambient vision serves to orient the individual relative to the perceived environment. When both focal and ambient vision are present, orienting a focally perceived object relative to the ambient visual environment is easy, whether the mechanism employed involves first orienting the object to oneself and then orienting oneself and the object to the environment or involves orienting the object directly to the environment. When only focal vision is available, however, it can be difficult to orient oneself correctly to a focally perceived environmental orientation cue because the natural tendency is to perceive oneself as stable and upright and to perceive the focally viewed object as oriented with respect to the stable and upright egocentric reference frame. This phenomenon can cause a pilot to misjudge his or her approach to a night landing, for example, when only the runway lights and a few other focal visual cues are available for spatial orientation.

Eye Movements

We distinguish between two fundamental types of eye movement: smooth movements, including pursuit, vergence, and those driven by the vestibular system; and saccadic (jerky) movements. Smooth eye movements are controlled at least in part by the posterior parietal cerebral cortex and surrounding areas, as evidenced by functional deficits resulting from damage to these areas. Eye movements of vestibular origin are primarily generated by very basic reflexes involving brain stem mechanisms; and because visual pursuit eye movements are impaired by vestibular and certain cerebellar lesions, the vestibular system appears to be involved in control of smooth eye movements of visual origin. Saccadic eye movements are controlled mainly by the frontal eye fields of the cerebral cortex, which work with the superior colliculus in generating these movements. The frontal eye fields receive their visual input from the cortical visual association areas.

The maintenance of visual orientation in a dynamic motional environment is greatly enhanced by the ability to move the eyes, primarily because the retinal image of the environment can be stabilized by appropriate eye movements. Very powerful and important mechanisms involved in reflexive vestibular stabilization of the retinal image will be discussed in the section dealing with vestibular function. Visual pursuit movements also serve to stabilize the retinal image, as long as the relative motion between the head and the visual environment (or object being observed in it) is less than about 60°/sec: targets moving at higher relative velocities necessitate either saccadic eye movements or voluntary head movements for adequate tracking. Saccadic eye movements are used voluntarily or reflexively to acquire a target, i.e., to move it into focal vision, or to catch up to a target that cannot be maintained on the fovea by pursuit movements. Under some circumstances, pursuit and saccadic eye movements alternate in a pattern of reflexive slow tracking and fast-back tracking called optokinetic nystagmus. This type of eye-movement response is typically elicited in the laboratory by surrounding the subject with a rotating striped drum; however, one can exhibit and experience optokinetic nystagmus quite readily in a more natural setting by watching railroad cars go by while waiting at a railroad crossing. Movement of the visual environment sufficient to elicit optokinetic nystagmus provides a stimulus that can either enhance or compete with the vestibular elicitation of eye movements, depending on whether the visually perceived motion is compatible or incompatible, respectively, with the motion sensed by the vestibular system.

Vergence movements, which aid binocular distance and motion perception at very close range, are of relatively minor importance in spatial orientation when compared with the image-stabilizing pursuit and saccadic eye movements. Vergence assumes some degree of importance, however, under conditions where a large visual environment is being simulated in a confined space. Failure to account for vergence effects can result in loss of simulation fidelity: a subject whose eyes are converged to fuse an image representing a large, distant object will perceive that object as small and near. To overcome this problem, visual flight simulators display distant scenes at the outer limit of vergence effects (7-10 meters) or use lenses or mirrors to put the displayed scene at optical infinity.

Even though gross stabilization of the retinal image aids object recognition and spatial orientation by enhancing visual acuity, absolute stability of an image is associated with a marked decrease in visual acuity and form perception.[8] This stability-induced decrement is avoided by continual voluntary and involuntary movements of the eyes, even during fixation of an object. We are unaware of these small eye movements, however, and the visual world appears stable.

Voluntary scanning and tracking movements of the eyes are associated with the appearance of a stable visual environment, but why this is so is not readily apparent. Early investigators postulated that proprioceptive information from the extraocular muscles provide not only feedback signals for the control of eye movements but also the afferent information needed to correlate eye movements with retinal image movements and arrive at a subjective determination of a stable visual environment. An alternative mechanism for oculomotor control and the subjective appreciation of visual stability is the "corollary discharge" or feed-forward mechanism first proposed by Helmholtz and subsequently by Sperry[9] and others. Sperry concluded: "Thus, an excitation pattern that normally results in a movement that will cause a displacement of the visual image on the retina may have a corollary discharge into the visual centers to compensate for the retinal displacement. This implies an anticipatory adjustment in the visual centers specific for each movement with regard to its direction and speed." The theoretical aspects of visual perception of movement and stability have been expanded over the years into various models based on "inflow" (afference), "outflow" (efference), and even hybrid sensory mechanisms. The interested reader will enjoy Cohen's concise discussion of these models as they relate to spatial orientation.[10]

In developing the important points on visual orientation, we have emphasized the "focal-ambient" dichotomy. As visual science matures further, this simplistic construct will likely be replaced by more complex but valid models of visual processes. Presently we are enthusiastic about a theory in which the dichotomy emphasized is that between the peripersonal (near) and focal extrapersonal (far) visual realms.[5] This theory argues that the dorsal cortical system and its magno projection pathways are more involved in processing visual information from peripersonal space, while the ventral system and its parvo projections attend to the focal extrapersonal visual environment. The theory also suggests that visual attention is organized to be employed more efficiently in some sectors of three-dimensional visual space than in others (e.g., far vision is biased toward the upper visual field and utilizes local form processing, while near vision is biased toward the lower visual field and is better at global form processing), and that ambient extrapersonal information is largely excluded from attentional mechanisms. Certainly, the current state of knowledge concerning visual orientation is fluid.

VESTIBULAR FUNCTION

The role of vestibular function in spatial orientation is not so overt as that of vision but is extremely important for three major reasons. First, the vestibular system provides the structural and functional substrate for reflexes that serve to stabilize vision when motion of the head and body would otherwise result in blurring of the retinal image. Second, the vestibular system provides orientational information with reference to which both skilled and reflexive motor activities are automatically executed. Third, the vestibular system provides, in the absence of vision, a reasonably accurate percept of motion and position, as long as the pattern of stimulation remains within certain naturally occurring bounds. Because the details of vestibular anatomy and physiology are not usually well known by medical professionals, and because a working knowledge of them is essential to the understanding of spatial disorientation in flight, these details will be presented in the following sections.

Vestibular Anatomy

End-Organs

The vestibular end-organs are smaller than most people realize, measuring just 1.5 cm across. They reside well-protected within some of the densest bone in the body, the petrous portion of the temporal bone. Each temporal bone contains a tortuous excavation known as the bony labyrinth, which is filled with perilymph, a fluid much like cerebrospinal fluid in composition. The bony labyrinth consists of three main parts: the cochlea, the vestibule, and the semicircular canals (Fig. 3). Within each part of the bony labyrinth is a part of the delicate, tubular, membranous labyrinth, which contains endolymph, a fluid characterized by its relatively high concentration of potassium. In the cochlea, the membranous labyrinth is called the cochlear duct or scala media; this organ converts acoustic energy into neural information. In the vestibule lie the two otolith organs, the utricle and the saccule. They translate gravitational and inertial forces into spatial orientation information--specifically, information about angular position (tilt) and linear motion of the head. The semicircular ducts, contained in the semicircular canals, convert inertial torques into information about angular motion of the head. The three semicircular canals and their included semicircular ducts are oriented in three mutually perpendicular planes, thus inspiring the names of the canals: anterior vertical (or superior), posterior vertical (or posterior), and horizontal (or lateral).

The semicircular ducts communicate at both ends with the utricle, and one end of each duct is dilated to form an ampulla. Inside each ampulla lies a crest of neuroepithelium, the crista ampullaris. Atop the crista, occluding the duct, is a gelatinous structure called the cupula (Fig. 4a). The hair cells of which the crista ampullaris is composed project their cilia into the base of the cupula, so that whenever inertial torques of the endolymph ring in the semicircular duct deviate the cupula, the cilia are bent.

Lining the bottom of the utricle is another patch of neuroepithelium, the macula utriculi, whose plane is close to horizontal except for a 20-30° upward slope of its anterior end; and on the medial wall of the saccule in an approximately vertical plane is still another, the macula sacculi (Fig. 4b). The cilia of the hair cells comprising these structures project into overlying otolithic membranes, one above each macula. The otolithic membranes are gelatinous structures containing many tiny calcium carbonate crystals, called otoconia, which are held together by a network of connective tissue. Having almost three times the density of the surrounding endolymph, the otolithic membranes displace endolymph and shift position relative to their respective maculae when subjected to changing gravitoinertial forces. This shifting of the otolithic membrane position results in bending of the cilia of the macular hair cells.

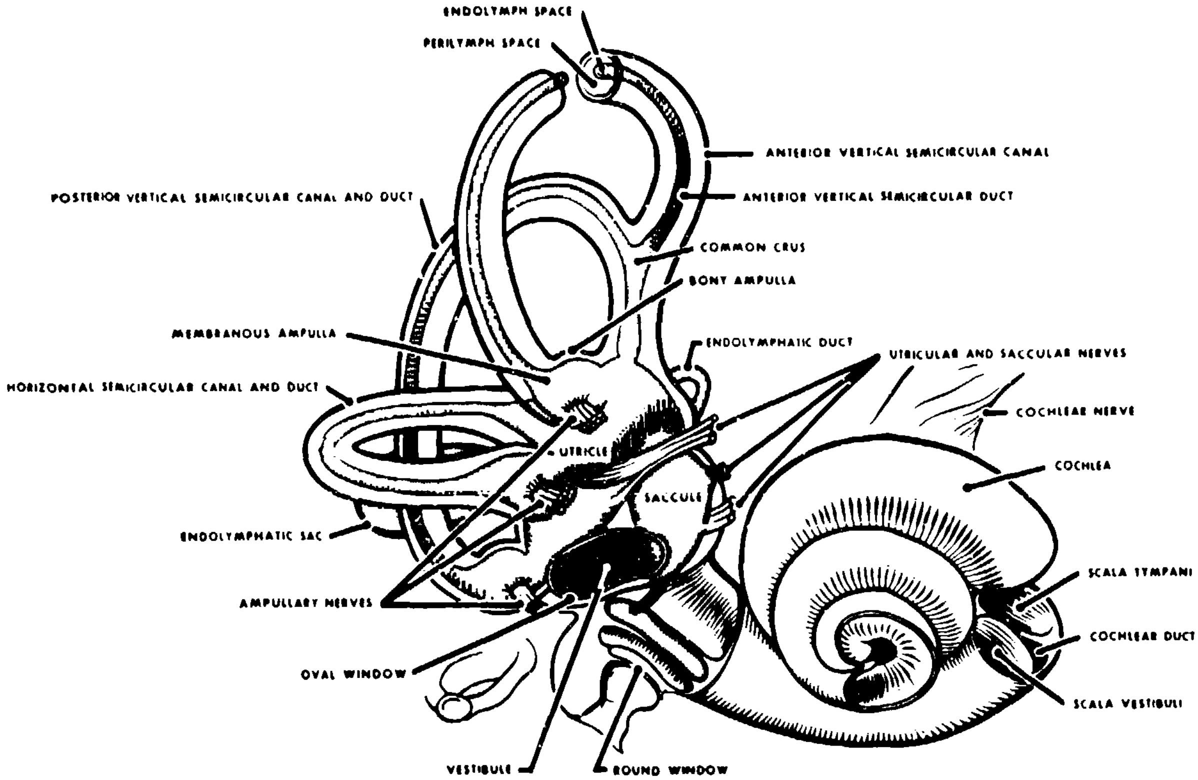


Figure 3. **Gross anatomy of the inner ear.** The bony semicircular canals and vestibule contain the membranous semicircular ducts and otolith organs, respectively.

The hair cell is the functional unit of the vestibular sensory system. It converts spatial and temporal patterns of mechanical energy applied to the head into neural information. Each hair cell possesses one relatively large kinocilium on one side of the top of the cell and up to 100 smaller stereocilia on the same surface. Hair cells thus exhibit morphologic polarization; that is, they are oriented in a particular direction. The functional correlate of this polarization is that when the cilia of a hair cell are bent in the direction of its kinocilium, the cell undergoes an electrical depolarization, and the frequency of action potentials generated in the vestibular neuron attached to the hair cell increases above a certain resting frequency; the greater the deviation of the cilia, the higher the frequency. Similarly, when its cilia are bent away from the side with the kinocilium, the hair cell undergoes an electrical hyperpolarization, and the frequency of action potentials in the corresponding neuron in the vestibular nerve decreases (Fig. 5).

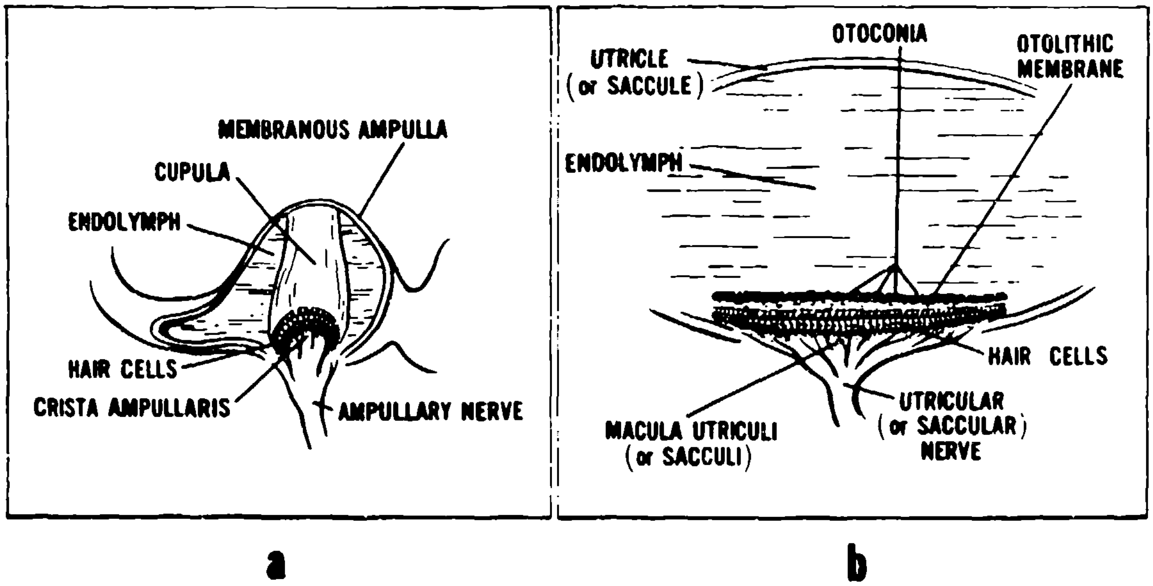


Figure 4. **Vestibular end-organs.** a. The ampulla of a semicircular duct, containing the crista ampullaris and cupula. b. A representative otolith organ, with its macula and otolithic membrane.

The same basic process just described occurs in all the hair cells in the three cristae and both maculae; the important differences lie in the physical events that cause the deviation of cilia in the directions in which the various groups of hair cells are oriented. The hair cells of a crista ampullaris respond to the inertial torque of the ring of endolymph contained in the attached semicircular duct as the reacting endolymph exerts pressure on the cupula and deviates it. The hair cells of a macula, on the other hand, respond to the gravitoinertial force acting to displace the overlying otolithic membrane. As indicated in Figure 6a, all of the hair cells in the crista of the horizontal semicircular duct are oriented so that their kinocilia are on the side of the cell facing the utricle. Thus, utriculopetal endolymphatic pressure on the cupula deviates the cilia of these hair cells toward the kinocilia, and all the hair cells in the crista depolarize. The hair cells in the cristae of the vertical semicircular ducts are oriented in the opposite fashion; that is, their kinocilia are all on the side away from the utricle. In the ampullae of the vertical semicircular ducts, therefore, utriculopetal endolymphatic pressure deviates the cilia away from the kinocilia, causing all the hair cells in these cristae to hyperpolarize. In contrast, the hair cells of the maculae are not oriented unidirectionally across the neuroepithelium: the direction of their morphologic polarization depends on where they lie on the macula (Fig. 6b). In both maculae there is a central line of reflection, on opposing sides of which the hair cells assume an opposite orientation. In the utricular macula, the kinocilia of the hair cells are all oriented toward this line of reflection; whereas in the saccular macula, they are oriented away from it. Because the line of reflection on each macula curves at least 90°, the hair cells, having morphologic polarization roughly perpendicular to this line, exhibit virtually all possible orientations on the plane of the macula. Thus, the orthogonality of the planes of the three semicircular ducts enables them efficiently to detect angular motion in any plane; and the perpendicularity of the planes of the maculae plus the omnidirectionality of the orientation of the hair cells in the maculae allow the efficient detection of gravitoinertial forces acting in any direction.

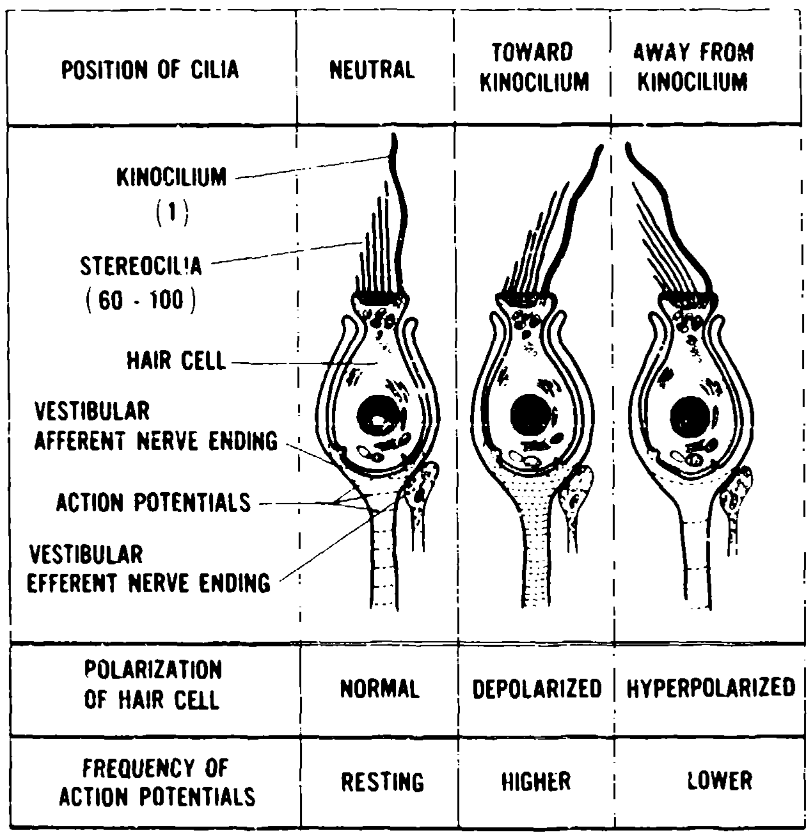


Figure 5. **Function of a vestibular hair cell.** When mechanical forces deviate the cilia toward the side of the cell with the kinocilium, the hair cell depolarizes and the frequency of action potentials in the associated afferent vestibular neuron increases. When the cilia are deviated in the opposite direction, the hair cell hyperpolarizes and the frequency of action potentials decreases.

Neural Pathways

To help the reader better organize the potentially confusing vestibular neuroanatomy, a somewhat simplified overview of the major neural connections of the vestibular system is presented in Figure 7. The utricular nerve, two saccular nerves, and the three ampullary nerves converge to form the vestibular nerve, a portion of the VIIIth cranial or statoacoustic nerve. Within the vestibular nerve lies the vestibular (or Scarpa's) ganglion, which is comprised of the cell bodies of the vestibular neurons. The dendrites of these bipolar neurons invest the hair cells of the cristae and maculae; most of their axons terminate in the four vestibular nuclei in the brain stem--the superior, medial, lateral, and inferior nuclei--but some axons enter the phylogenetically ancient parts of the cerebellum to terminate in the fastigial nuclei and in the cortex of the flocculonodular lobe and other parts of the posterior vermis.

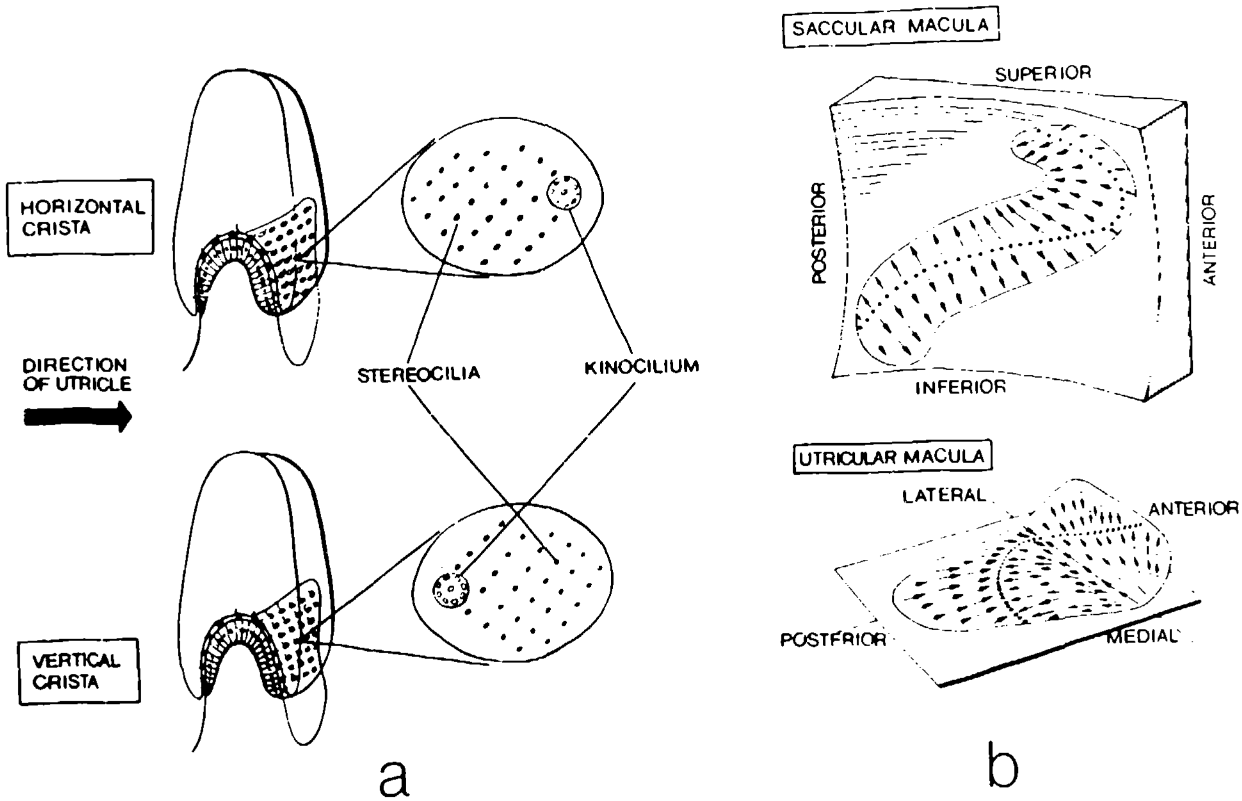


Figure 6. Morphologic polarization in vestibular neuroepithelia. a. All the hair cells in the cristae of the horizontal semicircular ducts are oriented so that their kinocilia are in the direction of the utricle; those hair cells in the cristae of the vertical ducts have their kinocilia directed away from the utricle. b. The maculae of the saccule (above) and utricle (below) also exhibit polarization: the arrows indicate the direction of the kinocilia of the hair cells in the various regions of the maculae. (Adapted from Spoendlin.[11])

The vestibular nuclei project via secondary vestibular tracts to motor nuclei of cranial and spinal nerves and to the cerebellum. Because vestibulo-ocular reflexes are a major function of the vestibular system, it is not surprising to find ample projections from the vestibular nuclei to the nuclei of the oculomotor, trochlear, and abducens nerves (cranial nerves III, IV, and VI, respectively). The major pathway of these projections is the ascending medial longitudinal fasciculus (MLF). The basic vestibulo-ocular reflex is thus served by sensor and effector cells and an intercalated three-neuron reflex arc from the vestibular nerve to the vestibular nuclei to the nuclei innervating the extraocular muscles. In addition, indirect multisynaptic pathways course from the vestibular nuclei through the paramedian pontine reticular formation to the oculomotor and other nuclei. The principle of ipsilateral facilitation and contralateral inhibition via an interneuron clearly operates in vestibulo-ocular reflexes, and numerous crossed internuclear connections provide evidence of this. The vestibulo-ocular reflexes that the various ascending and crossed pathways support serve to stabilize the retinal image by moving the eyes in the direction opposite that of the motion of the head.

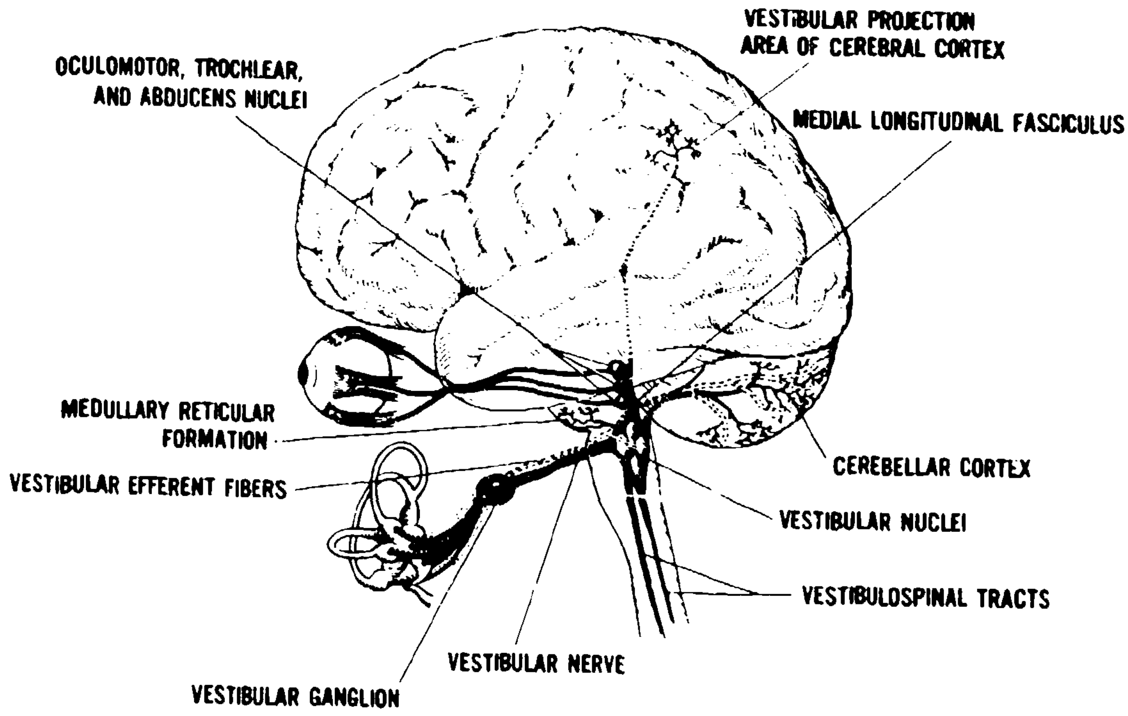


Figure 7. Major connections and projections of the vestibular system.

Via the descending MLF and medial vestibulospinal tract, crossed and uncrossed projections from the vestibular nuclei reach the nuclei of the spinal accessory nerve (cranial nerve XI) and motor nuclei in the cervical cord. These projections form the anatomic substrate for vestibulocollic reflexes, which serve to stabilize the head by appropriate action of the sternocleidomastoid and other neck muscles. A third projection is that from primarily the lateral vestibular nucleus into the ventral gray matter throughout the length of the spinal cord. This important pathway is the uncrossed lateral vestibulospinal tract, which enables the vestibulospinal (postural) reflexes to help stabilize the body with respect to an inertial frame of reference by means of sustained and transient vestibular influences on basic spinal reflexes.

Secondary vestibulocerebellar fibers course from the vestibular nuclei into the ipsilateral and contralateral fastigial nuclei and to the cerebellar cortex of the flocculonodular lobe and elsewhere. Returning from the fastigial and other cerebellar nuclei, crossed and uncrossed fibers of the cerebellobulbar tract terminate in the vestibular nuclei and in the associated reticular formation. There are also efferent fibers from the cerebellum, probably arising in the cerebellar cortex, that terminate not in nuclear structures but on dendritic endings of primary vestibular afferent neurons in the vestibular neuroepithelia. Such fibers are those of the vestibular efferent system, which appears to modulate or control the information arising from the vestibular end-organs. The primary and secondary vestibulocerebellar fibers and those returning from the cerebellum to the vestibular area of the brain stem comprise the juxtarestiform body of the inferior cerebellar peduncle. This structure, along with the vestibular end-organs, nuclei, and projection areas in the cerebellum, collectively constitute the so-called vestibulocerebellar axis, the neural complex responsible for processing primary spatial orientation information and initiating adaptive and protective behavior based on that information.

Several additional projections, more obvious functionally than anatomically, are those to certain autonomic nuclei of the brainstem and to the cerebral cortex. The dorsal motor nucleus of cranial nerve X (vagus) and other autonomic cell groups in the medulla and pons receive secondary vestibular fibers, largely from the medial vestibular nucleus; these fibers mediate vestibulovegetative reflexes, which are manifested in the symptons of motion sickness (pallor, perspiration, nausea, and vomiting) that can result from excessive or otherwise abnormal vestibular stimulation. Via vestibulothalamic and thalamocortical pathways, vestibular information eventually reaches the primary vestibular projection area of the cerebral cortex, located in the parietal and parieto-temporal cortex. This projection area is provided with vestibular, visual, and somatosensory (proprioceptive) inputs and is evidently associated with spatial orientation processing and with integration of higher-order sensorimotor activity. In addition, vestibular information can be transmitted via long polysynaptic pathways through the brain stem reticular formation and medial thalamus to wide areas of the cerebral cortex; the nonspecific cortical responses to vestibular stimuli that are evoked via this pathway appear to be associated with an arousal or alerting mechanism.

Vestibular Information Processing

As the reader probably deduced while reading the discussion of the anatomy of the vestibular end-organs, angular accelerations are the adequate (that is, physiologic) stimuli for the semicircular ducts, and linear accelerations and gravity are the adequate stimuli for the otolith organs. This statement, illustrated in Figure 8, is the cardinal principle of vestibular mechanics. How the reactive torques and gravitoinertial forces stimulate the hair cells of the cristae and maculae, respectively, and produce changes in the frequency of action potentials in the associated vestibular neurons has already been discussed. The resulting frequency-coded messages are transmitted into the several central vestibular projection areas as raw orientational data to be further processed as necessary for the various functions served by such data. These functions are the vestibular reflexes, voluntary movement, and the perception of orientation.

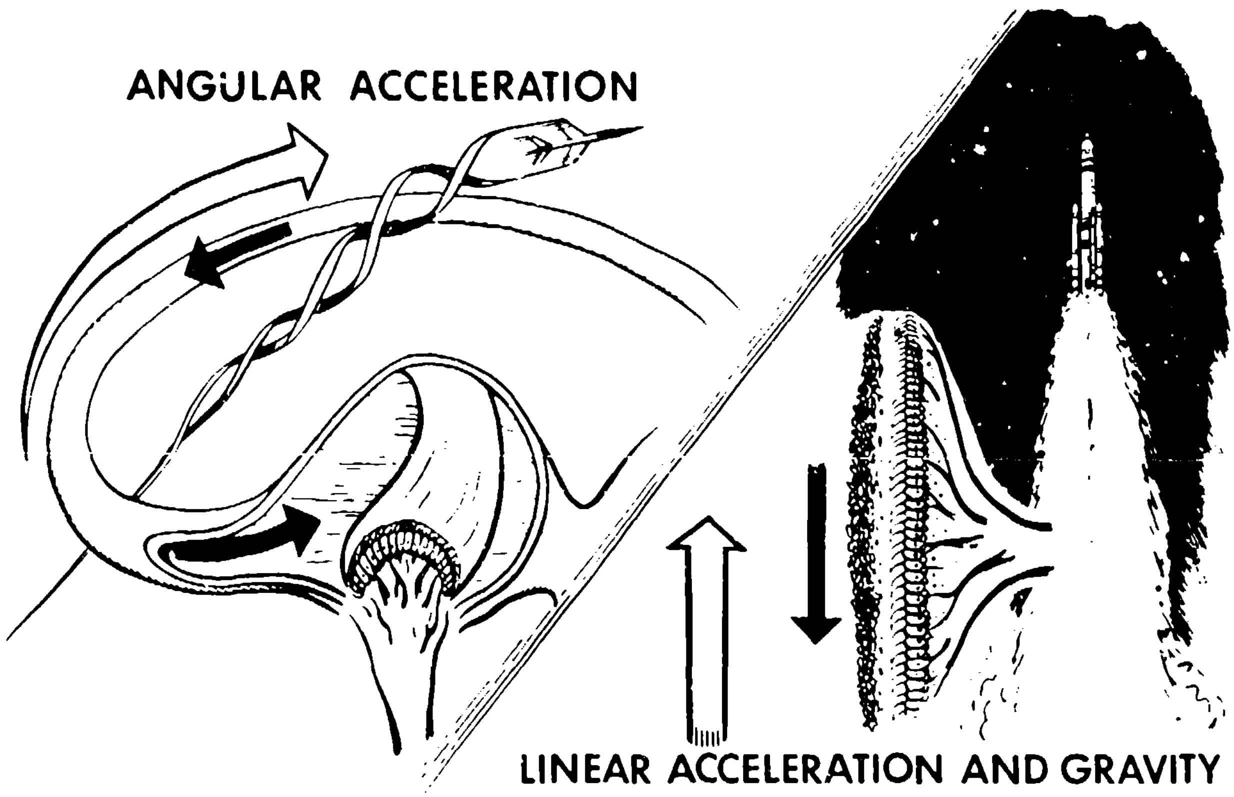


Figure 8. The cardinal principle of vestibular mechanics: angular accelerations stimulate the semicircular ducts; linear accelerations and gravity stimulate the otolith organs.

Vestibular Reflexes

As stated so well by G. Melvill Jones[12], "...for control of eye movement relative to space the motor outflow can operate on three fairly discrete anatomical platforms, namely: (1) the eye-in-skull platform, driven by the external eye muscles rotating the eyeball relative to the skull; (2) the skull-on-body platform driven by the neck muscles; and (3) the body platform, operated by the complex neuromuscular mechanisms responsible for postural control."

In humans, the retinal image is stabilized mainly by vestibulo-ocular reflexes, primarily those of semicircular-duct origin. A simple demonstration can help one appreciate the contribution of the vestibulo-ocular reflexes to retinal-image stabilization. Holding the extended fingers half a meter or so in front of the face, one can move the fingers slowly from side to side and still see them clearly because of visual (optokinetic) tracking reflexes. As the rate, or correspondingly, the frequency, of movement becomes greater, one eventually reaches a point where the fingers cannot be seen clearly--they are blurred by the movement. This point is at about 60°/sec or 1 to 2 Hz for most people. Now, if the fingers are held still and the head is rotated back and forth at the frequency at which the fingers became blurred when they were moved, the fingers remain perfectly clear. Even at considerably higher frequencies of head movement, the vestibulo-ocular reflexes initiated by the resulting stimulation of the semicircular ducts function to keep the image of the fingers clear. Thus, at lower frequencies of movement of the external world relative to the body or vice versa, the visual system stabilizes the retinal image by means of optokinetic reflexes. As the frequencies of such relative movement become greater, however, the vestibular system, by means of vestibulo-ocular reflexes, assumes progressively more of this function; and at the higher frequencies of relative motion characteristically generated only by motions of the head and body, the vestibular system is responsible for stabilizing the retinal image.

The mechanism by which stimulation of the semicircular ducts results in retinal image stabilization is simple, at least conceptually (Fig. 9). When the head is turned to the right in the horizontal (yaw) plane, the angular acceleration of the head creates a reactive torque in the ring of endolymph in (mainly) the horizontal semicircular duct. The reacting endolymph then exerts pressure on the cupula, deviating the cupula in the right ear in a utriculopetal direction, depolarizing the hair cells of the associated crista ampullaris and increasing the frequency of the action potentials in the corresponding ampullary nerve. In the left ear, the endolymph deviates the cupula in a utriculofugal direction, thereby hyperpolarizing the hair cells and decreasing the frequency of the action potentials generated. As excitatory neural signals are relayed to the contralateral lateral rectus and ipsilateral medial rectus muscles, and inhibitory signals are simultaneously relayed to the antagonists, a conjugate deviation of the eyes results from the described changes in ampullary neural activity. The direction of this conjugate eye deviation is thus the same as that of the angular reaction of the endolymph, and the angular velocity of the eye deviation is proportional to the pressure exerted by the endolymph on the cupula. The resulting eye movement is, therefore, compensatory; that is, it adjusts the angular position of the eye to compensate for changes in angular position of the head and thereby prevents slippage of the retinal image over the retina. Because the amount of angular deviation of the eye is physically limited, rapid movements of the eye in the direction opposite the compensatory motion are employed to return the eye to its initial position or to advance it to a position from which it can sustain a compensatory sweep for a suitable length of time. These rapid eye movements are anticompensatory; and because of their very high angular velocity, motion is not perceived during this phase of the vestibulo-ocular reflex.

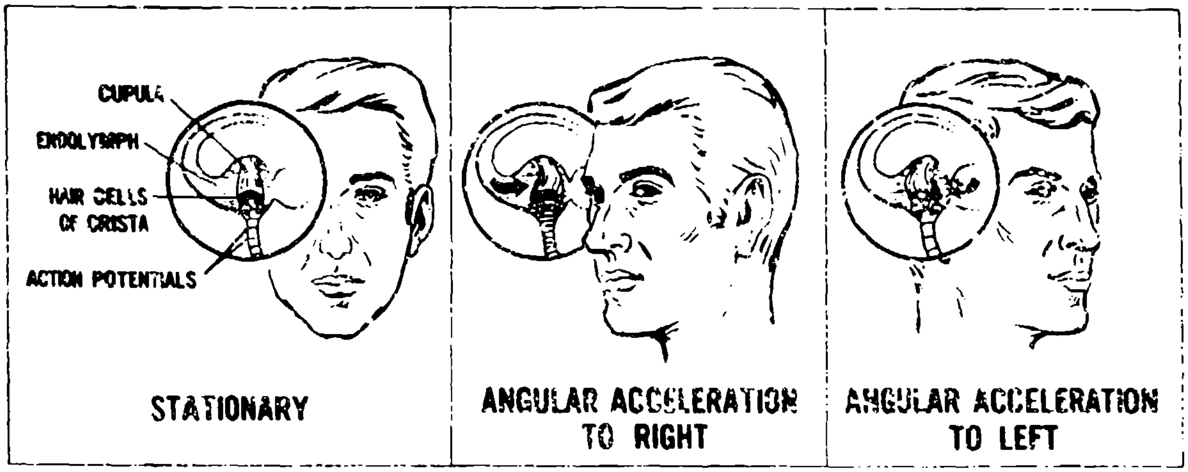


Figure 9 **Mechanism of action of a horizontal semicircular duct and the resulting reflex eye movement.** Angular acceleration to the right increases the frequency of action potentials originating in the right ampullary nerve and decreases those in the left. This pattern of neural signals causes extraocular muscles to rotate the eyes in the direction opposite that of head rotation, thus stabilizing the retinal image with a compensatory eye movement. Angular acceleration to the left has the opposite effect.

With the usual rapid, high-frequency rotations of the head, the rotational inertia of the endolymph acts to deviate the cupula as the angular velocity of the head builds, and the angular momentum gained by the endolymph during the brief acceleration acts to drive the cupula back to its resting position when the head decelerates to a stop. The cupula-endolymph system thus functions as an integrating angular accelerometer; that is, it converts angular acceleration data into a neural signal proportional to the angular velocity of the head. This is true for angular accelerations occurring at frequencies normally encountered in terrestrial activities; when angular accelerations outside the dynamic response range of the cupula-endolymph system are experienced, the system no longer provides accurate angular velocity information. When angular accelerations are relatively sustained or when a cupula is kept in a deviated position by other means, such as caloric testing, the compensatory and anticompensatory phases of the vestibulo-ocular reflex are repeated, resulting in beats of ocular nystagmus (Fig. 10). The compensatory phase of the vestibulo-ocular reflex is then called the slow phase of nystagmus, and the anticompensatory phase is called the fast or quick phase. The direction of the quick phase is used to label the direction of the nystagmus because the direction of the rapid motion of the eye is easier to detect clinically. The vertical semicircular ducts operate in an analogous manner, with the vestibulo-ocular reflexes elicited by their stimulation being appropriate to the plane of the angular acceleration resulting in that stimulation. Thus, a vestibulo-ocular reflex with downward compensatory and upward anti-compensatory phases results from the stimulation of the vertical semicircular ducts by pitch-up ($-\alpha_y$) angular acceleration; and with sufficient stimulation in this plane, up-beating vertical nystagmus results. Angular accelerations in the roll plane result in vestibulo-ocular reflexes with clockwise and counterclockwise compensatory and anticompensatory phases and in rotary nystagmus. Other planes of stimulation are associated with other directions of eye movement such as oblique or horizonto-rotary.

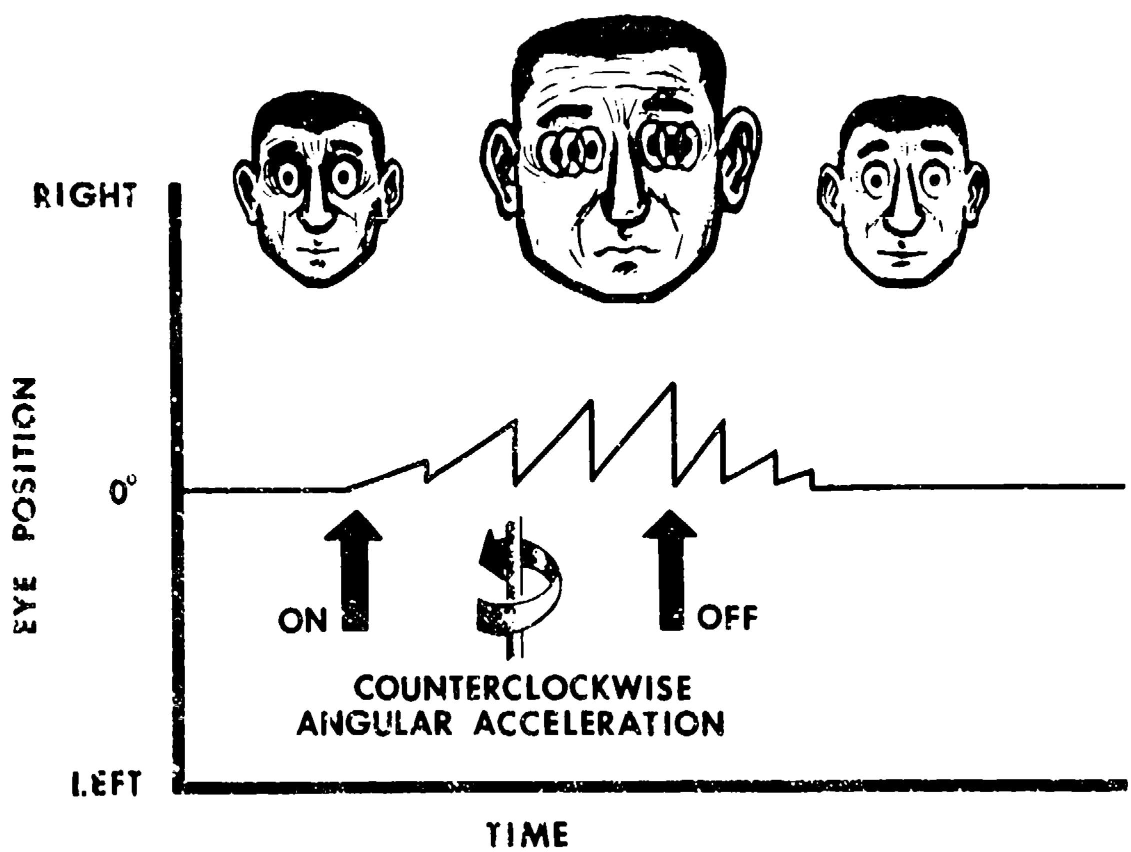


Figure 10. Ocular nystagmus--repeating compensatory and anticompensatory eye movements--resulting from vestibular stimulation. In this case, the stimulation is a yawing angular acceleration to the left, and the anticompensatory, or quick-phase, nystagmic response is also to the left.

As should be expected, there also are vestibulo-ocular reflexes of otolith-organ origin. Initiating these reflexes are the shearing actions that bend the cilia of macular hair cells as inertial forces or gravity cause the otolithic membranes to slide to various positions over their maculae (Fig. 11). Each position that can be assumed by an otolithic membrane relative to its macula evokes a particular spatial pattern of frequencies of action potentials in the corresponding utricular or saccular nerve, and that pattern is associated with a particular set of compatible stimulus conditions such as backward tilt of the head or forward linear acceleration. These patterns of action potentials from the various otolith organs are correlated and integrated in the vestibular nuclei and cerebellum with orientational information from the semicircular ducts and other sensory modalities; appropriate orientational percepts and motor activities eventually result. Lateral (a_y) linear accelerations can elicit horizontal reflexive eye movements, including nystagmus, presumably as a result of utricular stimulation. Similarly, vertical (a_z) linear accelerations can elicit vertical eye movements, most likely as a result of stimulation of the saccule; the term elevator reflex is sometimes used to describe this response because it is readily provoked by the vertical linear accelerations associated with riding in an elevator. The utility of these horizontal and vertical vestibulo-ocular reflexes of otolith-organ origin is readily apparent: like the reflexes of semicircular-duct origin, they help stabilize the retinal image. Less obvious is the usefulness of the ocular countertorsion reflex (Fig. 12), which repositions the eyes about their visual (anteroposterior) axes in response to the otolith-organ stimulation resulting from tilting the head laterally in the opposite direction. Presumably, this reflex contributes to retinal image stabilization by providing a response to changing directions of the force of gravity.

Our understanding of the vestibulocollic reflexes has not developed to the same degree as our understanding of the vestibulo-ocular reflexes, although some clinical use has been made of measurements of rotation of the head on the neck in response to vestibular stimulation. Perhaps this situation reflects the fact that vestibulocollic reflexes are not as effective as the vestibulo-ocular reflexes in stabilizing the retinal image, at least not in humans. Such is not the case in other species, however; birds exhibit extremely effective reflex control of head position under conditions of bodily motion--even nystagmic head movements are quite easy to elicit. The high level of development of the vestibulocollic reflexes in birds is certainly either a cause or a consequence of the relative immobility of birds' eyes in their heads. Nonetheless, the ability of a human (or any other vertebrate with a mobile head) to keep the head upright with respect to the direction of applied gravitoinertial force is maintained through tonic vestibular influences on the muscles of the neck.

Vestibulospinal reflexes operate to assure stability of the body. Transient linear and angular accelerations, such as those experienced in tripping and falling, provoke rapid activation of various groups of extensor and flexor muscles to return the body to the stable position or at least to minimize the ultimate effect of the instability. Everyone has experienced the reflex arm movements that serve to break a fall, and most have observed the more highly developed righting reflexes that cats exhibit when dropped from an upside-down position;

these are examples of vestibulospinal reflexes. Less spectacular, but nevertheless extremely important, are the sustained vestibular influences on posture that are exerted through tonic activation of so-called "antigravity" muscles such as hip and knee extensors. These vestibular reflexes, of course, help keep the body upright with respect to the direction of the force of gravity.

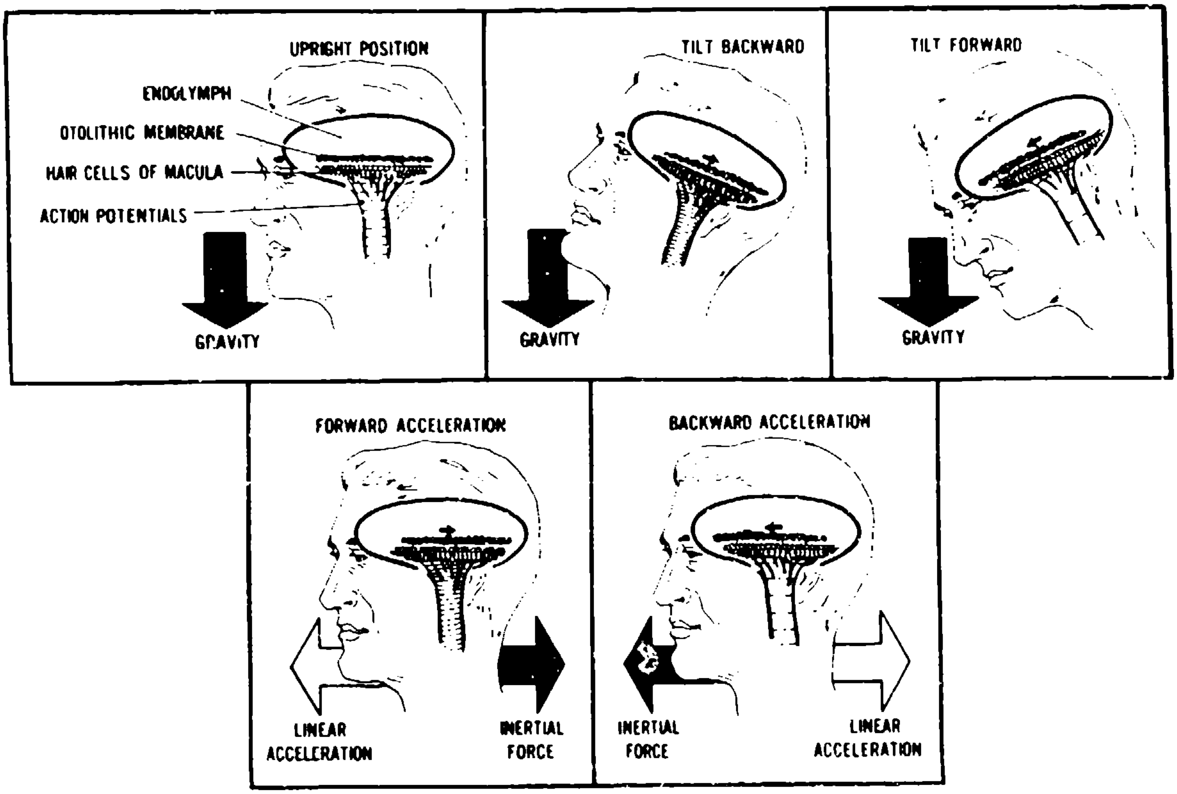


Figure 11. Mechanism of action of an otolith organ. A change in direction of the force of gravity (above) or a linear acceleration (below) causes the otolithic membrane to shift its position with respect to its macula, thereby generating a new pattern of action potentials in the utricular or saccular nerve. Shifting of the otolithic membranes can elicit compensatory vestibulo-ocular reflexes and nystagmus, as well as perceptual effects.

Voluntary Movement

It has been shown how the various reflexes of vestibular origin serve to stabilize the body in general and the retinal image in particular. The vestibular system is also important in that it provides data for the proper execution of voluntary movement. To realize just how important such vestibular data are in this context, one must first recognize the fact that skilled voluntary movements are preprogrammed; that is, once initiated, they are executed according to a predetermined pattern and sequence, without the benefit of simultaneous sensory feedback to the higher neural levels from which they originate. The simple act of writing one's signature, for example, involves such rapid changes in speed and direction of movement that conscious sensory feedback and adjustment of motor activity are virtually precluded, at least until the act is nearly completed. Learning an element of a skill thus involves developing a computer-program-like schedule of neural activations that can be called up, so to speak, to effect a particular desired end product of motor activity. Of course, the raw program for a particular voluntary action is not sufficient to permit the execution of that action: information regarding such parameters as intended magnitude and direction of movement must be furnished from the conscious sphere, and data indicating the position and motion of the body platform relative to the surface of the earth--that is, spatial orientation information--must be furnished from the preconscious sphere. The necessity for the additional information can be seen in the signature-writing example cited above: one can write large or small, quickly or slowly, and on a horizontal or vertical surface. Obviously, different patterns of neuromuscular activation, even grossly different muscle groups, are needed to accomplish a basic act under varying spatial and temporal conditions; the necessary adjustments are made automatically, however, without conscious intervention. Vestibular and other sensory data providing spatial orientation information for use in either skilled voluntary or reflexive motor activity are processed into a preconscious orientational percept that provides the informational basis upon which such automatic adjustments are made. Thus, one can decide what the outcome of his or her action is to be and initiate the command to do it, without consciously having to discern the direction of the force of gravity, analyze its potential effects on planned motor activity, select appropriate muscle groups and modes of activation to compensate for gravity, and then activate and deactivate each muscle in proper sequence and with proper timing to accomplish the desired motor activity. The body takes care of the details, using stored programs for elements of skilled motor activity, and the current preconscious orientational percept. This whole process is the major function and responsibility of the vestibulocerebellar axis.

Conscious Percepts

Usually as a result of the same information processing that provides the preconscious orientational percept, one also is provided a conscious orientational percept. This percept can be false, that is, illusory, in which case the individual is said to experience an orientational illusion, or to have spatial disorientation. We can be aware, moreover, that what our bodies tell us about our spatial orientation is not what can be concluded from other information such as flight instrument data. Conscious orientational percepts thus can be either natural or derived, depending on the source of the orientation information and the perceptual process involved; and an individual can experience both natural and derived conscious orientational percepts at the same time. Consequently, pilots who have become disoriented in flight commonly exhibit vacillating control inputs, as they alternate indecisively between responding first to one percept and then to the other.

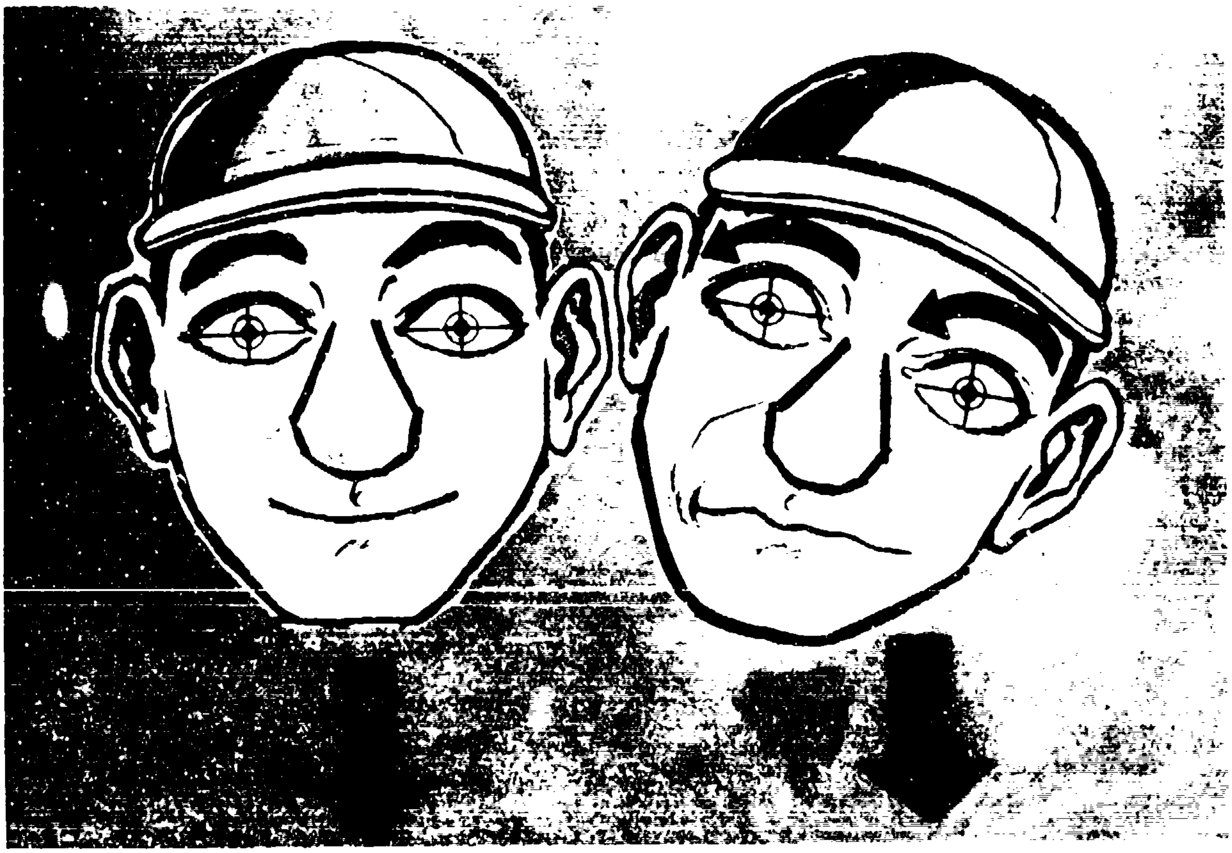


Figure 12. Ocular countertorsion, a vestibulo-ocular reflex of otolith-organ origin. When the head is tilted to the left, the eyes rotate to the right to assume a new angular position about the visual axes, as shown.

Thresholds of Vestibular Perception

Often an orientational illusion occurs because the physical event resulting in a change in bodily orientation is below the threshold of perception. For that reason, the student of disorientation should be aware of the approximate perceptual thresholds associated with the various modes of vestibular stimulation.

The lowest reported threshold for perception of rotation is $0.035°/sec^2$, but this degree of sensitivity is obtained only with virtually continuous angular acceleration and long response latencies (20 to 40 seconds).[13] Other observations put the perceptual threshold between roughly 0.1 and 2.0°/sec^2; reasonable values are 0.14, 0.5, and 0.5°/sec^2 for yaw, roll, and pitch motions, respectively.[14] It is common practice, however, to describe the thresholds of the semicircular ducts in terms of the angular acceleration-time product, or angular velocity, which results in just perceptible rotation. This product, known as Mulder's constant, remains fairly constant for stimulus times of about 5 seconds or less. Using the reasonable value of 2°/sec for Mulder's constant, an angular acceleration of 5°/sec^2 applied for half a second would be perceived because the acceleration-time product is above the 2°/sec angular velocity threshold. But a 10°/sec^2 acceleration applied for a tenth of a second would not be perceived because it would be below the angular velocity threshold; nor would a 0.2°/sec^2 acceleration applied for 5 seconds be perceived. Inflight experiments have shown that blindfolded pilot subjects are not able to consistently perceive roll rates of 1.0°/sec or less, but can perceive a roll when the velocity is 2.0°/sec or higher. Pitch rate thresholds in flight are also between 1.0 and 2.0°/sec. But when aircraft pitch motions are coupled with compensatory power adjustments to keep the net G force always directed toward the aircraft floor, the pitch threshold is raised well above 2.0°/sec.[15]

The perceptual threshold related to otolith-organ function necessarily involves both an angle and a magnitude because the otolith organs respond to linear accelerations and gravitoinertial forces, both of which have direction and intensity. A 1.5° change in direction of applied G force is perceptible under ideal (experimental) conditions. The minimum perceptible intensity of linear acceleration has been reported by various authors to be between 0.001 and 0.03 g, depending on the direction of acceleration and the experimental method used. Values of 0.01 g for a_z and 0.006 g for a_x accelerations are appropriate representative thresholds, and a similar value for a_y acceleration is probably reasonable. Again, these absolute thresholds apply when the acceleration is either sustained or applied at relatively low frequencies. The threshold for linear accelerations applied for less than about 5 seconds is a more or less constant acceleration-time product, or linear velocity, of about 0.3 to 0.4 m/sec.

Unfortunately for those who would like to calculate exactly what orientational percept results from a particular set of linear and angular accelerations (e.g., those occurring prior to an aircraft mishap), the actual vestibular perceptual thresholds are, as expressed by one philosopher, "constant except when they vary." Probably the most common reason for an orientational perceptual threshold to be raised is inattention to orientational cues because attention is directed to something else. Other reasons might be a low state of mental arousal, fatigue, drug effects, or innate individual variation. Whatever the reason, it appears that individuals can monitor their orientation with considerable sensitivity under some circumstances and with relative insensitivity under others, which inconsistency can itself lead to perceptual errors that result in orientational illusions.

Of paramount importance in the generation of orientational illusions, however, is not the fact that absolute vestibular thresholds exist or that vestibular thresholds are time-varying. Rather, it is the fact that the components of the vestibular system, like any complex mechanical or electrical system, have characteristic frequency responses; and stimulation by patterns of acceleration outside the optimal, or "design," frequency-response ranges of the semicircular ducts and otolith organs causes the vestibular system to make errors. In flight, much of the stimulation resulting from the acceleratory environment is indeed outside the design frequency-response ranges of the vestibular end-organs; consequently, orientational illusions occur in flight. Elucidation of this important point is provided in the section entitled "Spatial Disorientation."

Vestibular Suppression and Enhancement

Like all sensory systems, the vestibular system exhibits a decreased response to stimuli that are persistent (adaptation) or repetitious (habituation). Even more important to the aviator is the fact that, with time and practice, one can develop the ability to suppress natural vestibular responses, both perceptual and motor. This ability is termed vestibular suppression.[16] Closely related to the concept of vestibular suppression is that of visual dominance, the ability to obtain and use spatial orientation cues from the visual environment despite the presence of potentially strong vestibular cues. Vestibular suppression seems to be exerted, in fact, through visual dominance because it disappears in the absence of vision.[17] The opposite effect, that of an increase in perceptual and motor responsiveness to vestibular stimulation, is termed vestibular enhancement. Such enhancement can occur (1) when the stimulation is novel, as in an amusement park ride; (2) threatening, as in an aircraft spinning out of control; or (3) whenever spatial orientation is perceived to be especially important. It is tempting to attribute to the efferent vestibular neurons the function of controlling the gain of the vestibular system so as to effect suppression and enhancement, and some evidence exists to support that notion.[18] The actual mechanisms involved appear to be much more complex than would be necessary merely to provide gross changes in the gain of the vestibular end-organs. Precise control of vestibular responses to anticipated stimulation, based on sensory efferent copies of voluntary commands for movement, is probably exercised by the cerebellum via a feed-forward loop involving the vestibular efferent system. Thus, when discrepancies between anticipated and actual stimulation generate a neural error signal, a response is evoked, and vestibular reflexes and heightened perception occur.[19] Vestibular suppression, then, involves the development of accurate estimates of vestibular responses to orientational stimuli repeatedly experienced, and the active countering of anticipated responses by spatially and temporally patterned sensory efferent activity. Vestibular enhancement, on the other hand, results from the lack of available estimates of vestibular responses because of the novelty of the stimulation, or perhaps from a revision in neural processing strategy obligated by the failure of normal negative feed-forward mechanisms to provide adequate orientation information. Such marvelous complexity of vestibular function assures adaptability to a wide variety of motional environments and thereby promotes survival in them.

OTHER SENSES OF MOTION AND POSITION

Although the visual and vestibular systems play dominant roles in spatial orientation, the contributions of other sensory systems to orientation cannot be overlooked. Especially important are the nonvestibular proprioceptors--the muscle, tendon, and joint receptors--and the cutaneous exteroceptors, because the orientational percepts derived from their functioning in flight generally support those derived from vestibular information processing, whether accurate or inaccurate. The utility of these other sensory modalities can be appreciated in view of the fact that, in the absence of vision, our vestibular, muscle, tendon, joint, and skin receptors allow us to maintain spatial orientation and postural equilibrium, at least on the earth's surface. Similarly, in the absence of vestibular function, vision and the remaining proprioceptors and cutaneous mechanoreceptors are sufficient for orientation and balance. When two components of this triad of orientational senses are absent or substantially compromised, however, it becomes impossible to maintain sufficient spatial orientation to permit postural stability and effective locomotion. The following limited discussion of the nonvisual, nonvestibular, orientational sensory modalities should not imply that they are either unstudied or uninteresting. On the contrary, a large body of knowledge has accumulated in this area, and the reader is referred elsewhere for comprehensive reviews of this subject matter.[20,21]

Nonvestibular Proprioceptors

Sherrington's "proprioceptive" or "self-sensing" sensory category includes the vestibular (or labyrinthine), muscle, tendon, and joint senses. Proprioception generally is spoken of as though it means only the nonvestibular components, however.

Muscle and Tendon Senses

All skeletal muscle contains within it complex sensory end-organs called muscle spindles (Fig. 13a). These end-organs are comprised mainly of small intrafusal muscle fibers that lie in parallel with the larger, ordinary, extrafusal muscle fibers and are enclosed over part of their length by a fluid-filled bag. The sensory innervation of these structures consists mainly of large, rapidly conducting afferent neurons that originate as primary (annulospiral) or secondary (flower-spray) endings on the intrafusal fibers and terminate in the spinal cord on anterior horn cells and interneurons. Stretching of the associated extrafusal muscle results in an increase in the frequency of action potentials in the afferent nerve from the intrafusal fibers; contraction of the muscle results in a decrease or absence of action potentials. The more interesting aspect of muscle spindle function, however, is that the intrafusal muscle fibers are innervated by motoneurons (gamma efferents and others) and can be stimulated to contract, thereby altering the afferent information arising from the spindle.

Thus, the sensory input from the muscle spindles can be biased by descending influences from higher neural centers such as the vestibulocerebellar axis.

Although the muscle spindles are structurally and functionally in parallel with associated muscle groups and respond to changes in their length, the Golgi tendon organs (Fig. 13b) are functionally in series with the muscles and respond to changes in tension. A tendon organ consists of a fusiform bundle of small tendon fascicles with intertwining neural elements, and is located at the musculotendinous junction or wholly within the tendon. Unlike that of the muscle spindle, its innervation is entirely afferent.

The major function of both the muscle spindles and the tendon organs is to provide the sensory basis for myotatic (or muscle stretch) reflexes. These elementary spinal reflexes operate to stabilize a joint by providing, in response to an increase in length of a muscle and concomitant stimulation of its included spindles, monosynaptic excitation and contraction of the stretched agonist (e.g., extensor) muscle and disynaptic inhibition and relaxation of its antagonist (e.g., flexor) muscle through the action of an inhibitory interneuron. In addition, tension developed on associated tendon organs results in disynaptic inhibition of the agonist muscle, thus regulating the amount of contraction generated. The myotatic reflex mechanism is, in fact, the foundation of posture and locomotion. Modification of this and other basic spinal reflexes by organized facilitatory or inhibitory intervention originating at higher neural levels, either through direct action on skeletomotor (alpha) neurons or through stimulation of fusimotor (primarily gamma) neurons to muscle spindles, results in sustained postural equilibrium and other purposive motor behavior. Some researchers have speculated, moreover, that in certain types of spatial disorientation in flight, this organized modification of spinal reflexes is interrupted as cerebral cortical control of motor activity is replaced by lower brainstem and spinal control. Perhaps the "frozen-on-the-controls" type of disorientation-induced deterioration of flying ability is a reflection of primitive reflexes made manifest by disorganization of higher neural functions.

Despite the obvious importance of the muscle spindles and tendon organs in the control of motor activity, there is little evidence to indicate that their responding to orientational stimuli (such as occur when one stands vertically in a 1-G environment) results in any corresponding conscious proprioceptive percept.[22] Nevertheless, it is known that the dorsal columns and other ascending spinal tracts carry muscle afferent information to medullary and thalamic relay nuclei and thence to the cerebral sensory cortex. Furthermore, extensive projections into the cerebellum, via dorsal and ventral spinocerebellar tracts, ensure that proprioceptive information from the afferent terminations of the muscle spindles and tendon organs is integrated with other orientational information and is relayed to the vestibular nuclei, cerebral cortex, and elsewhere as needed.

Joint Sensation

In contrast to the situation with the so-called "muscle sense of position" just discussed, it has been well established that sensory information from the joints does reach consciousness. In fact, the threshold for perception of joint motion and position can be quite low: as low as 0.5° for the knee joint when moved at greater than 1.0°/sec. The receptors in the joints are of three types, as shown in Figure 13c: (1) lamellated or encapsulated Pacinian corpuscle-like end-organs; (2) spray-type structures, known as Ruffini-like endings when found in joint capsules and Golgi tendon organs when found in ligaments; and (3) free nerve endings. The Pacinian corpuscle-like terminals are rapidly adapting and are sensitive to quick movement of the joint, whereas both of the spray-type endings are slowly adapting and serve to signal slow joint movement and joint position. There is evidence that polysynaptic spinal reflexes can be elicited by stimulation of joint receptors, but their nature and extent are not well understood. Proprioceptive information from the joint receptors projects via the dorsal funiculi eventually to the cerebral sensory cortex and via the spinocerebellar tracts to the anterior lobe of the cerebellum.

One must not infer from this discussion that only muscles, tendons, and joints have proprioceptive sensory receptors. Both lamellated and spray-type receptors, as well as free nerve endings, are found in fascia, aponeuroses, and other connective tissues of the musculoskeletal system, and they presumably provide proprioceptive information to the central nervous system as well.

Cutaneous Exteroceptors

The exteroceptors of the skin include the: (1) mechanoreceptors, which respond to touch and pressure; (2) thermoreceptors, which respond to heat and cold; and (3) nociceptors, which respond to noxious mechanical and/or thermal events and give rise to sensations of pain. Of the cutaneous exteroceptors, only the mechanoreceptors contribute significantly to spatial orientation.

A variety of receptors are involved in cutaneous mechanoreception: spray-type Ruffini corpuscles, lamellated Pacinian and Meissner corpuscles, branched and straight lanceolate terminals, Merkel cells, and free nerve endings (Fig. 13d). The response patterns of mechanoreceptors also are numerous: eleven different types of response, varying from high-frequency transient detection through several modes of velocity detection to more or less static displacement detection, have been recognized. Pacinian corpuscles and certain receptors associated with hair follicles are very rapidly adapting and have the highest mechanical frequency responses, responding to sinusoidal skin displacements in the range of 50 to 400 Hz. They are thus well suited to monitor vibration and transient touch stimuli. Ruffini corpuscles are slowly adapting and, therefore, respond primarily to sustained touch and pressure stimuli. Merkel cells appear to have a moderately slowly adapting response, making them suitable for monitoring static skin displacement and velocity. Meissner corpuscles seem to detect primarily velocity of skin deformation. Other receptors provide other types of response, so as to complete the spectrum of mechanical stimuli that can be sensed through the skin. The mechanical threshold for the touch receptors is quite low--less than 0.03 dyne/cm^2 on the thumb. (In comparison with the labyrinthine receptors subserving audition, however, this threshold is not so impressive: a 0-dB sound pressure level represents 0.0002 dyne/cm^2, more than 100 times lower.) Afferent information from the described mechanoreceptors is conveyed to the cerebral cortex mainly by way of the dorsal funiculi and medullary relay nuclei into the medial lemnisci and thalamocortical projections. The dorsal spinocerebellar tract and other tracts to the cerebellum provide the pathways by which cutaneous exteroceptive information reaches the cerebellum and is integrated with proprioceptive information from muscles, tendons, joints, and vestibular end-organs.

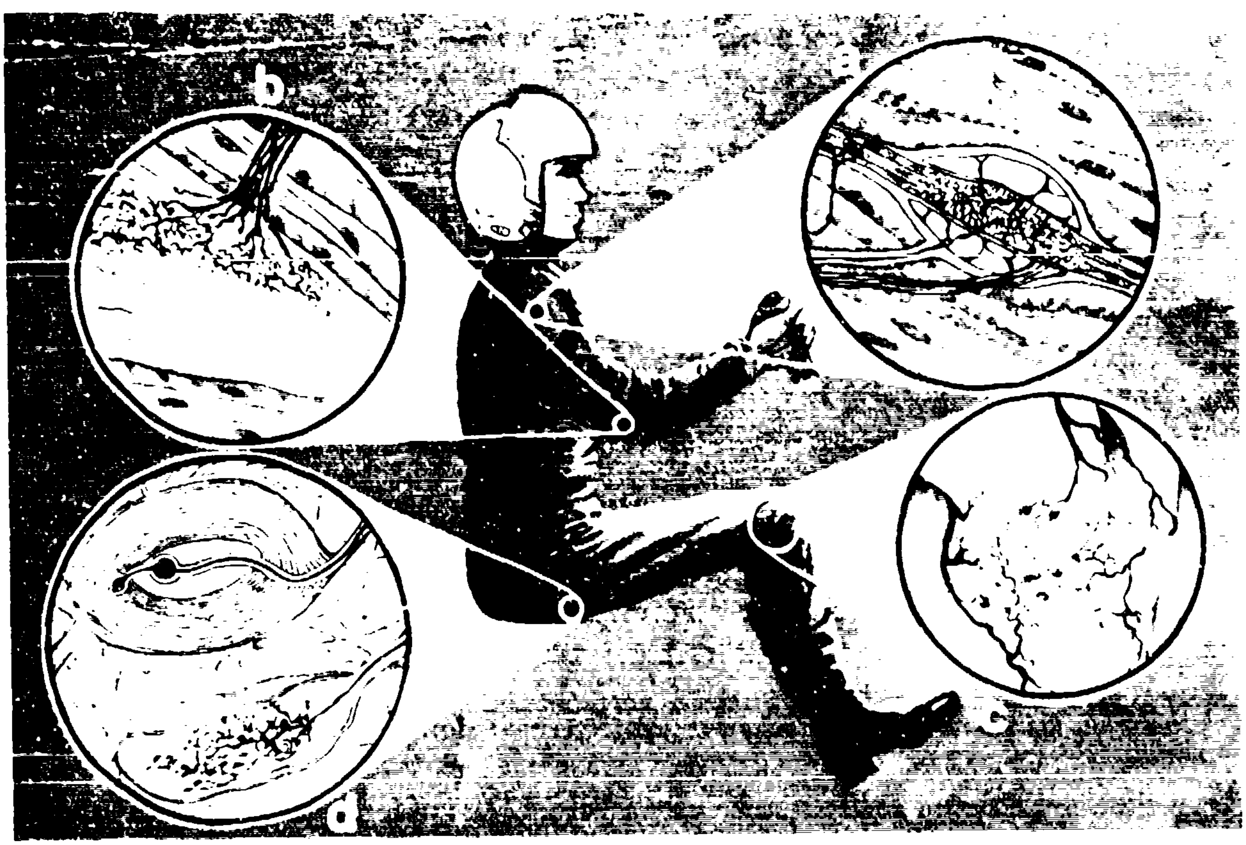


Figure 13. Some of the nonvestibular proprioceptive and cutaneous exteroceptive receptors subserving spatial orientation. a. Muscle spindle, with central afferent (sensory) and more peripheral efferent (fusimotor) innervations. b. Golgi tendon organ. c. Lamellated, spray-type, and free-nerve-ending joint receptors. d. Two of the many types of mechanoreceptors found in the skin: lamellated Pacinian corpuscles and spray-type Ruffini corpuscles.

Auditory Orientation

On the surface of the earth, the ability to determine the location of a sound source can play a role in spatial orientation, as evidenced by the fact that a revolving sound source can create a sense of self-rotation and even elicit reflex compensatory and anticompensatory eye movements called audiokinetic nystagmus. Differential filtering of incident sound energy by the external ear, head, and shoulders at different relative locations of the sound source provides the ability to discriminate sound location. Part of this discrimination process involves analysis of interaural differences in arrival time of congruent sounds; but direction-dependent changes in spectral characteristics of incident sound energies allow the listener to localize sounds in elevation and azimuth (and to some extent range), even when the interaural arrival times are not different. In aircraft, binaural sound localization is of little use in spatial orientation because of high ambient noise levels and the absence of audible external sound sources. Pilots do extract some orientation information, however, from the auditory cues provided by the rush of air past the airframe: the sound frequencies and intensities characteristic of various airspeeds and angles of attack are recognized by the experienced pilot, who uses them in conjunction with other orientation information to create a percept of velocity and pitch attitude of the aircraft. As aircraft have become more capable, however, and the pilot has become more insulated from such acoustic stimuli, the usefulness of aircraft-generated auditory orientation cues has diminished.

SPATIAL DISORIENTATION

The evolution of humans saw them develop over millions of years as aquatic, terrestrial, and even arboreal creatures, but never aerial ones. In this development, humans subjected themselves to and were subjected to many different varieties of transient motions, but not to the relatively sustained linear and angular accelerations commonly experienced in aviation. As a result, we acquired sensory systems well suited for maneuvering under our own power on the surface of the earth but poorly suited for flying. Even the birds, whose primary mode of locomotion is flying, are unable to maintain spatial orientation and fly safely when deprived of vision by fog or clouds. Only bats seem to have developed the ability to fly without vision, and then only by replacing vision with auditory echolocation. Considering our phylogenetic heritage, it should come as no surprise that our sudden entry into the aerial environment resulted in a mismatch between the orientational demands of the new environment and our innate ability to orient. The manifestation of this mismatch is spatial disorientation.

Illusions in Flight

An illusion is a false percept. An orientational illusion is a false percept of one's position or motion--either linear or angular--relative to the plane of the earth's surface. A great number of orientational illusions occur during flight: some named, others unnamed; some understood, others not understood. Those that are sufficiently impressive to cause pilots to report them, whether because of their repeatability or because of their emotional impact, have been described in the aeromedical literature and will be discussed here. The illusions in flight are categorized into those resulting from visual misperceptions and those involving vestibular errors.

Visual Illusions

We shall organize the visual illusions in flight according to whether they involve primarily the focal mode of visual processing or primarily the ambient mode. Although this categorization is somewhat arbitrary and may seem too coarse in some cases, it serves to emphasize the dichotomous nature of visual orientation information processing. We begin with illusions involving primarily focal vision. (Many of the visual illusions related in this section were first described by Pitts.[23])

Shape Constancy

To appreciate how false shape constancy cuing can create orientational illusions in flight, consider the example provided by a runway that is constructed on other than level terrain. Figure 14a shows the pilot's view of the runway during an approach to landing and demonstrates the linear perspective and foreshortening of the runway that the pilot associates with a 3° approach slope. If the runway slopes upward 1° (a rise of only 35 m in a 2-km runway), the foreshortening of the runway for a pilot on a 3° approach slope is substantially less (the height of the retinal image of the runway is greater) than it would be if the runway were level. This can give the pilot the illusion of being too high on the approach. The pilot's natural response to such an illusion is to reshape the image of the runway by seeking a shallower approach slope (Fig. 14b). This response, of course, could be hazardous. The opposite situation results when the runway slopes downward. To perceive the accustomed runway shape under this condition, the pilot flies a steeper approach slope than usual (Fig. 14c).

Size Constancy

Size constancy is very important in judging distance, and false cues are frequently responsible for aircraft mishaps due to illusions of focal visual origin. The runway width illusions are particularly instructive in this context. Figure 15a shows the accustomed runway width and a normal approach. A runway that is narrower than that to which a pilot is accustomed can create a hazardous illusion on the approach to landing. Size constancy causes the pilot to perceive the narrow runway to be farther away (i.e., the aircraft is higher) than is actually the case; hence, the pilot may flare too late and touch down sooner than expected (Fig. 15b). Likewise, a runway that is wider than expected can lead to the perception of being closer to the runway (i.e., lower) than is actually the case, and the pilot may flare too soon and drop in from too high above the runway (Fig. 15c). Both of these runway-width illusions are especially troublesome at night when peripheral visual orientation cues are largely absent. The common tendency for pilots to flare too high at night results at least partly from the fact that the runway lights, being displaced laterally from the actual edge of the runway, make the runway seem wider, and therefore closer, than it actually is. A much more serious problem at night, however, is the tendency for pilots to land (or crash) short of the runway when arriving at an unfamiliar airport having a runway that is narrower than the one to which they are accustomed.

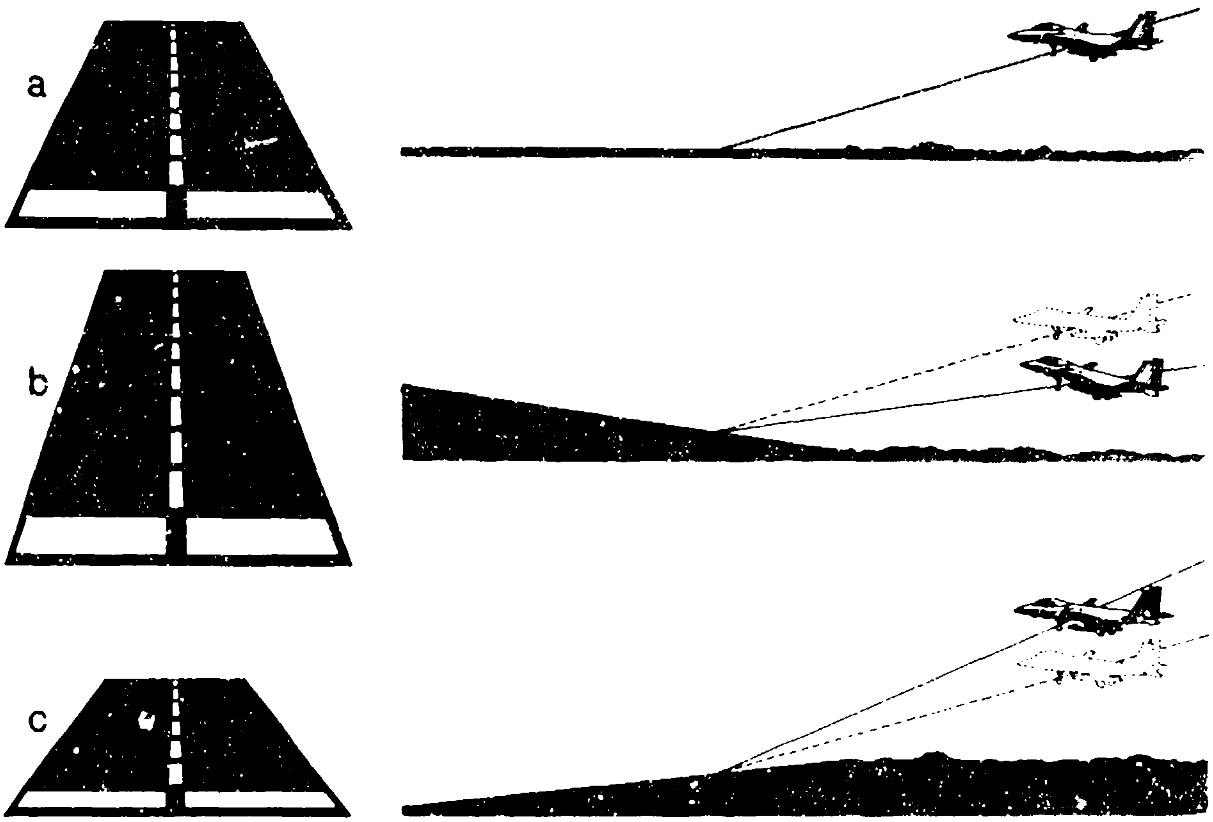


Figure 14. Effect of runway slope on the pilot's image of runway during final approach (left) and potential effect on the approach slope angle flown (right). a. Flat runway--normal approach. b. An upsloping runway creates the illusion of being high on approach--pilot flies the approach too low. c. A downsloping runway has the opposite effect.

The slope and composition of the terrain under the approach path also can influence the pilot's judgment of height above the touchdown point. If the terrain descends to the approach end of the runway, the pilot tends to fly a steeper approach than if the approach terrain were level (Fig. 16a). If the approach terrain slopes up to the runway, on the other hand, the pilot tends to fly a less steep approach (Fig. 16b). Although the estimation of height above the approach terrain depends on both focal and ambient vision, the contribution of focal vision is particularly clear: consider the pilot who looks at a building below and, seeing it to be closer than such buildings usually are, seeks a higher approach slope. By the same token, focal vision and size constancy are responsible for poor height and distance judgments pilots sometimes make when flying over terrain having an unfamiliar composition (Fig. 17). A reported example of this is the tendency to misjudge the approach height when landing in the Aleutians, where the evergreen trees are much smaller than those to which most pilots are accustomed. Such height-estimation difficulties are by no means restricted to the approach and landing phases of flight. One fatal mishap occurred during air combat training over the Southwest desert when the pilot of a high-performance fighter aircraft presumably misjudged the aircraft's height over the desert floor because of the small, sparse vegetation and was unable to arrest a deliberate descent to a ground-hugging altitude.

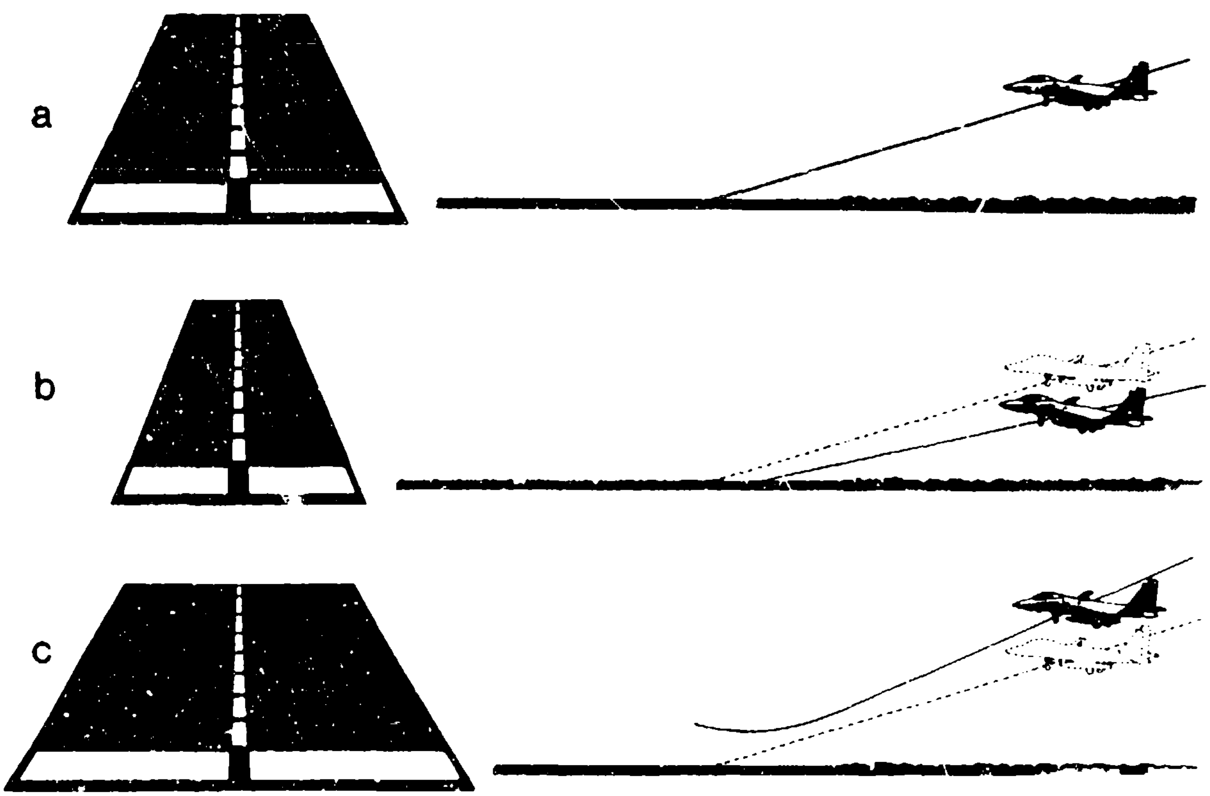


Figure 15. Effect of runway width on the pilot's image of runway (left) and the potential effect on approach flown (right). a. Accustomed width--normal approach. b. A narrow runway makes the pilot feel the aircraft is higher than it actually is, which results in the approach being too low and the flare being too late. c. A wide runway gives the illusion of being closer than it actually is--the pilot tends to approach too high and flares too soon.

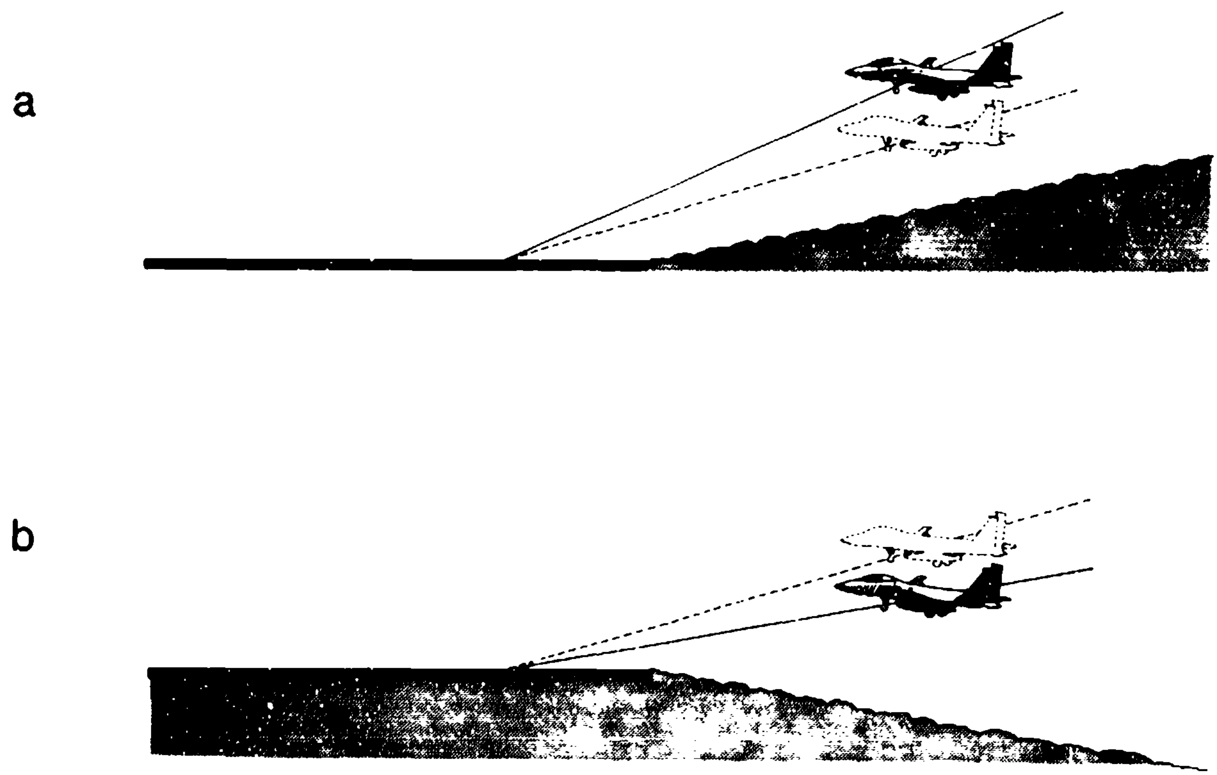


Figure 16. Potential effect of the slope of the terrain under the approach on the approach slope flown. a. The terrain slopes down to the runway; the pilot thinks the approach is too shallow and steepens it. b. Upsloping terrain makes the pilot think the aircraft is too high, which is corrected by making the approach too shallow.

Aerial Perspective

Aerial perspective also can play a role in deceiving the pilot, and the approach-to-landing regime again provides examples. In daytime, fog or haze can make a runway appear farther away as a result of the loss of visual discrimination. At night, runway and approach lights in fog or rain appear less bright than they do in clear weather and can create the illusion that they are farther away. It has even been reported that a pilot can have an illusion of being banked to the right, for example, if the runway lights are brighter on the right side of the runway than they are on the left. Another hazardous illusion of this type can occur during approach to landing in a shallow fog or haze, especially during a night approach. The vertical visibility under such conditions is much better than the horizontal visibility, so that descent into the fog causes the more distant approach or runway lights to diminish in intensity at the same time that the peripheral visual cues are suddenly occluded by the fog. The result is an illusion that the aircraft has pitched up, with the concomitant danger of a nose-down corrective action by the pilot.

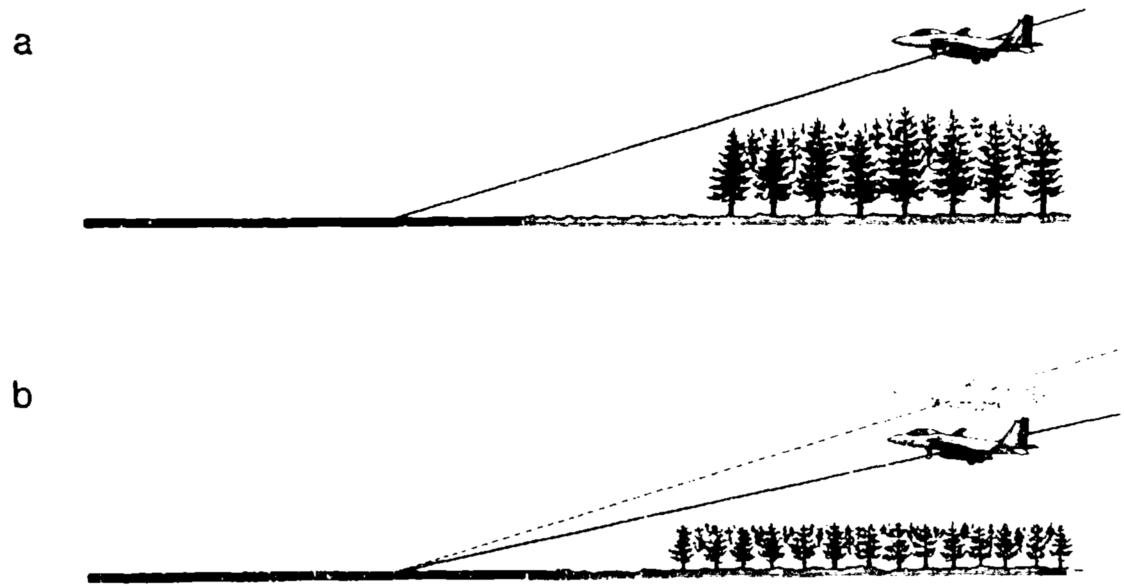


Figure 17. Potential effect of unfamiliar composition of approach terrain on the approach slope flown. a. Normal approach over trees of familiar size. b. Unusually small trees under the approach path make the pilot think the aircraft is too high, leading to a lower-than-normal approach.

Absent Focal Cues

A well-known pair of approach-to-landing situations that create illusions because of the absence of adequate focal visual orientation cues are the smooth-water (or glassy-water) and snow-covered approaches. In a seaplane, one's perception of height is degraded substantially when the water below is still: for that reason, a seaplane pilot routinely just sets up a safe descent rate and waits for the seaplane to touch down, rather than attempting to flare to a landing when the water is smooth. A blanket of fresh snow on the ground and runway also deprives the pilot of visual cues with which to estimate height above ground, thus making the approach extremely difficult. Again, approaches are not the only regime in which smooth water and fresh snow cause problems. A number of aircraft have crashed as a result of pilots maneuvering over smooth water or snow-covered ground and misjudging their height above the surface.

Absent Ambient Cues

Two runway approach conditions that create considerable difficulty for the pilot, by requiring focal vision alone to accomplish what is normally accomplished with both focal and ambient vision, are the black-hole and whiteout approaches. A black-hole approach is one that is made on a dark night over water or unlighted terrain to a runway beyond which the horizon is indiscernible, the worst case being when only the runway lights are visible (Fig. 18). Without peripheral visual cues to help orient the aircraft relative to the earth, the pilot tends to feel that the aircraft is stable and situated appropriately but that the runway itself moves about or remains malpositioned (is down-sloping, for example). Such illusions make the black-hole approach difficult and dangerous, and often result in a landing far short of the runway. A particularly hazardous type of black-hole approach is one made under conditions wherein the earth is totally dark except for the runway and the lights of a city situated on rising terrain beyond the runway. Under these conditions, the pilot may try to maintain a constant vertical visual angle for the distant city lights, thus causing the aircraft to arc far below the intended approach slope as it gets closer to the runway (Fig. 19).[24] An alternative explanation is that the pilot falsely perceives through ambient vision that the rising terrain is flat, which leads to a lower-than-normal approach.

An approach made under whiteout conditions can be as difficult as a black-hole approach, and for essentially the same reason--lack of sufficient ambient visual orientation cues. There are actually two types of whiteout, the atmospheric whiteout and the blowing-snow whiteout. In the atmospheric white-out, a snow-covered ground merges with a white overcast, creating a condition in which ground textural cues are absent and the horizon is indistinguishable. Although visibility may be unrestricted in the atmospheric whiteout, there is essentially nothing to see except the runway or runway markers; an approach made in this condition must therefore be accomplished with a close eye on the altitude and attitude instruments to prevent spatial disorientation and inadvertent ground contact. In the blowing-snow whiteout, visibility is restricted drastically by snowflakes, and often those snowflakes have been driven into the air by the propeller or rotor wash of the affected aircraft. Helicopter landings on snow-covered ground are particularly likely to create blowing-snow whiteouts. Typically, the helicopter pilot tries to maintain visual contact with the ground during the sudden rotor-induced whiteout, gets into an unrecognized drift to one side, and shortly thereafter contacts the ground with sufficient lateral motion to cause the craft to roll over. Pilots flying where whiteouts can occur must be made aware of the hazards of whiteout approaches, as the disorientation induced usually occurs unexpectedly under visual rather than instrument meteorological conditions.

Another condition in which a pilot is apt to make a serious misjudgment is in closing on another aircraft at high speed. When the pilot has numerous peripheral visual cues by which to establish both the aircraft's position and velocity relative to the earth and the target's position and velocity relative to the earth, the difficulty of tracking and closing is not much different from what it would be on the ground giving chase to a moving quarry. When relative position and closure rate cues must come from foveal vision alone, however--as is generally the case at altitude, at night, or under other conditions of reduced visibility--the tracking and closing problem is much more difficult.

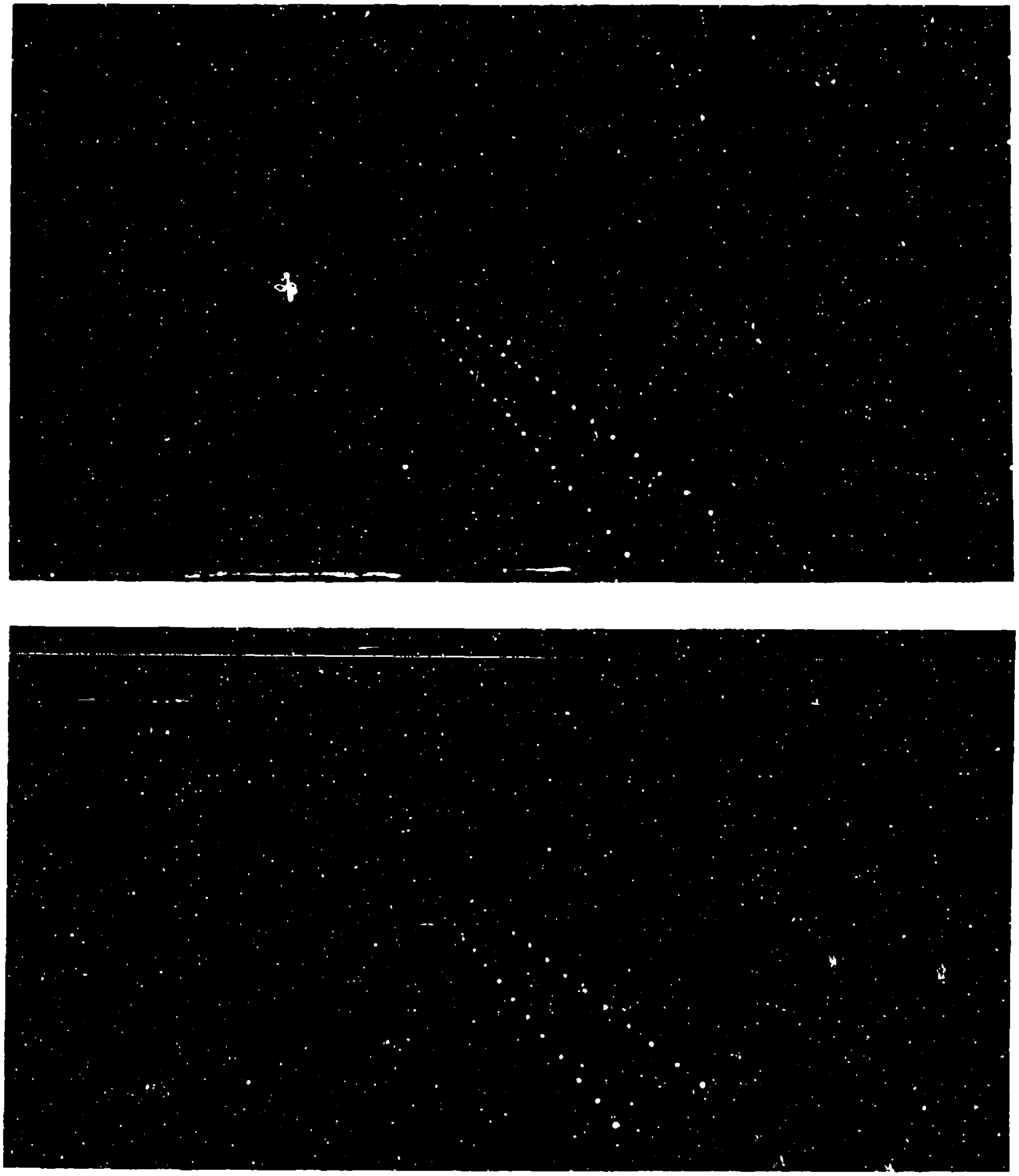


Figure 18. Effect of loss of ambient orientation cues on the perception of runway orientation during a black-hole approach. a. When ambient orientation cues are absent, the pilot feels horizontal and (in this example) perceives the runway to be tilted left and upsloping. b. With the horizon visible, the pilot can orient correctly with peripheral vision and the runway appears horizontal in central vision.

An overshoot, or worse, a midair collision, can easily result from the perceptual difficulties inherent in such circumstances, especially when the pilot lacks experience in an environment devoid of peripheral visual cues.

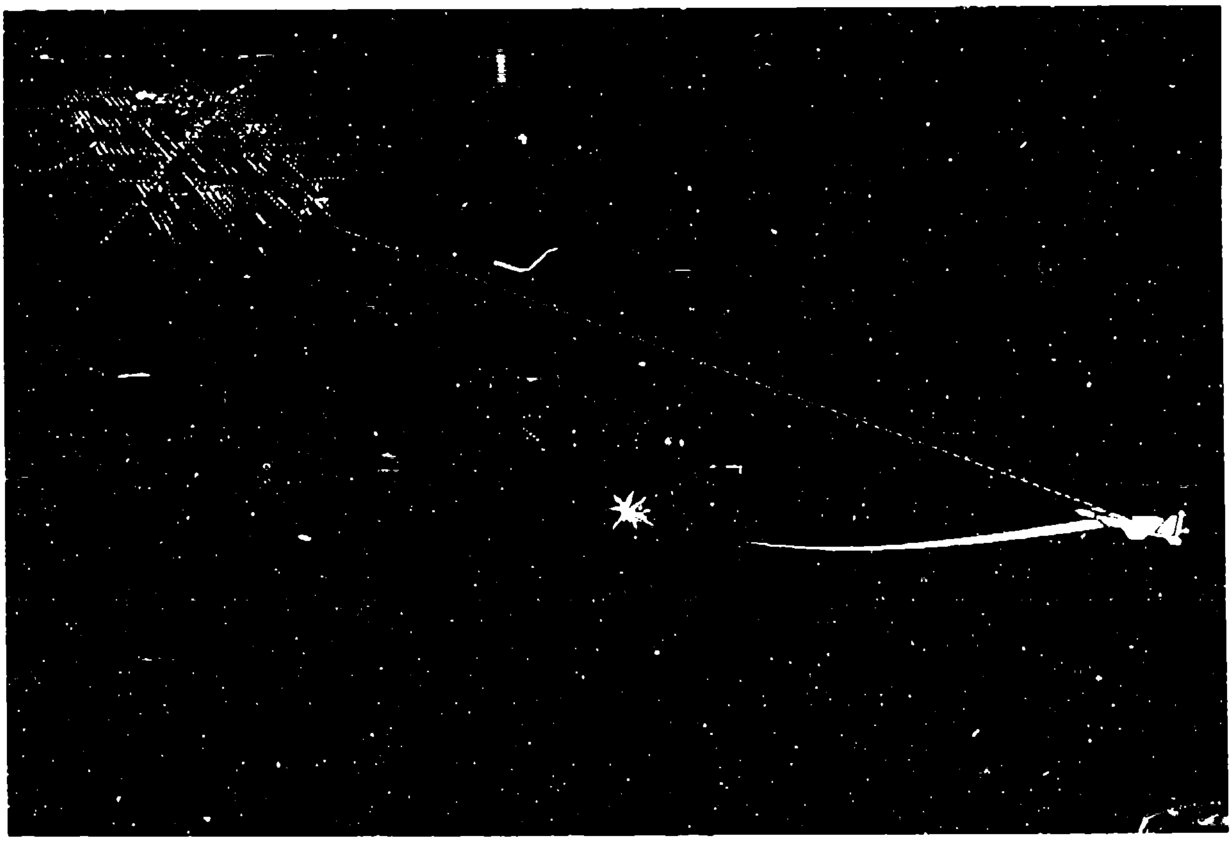


Figure 19. A common and particularly dangerous type of black-hole approach, in which the pilot falsely perceives the distant city to be on flat terrain and arcs below the desired approach slope.

A related phenomenon that pilots need especially to be aware of is the dip illusion. It occurs during formation flying at night, when one aircraft is in trail behind another. To avoid wake turbulence and maintain sight of the lead aircraft, the pilot in trail flies at a small but constant angle below the lead aircraft by placing the image of the lead aircraft in a particular position on the windscreen and keeping it there. Now suppose the pilot is told to "take spacing" (separate) to 5 nautical miles (10 km). For every 1° below lead the trailing pilot flies, he or she is lower than lead by 1.7% (sin 1°) of the distance behind lead. Thus, if the trail pilot is 2° below lead and keeps the image of the lead aircraft at the same spot on the windscreen all the way back to 5 miles, the trail aircraft will descend to about 1100 ft (350 m) below the lead aircraft. To make matters worse, when the aircraft in trail slows down to establish separation, its pitch attitude increases by several degrees; and if the pilot does not compensate for this additional angle and tries to maintain the lead aircraft image in the same relative position, the altitude difference between the two aircraft can be doubled or even tripled. In the absence of ambient visual orientation cues, the pilot cannot detect the large loss of altitude without monitoring the flight instruments, and may inadvertently "dip" far below the intended flight path. Clearly this situation would be extremely hazardous if it were to occur at low altitude or during maneuvers in which altitude separation from other aircraft is critical.

Autokinesis

One puzzling illusion that occurs when ambient visual orientation cues are minimal is visual autokinesis (Fig. 20). A small, dim light seen against a dark background is an ideal stimulus for producing autokinesis. After 6 to 12 seconds of visually fixating the light, one can observe it to move at up to 20°/sec in a particular direction or in several directions in succession, but there is little apparent displacement of the object fixated. In general, the larger and brighter the object, the less the autokinetic effect. The physiologic mechanism of visual autokinesis is not entirely understood. One suggested explanation for the autokinetic phenomenon is that the eyes tend to drift involuntarily, perhaps because of inadequate or inappropriate vestibular stabilization, and that checking the drift requires efferent oculomotor activity having sensory correlates that create the illusion.

Whatever the mechanism, the effect of visual autokinesis on pilots is of some importance. Anecdotes abound of pilots who fixate a star or a stationary ground light at night, and seeing it move because of autokinesis, mistake it for another aircraft and try to intercept or join up with it. Another untoward effect of the illusion occurs when a pilot flying at night perceives a relatively stable tracked aircraft to be moving erratically when in fact it is not; the unnecessary and undesirable control inputs the pilot makes to compensate for the illusory movement of the target aircraft represent increased work and wasted motion at best and an operational hazard at worst.

To help avoid or reduce the autokinetic illusion, the pilot should try to maintain a well-structured visual environment in which spatial orientation is unambiguous. Because this is rarely possible in night flying, it has been suggested that: (1) the pilot's gaze should be shifted frequently to avoid prolonged fixation of a target light; (2) the target should be viewed beside, through, or in some other reference to a relatively stationary structure such as a canopy bow; (3) the pilot should make eye, head, and body movements to try to destroy the illusion; and (4) as always, the pilot should monitor the flight instruments to help prevent or resolve any perceptual conflict. Equipping aircraft with more than one light or with luminescent strips to enhance recognition at night probably has helped reduce problems with autokinesis.

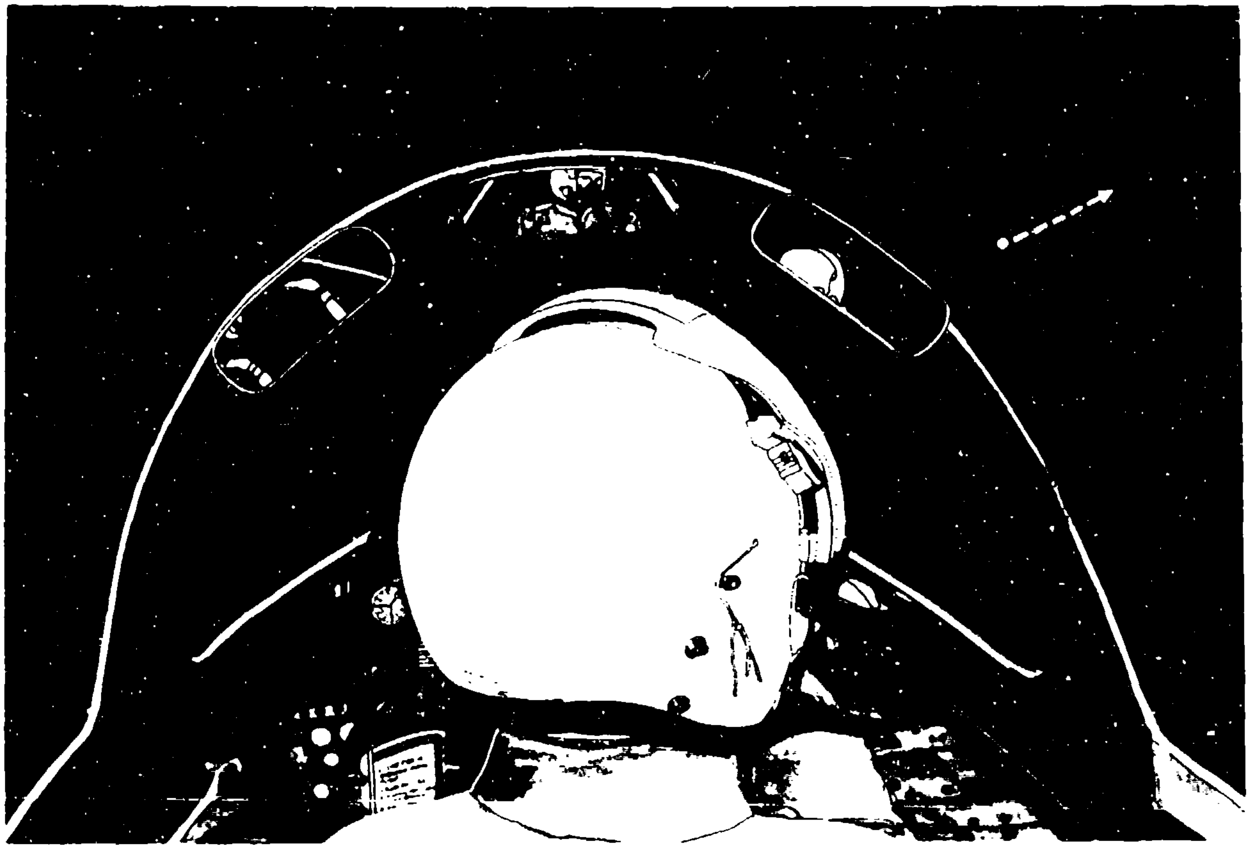


Figure 20. Visual autokinesis. A small, solitary light or small group of lights seen in the dark can appear to move, when in fact they are stationary.

Vection Illusions

So far, this section has dealt with visual illusions created by excessive orientation-processing demands being placed on focal vision when adequate orientation cues are not available through ambient vision or when strong but false orientation cues are received through focal vision. Ambient vision can itself be responsible for creating orientational illusions, however, whenever orientation cues received in the visual periphery are misleading or misinterpreted. Probably the most compelling of such illusions are the vection illusions. Vection is the visually induced perception of self-motion in the spatial environment and can be a sensation of linear self-motion (linear vection) or angular self-motion (angular vection).

Nearly everyone who drives an automobile has experienced one very common linear vection illusion: when we are stopped at a stoplight and a large, presumably stationary vehicle in the adjacent lane creeps forward, a compelling illusion that our own car is creeping backward can result (prompting a swift but surprisingly ineffectual stomp on the brakes). Similarly, when one is sitting in a stationary train and the train on the adjacent track begins to move, a strong sensation that one's own train is moving in the opposite direction can be experienced (Fig. 21a). Linear vection is one of the factors that make close formation flying so difficult, because the pilot can never be sure whether his or her own aircraft or that of lead or wingman is responsible for the perceived relative motion.

Angular vection occurs when peripheral visual cues convey the information that one is rotating; the perceived rotation can be in pitch, roll, yaw, or any other plane. Although angular vection illusions are not common in everyday life, they can be generated readily in a laboratory by enclosing a stationary subject in a rotating striped drum. Usually within 10 seconds after the visual motion begins, the subject perceives that he or she rather than the striped drum is rotating. A pilot can experience angular vection if the rotating anticollision light on the aircraft is left on during flight through clouds or fog: the revolving reflection provides a strong ambient visual stimulus signaling rotation in the yaw plane.

Another example of vection illusions is the so-called "Star Wars" effect, named after the popular motion picture famous for its vection-inducing visual effects. This phenomenon involves linearly and angularly moving reflections of ground lights off of the curved inside surface of a fighter aircraft canopy, which create in the pilot disconcerting sensations of motion that conflict with the actual motion of the aircraft.

Fortunately, vection illusions are not all bad. The most advanced flight simulators depend on linear and angular vection to create the illusion of flight (Fig. 21b). When the visual flight environment is dynamically portrayed in flight simulators with wide field-of-view and infinity-optics, the illusion of actual flight is so compelling that additional mechanical motion is often not even needed (although mechanically generated motion-onset cues do seem to improve the fidelity of the simulation).

False Horizons and Surface Planes

Sometimes the horizon perceived through ambient vision is not really horizontal. Quite naturally, this misperception of the horizontal creates hazards to flight. A sloping cloud deck, for example, is very difficult to perceive as anything but horizontal if it extends for any great distance into the pilot's peripheral visual field (Fig. 22). Uniformly sloping terrain, particularly upsloping terrain, can also create an illusion of horizontality with disastrous consequences for the pilot thus deceived. Many aircraft have crashed as a result of the pilot's entering a canyon with an apparently level floor, only to find that the floor actually rose faster than the airplane could climb. At night, the lights of a city built on sloping terrain can create the false impression that the extended plane of the city lights is the horizontal plane of the earth's surface, as already noted (Fig. 19). A distant rain shower can obscure the real horizon and create the impression of a horizon at the proximal edge (base) of the rainfall. If the shower is seen just beyond the runway during an approach to landing, the pilot can misjudge the pitch attitude of the aircraft and make inappropriate pitch corrections on the approach.

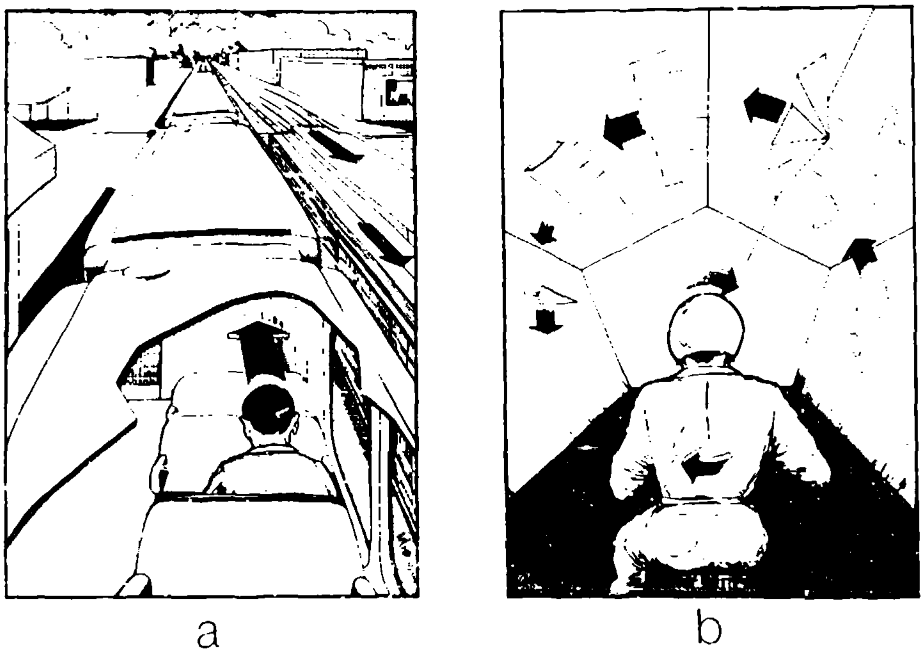


Figure 21. Vection illusions. a. Linear vection. In this example, the adjacent vehicle seen moving aft in the subject's peripheral vision causes the sensation of moving forward. b. Angular vection. Objects seen revolving around the subject in the flight simulator result in a perception of self-rotation in the opposite direction--in this case, a rolling motion to the right.

Pilots are especially susceptible to misperception of the horizontal while flying at night (Figs. 23a and 23b). Isolated ground lights can appear to the pilot as stars, creating the perception of a nose-high or one-wing-low attitude. Flying under such a false impression can, of course, be fatal. Frequently, no stars are visible because of overcast conditions. Unlighted areas of terrain can then blend with the dark overcast to create the illusion that the unlighted terrain is part of the sky. One extremely hazardous situation is that in which a takeoff is made over an ocean or other large body of water that cannot be distinguished visually from the night sky. Many pilots in this situation have perceived the shoreline receding beneath them to be the horizon, and some have responded to this false percept with a disastrous nose-down control input.

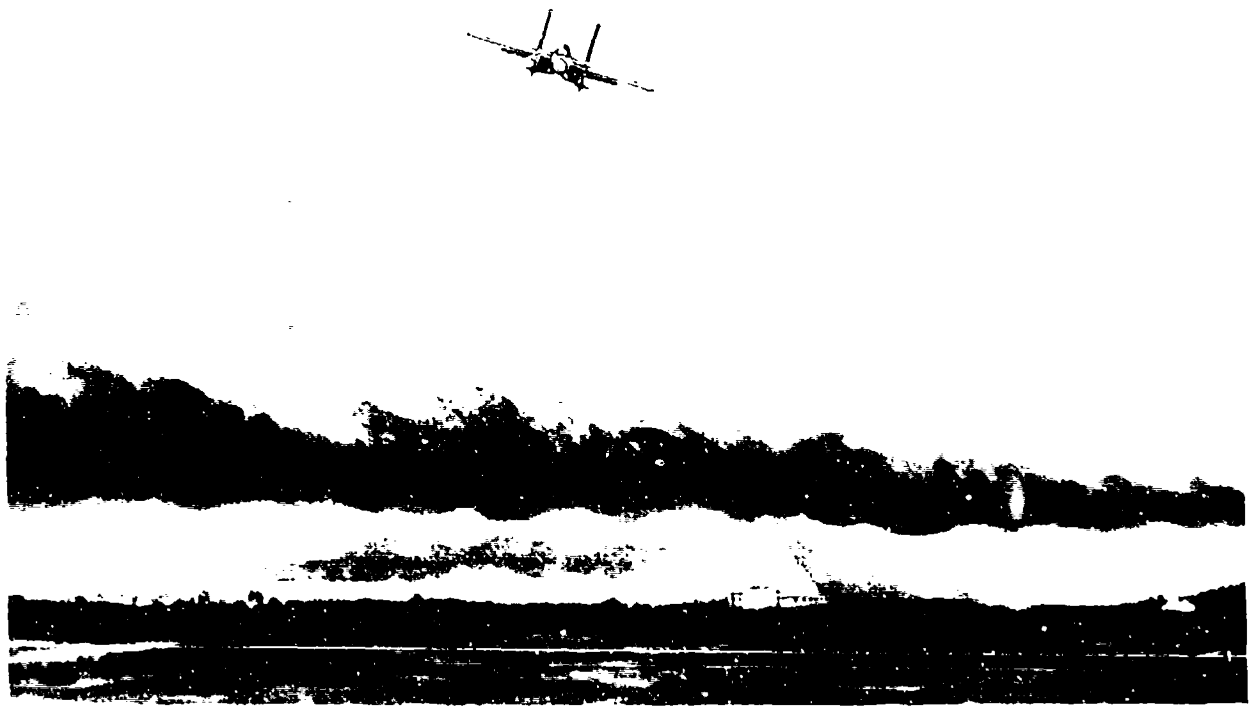
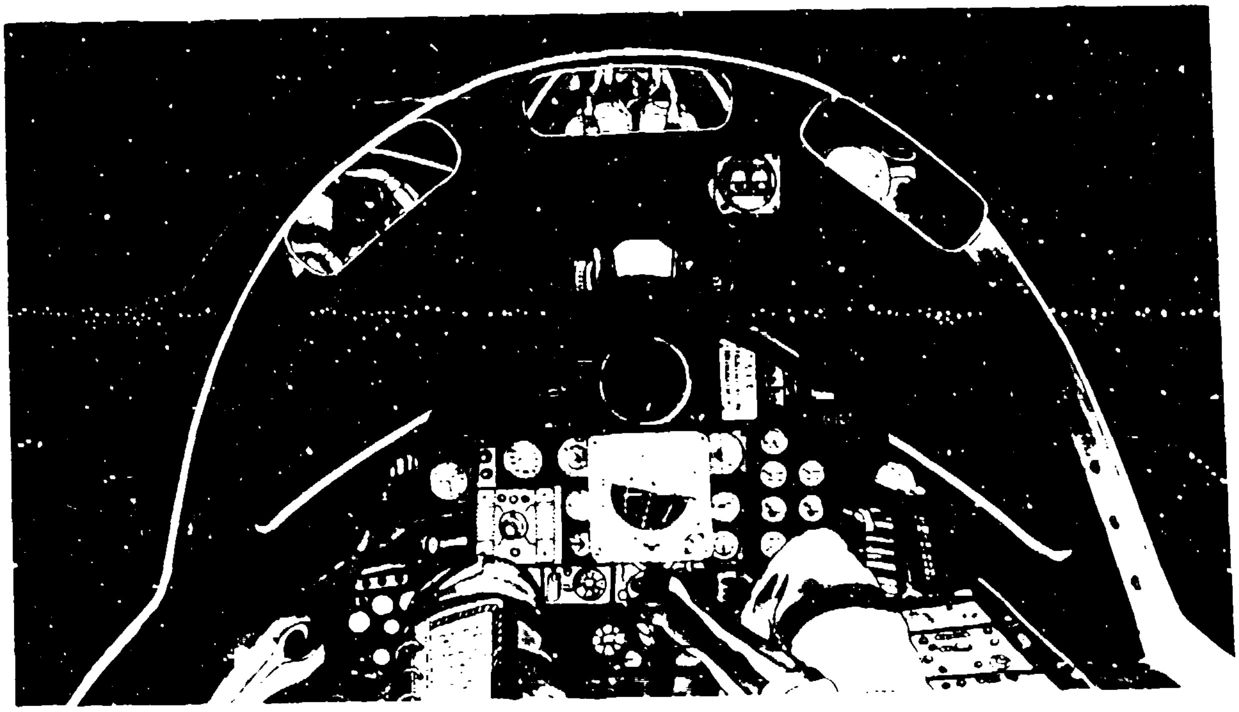


Figure 22. A sloping cloud deck, which the pilot misperceives as a horizontal surface.

Pilots flying at high altitudes can sometimes experience difficulties with control of aircraft attitude, because at high altitudes the horizon is lower with respect to the plane of level flight than it is at the lower altitudes where most pilots are accustomed to flying. As a reasonable approximation, the angle of depression of the horizon in degrees equals the square root of the altitude in kilometers. A pilot flying at an altitude of 49,000 ft (15 km) thus sees the horizon almost 4° below the extension of the horizontal plane of the aircraft. By visually orienting to the view from the left cockpit window, the pilot might be inclined to fly with the left wing 4° down to level it with the horizon. If the pilot does this and then looks out the right window, the right wing would be seen 8° above the horizon, with half of that elevation due to the erroneous control input. The pilot also might experience problems with pitch control because the depressed horizon can cause a false perception of a 4° nose-high pitch attitude.



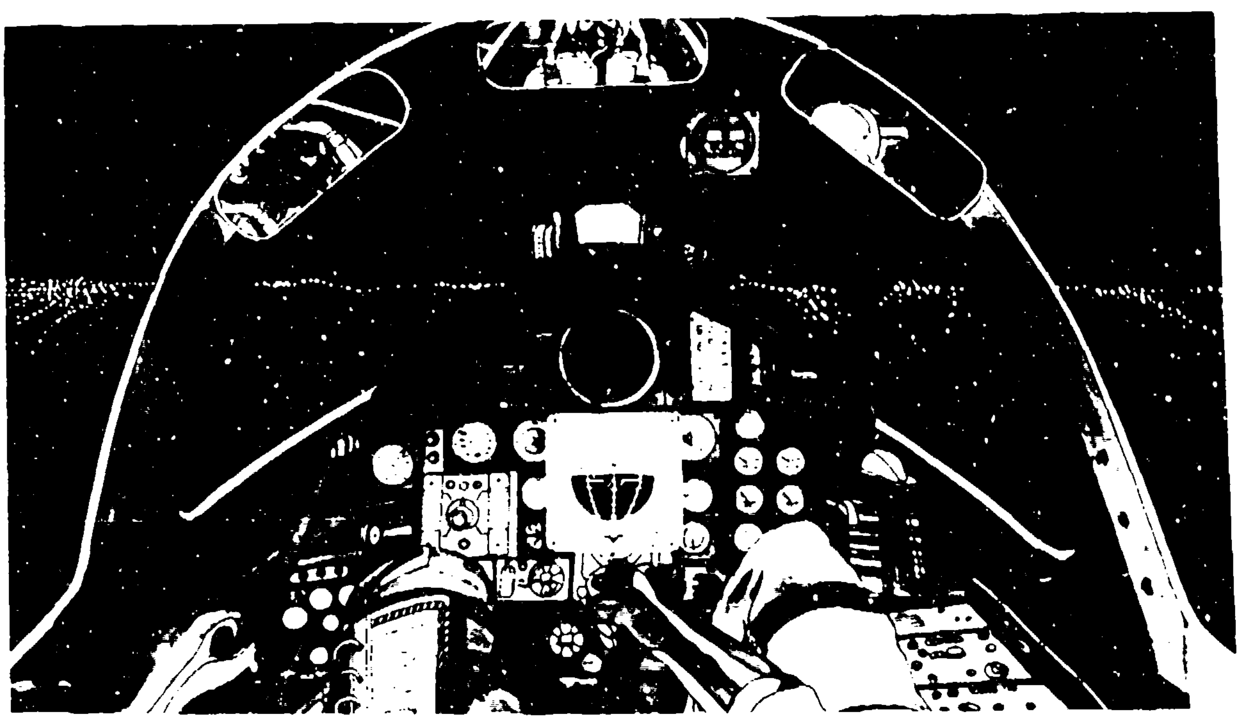


Figure 23. Misperception of the horizontal at night. a. Ground lights appearing to be stars cause the earth and sky to blend and a false horizon to be perceived. b. Blending of overcast sky with unlighted terrain or water causes the horizon to appear lower than is actually the case.

Other False Ambient Cues

One very important aspect of ambient visual orientational cuing in flight is the stabilizing effect of the surrounding instrument panel, glare shield, and canopy bow or windshield frame, and especially the reflections of panel lights and other cockpit structures off the windshield or canopy at night. When the aircraft rolls or pitches while the pilot is inattentive, the stable visual surround provided by these objects tends to cause the motion not to be perceived, even though it may be well above the usual threshold for vestibular motion perception. While flying at night or in instrument weather, a pilot may thus have a false sense of security because no motion is felt, due to the apparently stable ambient visual environment. Of course, this falsely stabilizing effect does not occur when the visual environment contains the usually valid ambient visual references (natural horizon, earth's surface, etc.).

Another result of false ambient visual orientational cuing is the lean-on-the-sun illusion. On the ground, we are accustomed to seeing the brighter visual surround above and the darker below, regardless of the position of the sun. The direction of this gradient in light intensity thus helps us orient with respect to the surface of the earth. In clouds, however, such a gradient usually does not exist, and when it does, the lighter direction is generally toward the sun and the darker direction is away from it. But the sun is almost never directly overhead; as a consequence, a pilot flying in a thin c' d layer tends to perceive falsely that the sun is directly overhead. Thi, misperception prompts the pilot to bank in the direction of the sun, hence the name of the illusion.

Final , the disorienting effects of the northern lights and of aerial flares should be mentioned. Aerial refueling at night in high northern latitudes often is made quite difficult by the northern lights, which provide false cues of verticality to the pilot's peripheral vision. Similarly, when aerial flares are dropped, they may drift with the wind, creating false cues of verticality. Their motion also may create vection illusions. Another phenomenon associated with use of aerial flares at night is the "moth" effect. The size of the area on the ground illuminated by a dropped flare slowly decreases as the flare descends. Because of the size constancy mechanism of visual orientation discussed earlier, a pilot circling the illuminated area may tend to fly in a descending spiral with gradually decreasing radius. Another important factor is that the aerial flares can be so bright as to reduce the apparent intensity of the aircraft instrument displays and thereby minimize their orientational cuing strength.

Vestibular Illusions

The vestibulocerebellar axis processes orientation information from the vestibular, visual, and other sensory systems. In the absence of adequate ambient visual orientation cues, the inadequacies of the vestibular and other orienting senses can result in orientational illusions. It is convenient and conventional to discuss the vestibular illusions in relation to the two functional components of the labyrinth that generate them--the semicircular ducts and the otolith organs.

Somatogyral Illusion

A somatogyral illusion is a false sensation of rotation (or absence of rotation) that results from misperceiving the magnitude or direction of an actual rotation. In essenc , somatogyral illusions result from the inability of the semicircular ducts to r gister accurately a prolonged rotation, i.e., sustained angular velocity. When a person is subjected to an angular acceleration about the yaw axis, for example, the angular motion is at first perceived accurately because the dynamics of the cupula-endolymph system cause it to respond as an integrating angular accelerometer (i.e., as a rotation-rate sensor) at stimulus frequencies in the physiologic range (Fig. 24). If the acceleration is followed immediately by a deceleration, as usually happens in the terrestrial environment, the total sensation of turning one way and then stopping the turn is quite accurate (Fig. 25). If, however, the angular acceleration is not followed by a deceleration and a constant angular velocity results instead, the sensation of rotation becomes less and less and eventually disappears as the cupula gradually returns to its resting position in the absence of an angular acceleratory stimulus (Fig. 26). If we are subsequently subjected to an angular deceleration after a period of prolonged constant angular velocity, say after 10 seconds or so of constant-rate turning, our cupula-endolymph systems signal a turn in the direction opposite that of the prolonged constant angular velocity, even though we are really only turning less rapidly in the same direction. This is because the angular momentum of the rotating endolymph causes it to press against the cupula, forcing the cupula to deviate in the direction of endolymph flow, which is the same direction the cupula would deviate if we were to accelerate in the direction opposite the initial acceleration. Even after rotation actually ceases, the sensation of rotation in the direction opposite that of the sustained angular velocity persists for several seconds--half a minute or longer with a large decelerating rotational impulse. Another, more mechanistic, definition of the somatogyral illusion is "any discrepancy between actual and perceived rate of self-rotation that results from an abnormal angular acceleratory stimulus pattern." The term "abnormal" in this case implies the application of low-frequency stimuli outside the useful portion of the transfer characteristics of the semicircular duct system.

In flight under conditions of reduced visibility, somatogyral illusions can be deadly. The graveyard spin is the classic example of how somatogyral illusions can disorient a pilot with fatal results. This situation begins with the pilot intentionally or unintentionally entering a spin, let's say to the left (Fig. 27). At first, the pilot perceives the spin correctly because the angular acceleration associated with entering the spin deviates the appropriate cupulae the appropriate amount in the appropriate direction. The longer the spin persists, however, the more the sensation of spinning to the left diminishes as the cupulae return to their resting positions. On trying to stop the spin to the left by applying the right rudder, the angular deceleration causes the pilot to perceive a spin to the right, even though the only real result of this action was termination of the spin to the left. A pilot who is ignorant of the possibility of such an illusion is then likely to make counterproductive left-rudder inputs to negate the unwanted erroneous sensation of spinning to the right. These inputs keep the airplane spinning to the left, which gives the pilot the desired sensation of not spinning but does not bring the airplane under control. To extricate himself from this very hazardous situation, the pilot must read the aircraft flight instruments and apply control inputs to make the instruments give the desired readings (push right rudder to center the turn needle, in this example). Unfortunately, this may not be so easy to do. The angular accelerations created by both the multiple-turn spin and the pilot's spin-recovery attempts can elicit strong but inappropriate vestibulo-ocular reflexes, including nystagmus. In the usual terrestrial environment, these reflexes help stabilize the retinal image of the visual surround; in this situation, however, they only destabilize the retinal image because the visual surround (cockpit) is already fixed with respect to the pilot. Reading the flight instruments thus becomes difficult or impossible, and the pilot is left with only false sensations of rotation to rely on for spatial orientation and aircraft control.[26]

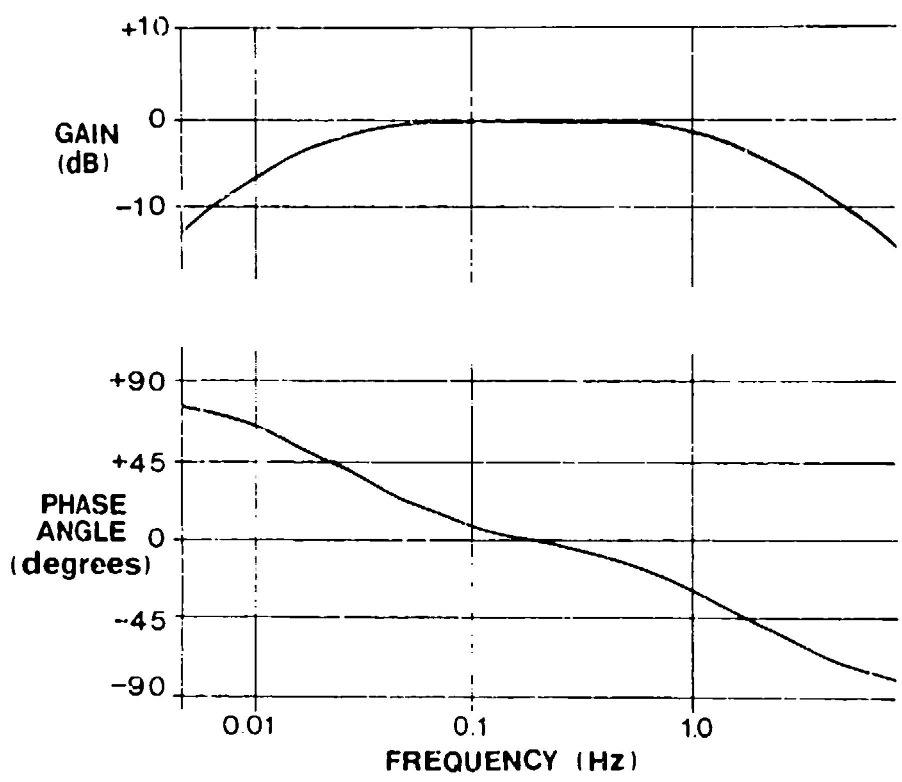


Figure 24. Transfer characteristics of the semicircular duct system as a function of sinusoidal stimulus frequency. Gain is the ratio of the magnitude of the peak perceived angular velocity to the peak delivered angular velocity; phase angle is a measure of the amount of advance or delay between the peak perceived and peak delivered angular velocities. Note that in the physiologic frequency range (roughly 0.05 to 1 Hz), perception is accurate; that is, gain is close to unity (0 dB) and phase angle is minimal. At lower stimulus frequencies, however, the gain drops off rapidly, and the phase shift approaches 90°, which means that angular velocity becomes difficult to detect and that angular acceleration is perceived as velocity. (Adapted from Peters.[25])

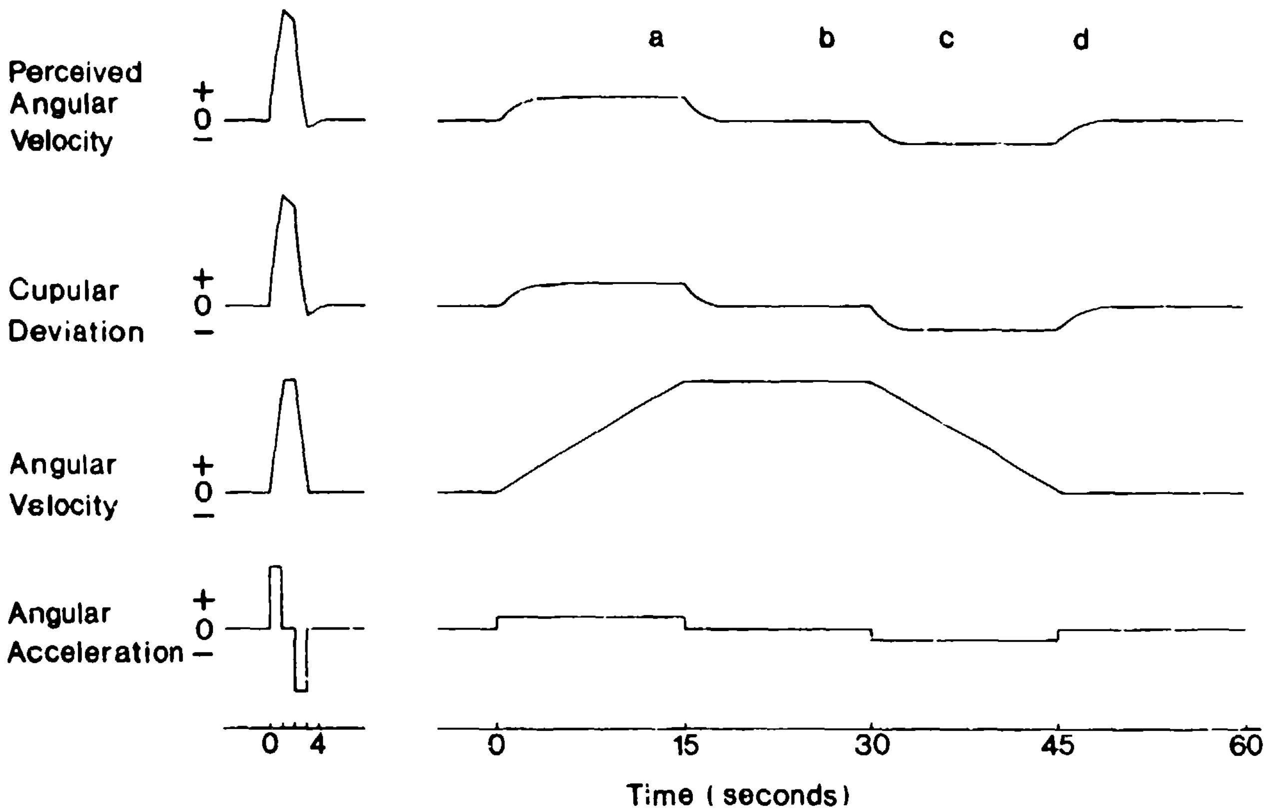


Figure 25. Effect of the stimulus pattern on the perception of angular velocity. On the left, the high-frequency character of the applied angular acceleration results in a cupular deviation that is nearly proportional to, and a perceived angular velocity that is nearly identical to, the angular velocity developed. On the right, the peak angular velocity developed is the same as that on the left, but the low-frequency character of the applied acceleration results in cupular deviation and perceived angular velocity that appear more like the applied acceleration than the resulting velocity. This causes one to perceive: (a) less than the full amount of the angular velocity, (b) absence of rotation while turning persists, (c) a turn in the opposite direction from that of the actual turn, and (d) that turning persists after it has actually stopped. These false percepts are somatogyral illusions.

Although the lore of early aviation provided the graveyard spin as an illustration of the hazardous nature of somatogyral illusions, a much more common example occurring all too often in modern aviation is the graveyard spiral (Fig. 28). In this situation, the pilot has intentionally or unintentionally entered into a prolonged turn with a moderate amount of bank. After a number of seconds in the turn, the pilot loses the sensation of turning because the cupula-endolymph system cannot respond to constant angular velocity. The percept of being in a bank as a result of the initial roll into the banked attitude also decays with time because the net gravitoinertial force vector points toward the floor of the aircraft during coordinated flight (whether the aircraft is in a banked turn or flying straight and level), and the otolith organs and other graviceptors normally signal that down is in the direction of the net sustained gravitoinertial force. As a result, when trying to stop the turn by rolling back to a wings-level attitude, the pilot feels not only a turning in the direction opposite to that of the original turn, but also a bank in the direction opposite to that of the original bank. Unwilling to accept this sensation of making the wrong control input, the hapless pilot rolls back into the original banked turn. Now the pilot's sensation is compatible with a desired mode of flight, but the flight instruments indicate a loss of altitude (because the banked turn is wasting lift) and a continuing turn. So the pilot pulls back on the stick and perhaps adds power to arrest the unwanted descent and regain the lost altitude. This action would be successful if the aircraft were flying wings-level, but with the aircraft in a steeply banked attitude it tightens the turn, serving only to make matters worse. Unless the pilot eventually recognizes what is occurring and rolls out of the unperceived banked turn, the aircraft will continue to descend in an ever-tightening spiral toward the ground, hence the name graveyard spiral.

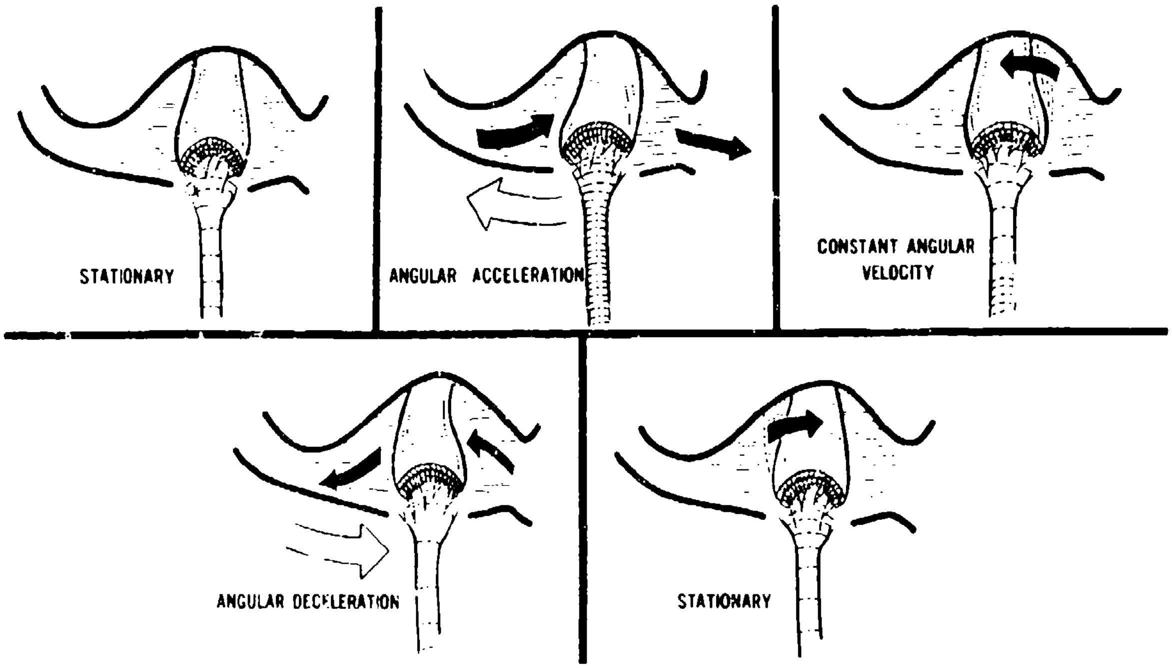


Figure 26. Representation of the mechanical events occurring in a semicircular duct and resulting action potentials in the associated ampullary nerve during somatogyral illusions. The angular acceleration pattern applied is that shown in the right side of Figure 25.

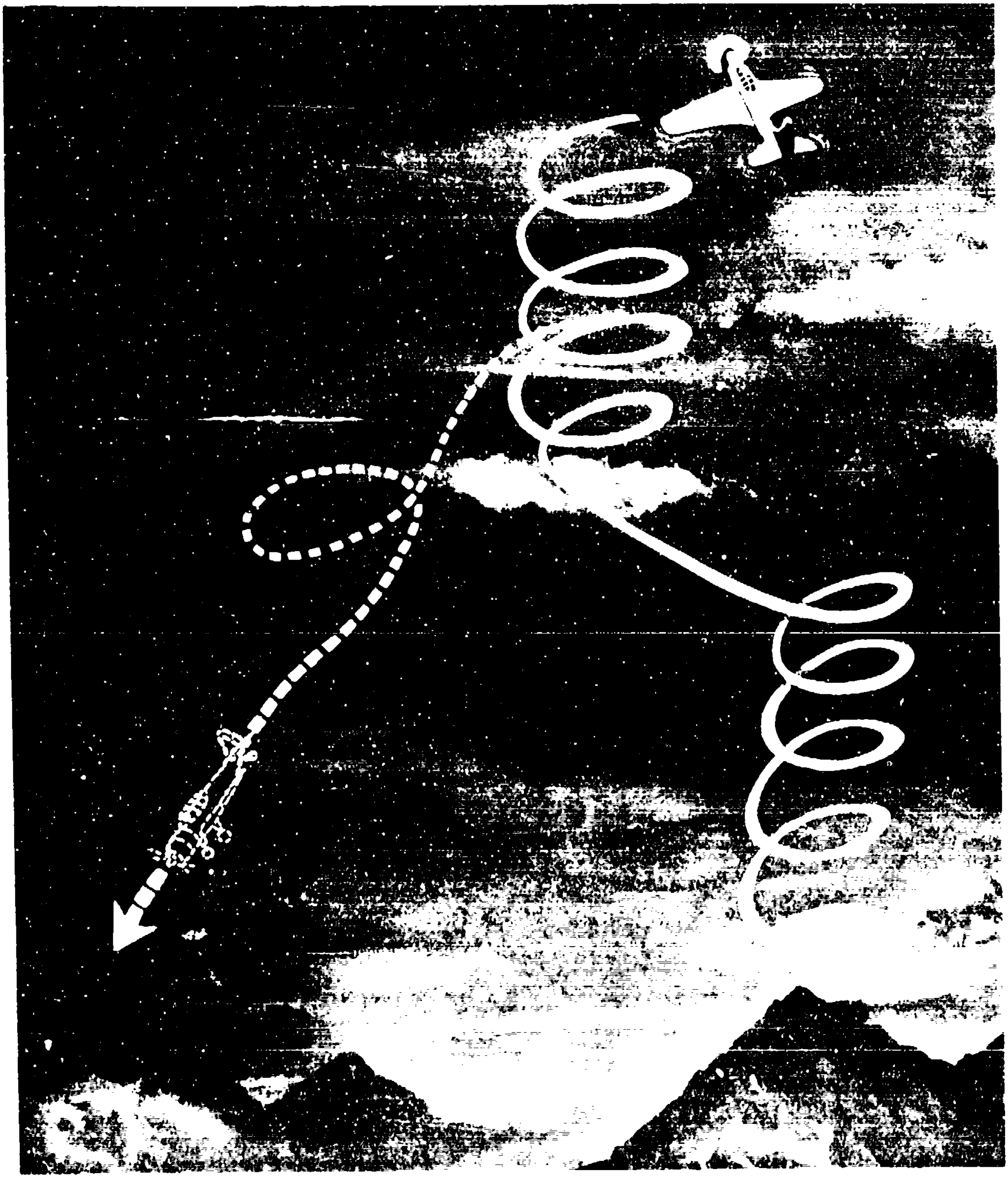


Figure 27. The graveyard spin. After several turns of a spin the pilot begins to lose the sensation of spinning. When trying to stop the spin, the resulting somatogyral illusion of spinning in the opposite direction makes the pilot reenter the original spin. (The solid line indicates actual motion; the dotted line indicates perceived motion.)

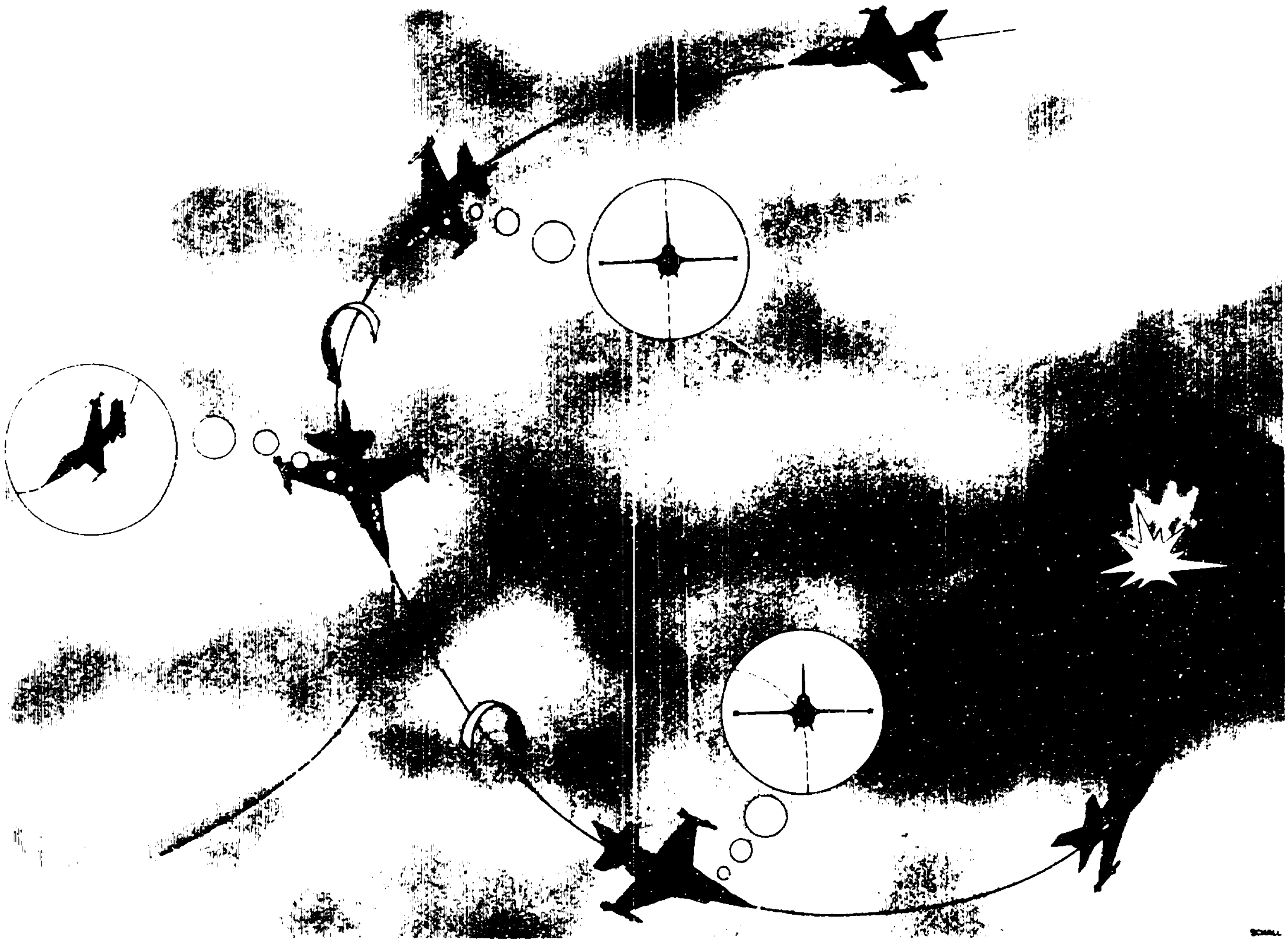


Figure 28. The graveyard spiral. The pilot in a banked turn loses the sensations of being banked and turning. Upon trying to establish a wings-level attitude and stop the turn, the pilot perceives a bank and a turning in the opposite direction from the original banked turn. Unable to tolerate the sensation of making an inappropriate control input, the pilot banks back into the original turn.

Oculogyral Illusion

Whereas a somatogyral illusion is a false sensation, or lack of sensation, of self-rotation in a subject undergoing unusual angular motion, an oculogyral illusion is a false sensation of motion of an object viewed by such a subject.[27] For example, if a vehicle with a subject inside is rotating about a vertical axis at a constant velocity and suddenly stops rotating, the subject experiences not only a somatogyral illusion of rotation in the opposite direction, but also an oculogyral illusion of an object in front moving in the opposite direction. Thus, a somewhat oversimplified definition of the oculogyral illusion is that it is the visual correlate of the somatogyral illusion, however, its low threshold and lack of total correspondence with presumed cupular deviation suggest a more complex mechanism. The attempt to maintain visual fixation during a vestibulo-ocular reflex elicited by angular acceleration is probably at least partially responsible for the oculogyral illusion. In an aircraft during flight at night or in weather, an oculogyral illusion generally confirms a somatogyral illusion: the pilot who falsely perceives a turning in a particular direction also observes the instrument panel to move in the same direction.

Coriolis Illusion

The vestibular Coriolis effect, also called the Coriolis cross-coupling effect, vestibular cross-coupling effect, or simply the Coriolis illusion, is another false percept that can result from unusual stimulation of the semicircular duct system. To illustrate this phenomenon, let us consider a subject who has been rotating in the plane of the horizontal semicircular ducts (roughly the yaw plane) long enough for the endolymph in those ducts to attain the same angular velocity as the head: the cupulae in the ampullae of the horizontal ducts have returned to their resting positions, and the sensation of rotation has ceased (Fig. 29a). If the subject then nods forward in the pitch plane, let's say a full 90° for the sake of simplicity, the horizontal semicircular ducts are removed from the plane of rotation and the two sets of vertical semicircular ducts are inserted into the plane of rotation (Fig. 29b). Although the angular momentum of the subject's rotating head is forcibly transferred at once out of the old plane of rotation relative to the head, the angular momentum of the endolymph in the horizontal duct is dissipated more gradually. The torque resulting from the continuing rotation of the endolymph causes the cupulae in the horizontal ducts to be deviated, and a sensation of angular motion occurs in the new plane of the horizontal ducts--now the roll plane relative to the subject's body. Simultaneously, the endolymph in the two sets of vertical semicircular ducts must acquire angular momentum because these ducts have been brought into the plane of constant rotation. The torque required to impart this change in momentum causes deflection of the cupulae in the ampullae of these ducts, and a sensation of angular motion in this plane--the yaw plane relative to the subject's body--results. The combined effect of the cupular deflection in all three sets of semicircular ducts is that of a suddenly imposed angular velocity in a plane in which no actual angular acceleration relative to the subject has occurred. In the example given, if the original constant-velocity yaw is to the right and the subject's head pitches forward, the resulting Coriolis illusion experienced is that of suddenly rolling and yawing to the right.

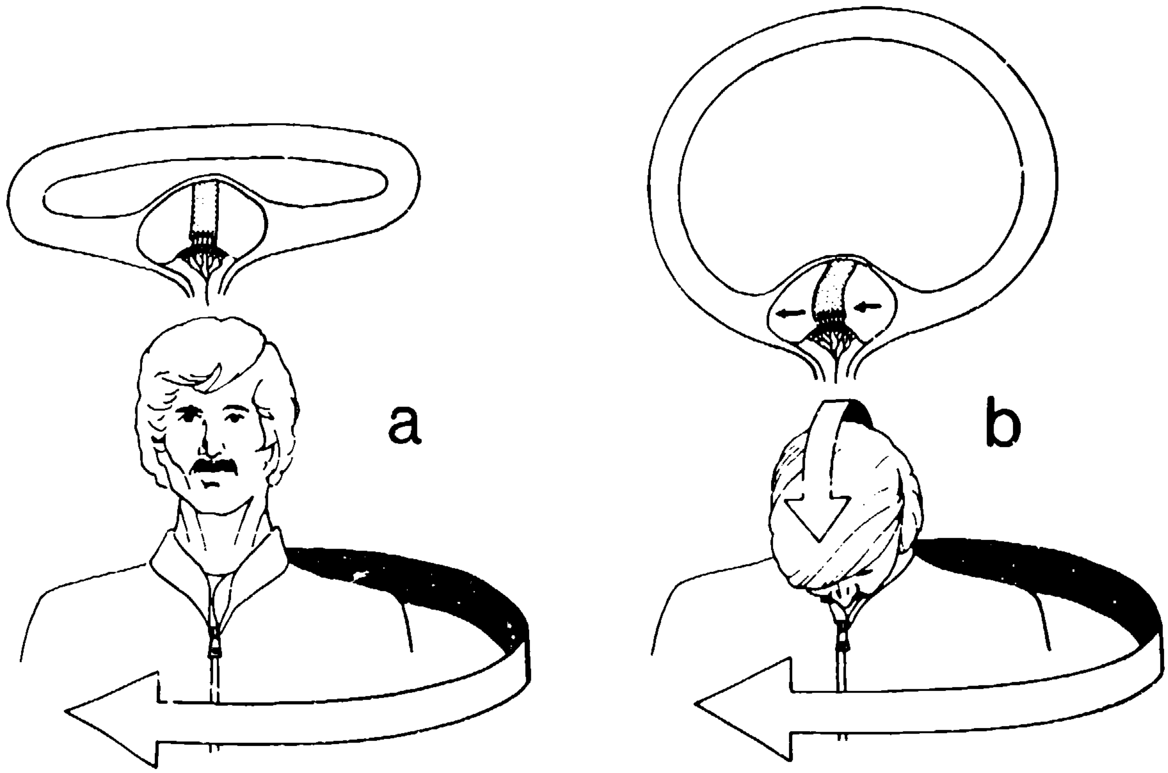


Figure 29. Mechanism of the Coriolis illusion. A subject rotating in the yaw plane long enough for the endolymph to stabilize in the horizontal semicircular duct (a) pitches the head forward (b). Angular momentum of the endolymph causes the cupula to deviate, and the subject perceives rotation in the new (i.e., roll) plane of the horizontal semicircular duct, even though no actual rotation occurred in that plane.

A particular perceptual phenomenon experienced occasionally by pilots of relatively high-performance aircraft during instrument flight has been attributed to the Coriolis illusion because it occurs in conjunction with large movements of the head under conditions of prolonged constant angular velocity. It consists of a sensation of rolling and/or pitching that appears suddenly after the pilot's attention has been diverted from the instruments in front and his or her head is moved to view some switches or displays elsewhere in the cockpit. This illusion is especially deadly because it is most likely to occur during an instrument approach, a phase of flight in which altitude is being lost rapidly and cockpit chores (e.g., radio frequency changes) repeatedly require the pilot to break up his instrument cross-check. The sustained angular velocities associated with instrument flying are insufficient to create Coriolis illusions of any great magnitude, however;[28] and another mechanism (the G-excess effect) has been proposed to explain the illusory rotations experienced with head movements in flight.[29] Even if not responsible for spatial disorientation in flight, the Coriolis illusion is useful as a tool to demonstrate the fallibility of our nonvisual orientation senses. Nearly every military pilot living today has experienced the Coriolis illusion in the Barany chair or some other rotating device as part of physiological training, and for most of these pilots it was then they first realized that their own orientation senses really cannot be trusted--the most important lesson of all for instrument flying.

Somatogravic Illusion

The otolith organs are responsible for a set of illusions known as somatogravic illusions. The mechanism of illusions of this type involves the displacement of otolithic membranes on their maculae by inertial forces so as to signal a false orientation when the resultant gravitoinertial force is perceived as gravitational (and therefore vertical). Thus, a somatogravic illusion can be defined as a false sensation of body tilt that results from perceiving as vertical the direction of a nonvertical gravitoinertial force. The illusion of pitching up after taking off into conditions of reduced visibility is perhaps the best illustration of this mechanism. Consider the pilot of a high-performance aircraft waiting at the end of the runway to take off. Here, the only force acting on the otolithic membranes is the force of gravity, and the positions of those membranes on their maculae signal accurately that down is toward the floor of the aircraft. Suppose the aircraft now accelerates on the runway, rotates, takes off, cleans up gear and flaps, and maintains a forward acceleration of 1 g until reaching the desired climb speed. The 1 G of inertial force resulting from the acceleration displaces the otolithic membranes toward the back of the pilot's head. In fact, the new positions of the otolithic membranes are nearly the same as they would be if the aircraft and pilot had pitched up 45°, because the new direction of the resultant gravitoinertial force vector, if one neglects the angle of attack and climb angle, is 45° aft relative to the gravitational vertical (Fig. 30). Naturally, the pilot's percept of pitch attitude based on the information from the otolith organs is one of having pitched up 45°; and the information from nonvestibular proprioceptive and cutaneous mechanoreceptive senses supports this false percept, because the sense organs subserving those modalities also respond to the direction and intensity of the resultant gravitoinertial force. Given the very strong sensation of a nose-high pitch attitude, one that is not challenged effectively by the focal visual orientation cues provided by the attitude indicator, the pilot is tempted to push the nose of the aircraft down to cancel the unwanted sensation of flying nose-high. Pilots succumbing to this temptation characteristically crash in a nose-low attitude a few miles beyond the end of the runway. Sometimes, however, they are seen to descend out of the overcast nose-low and try belatedly to pull up, as though they suddenly regained the correct orientation upon seeing the ground again. Pilots of carrier-launched aircraft need to be especially wary of the somatogravic illusion. These pilots experience pulse accelerations lasting 2 to 4 seconds and generating peak inertial forces of +3 to +5 G_x. Although the major acceleration is over quickly, the resulting illusion of nose-high pitch can persist for half a minute or more afterward, resulting in a particularly hazardous situation for the pilot who is unaware of this phenomenon.[30]

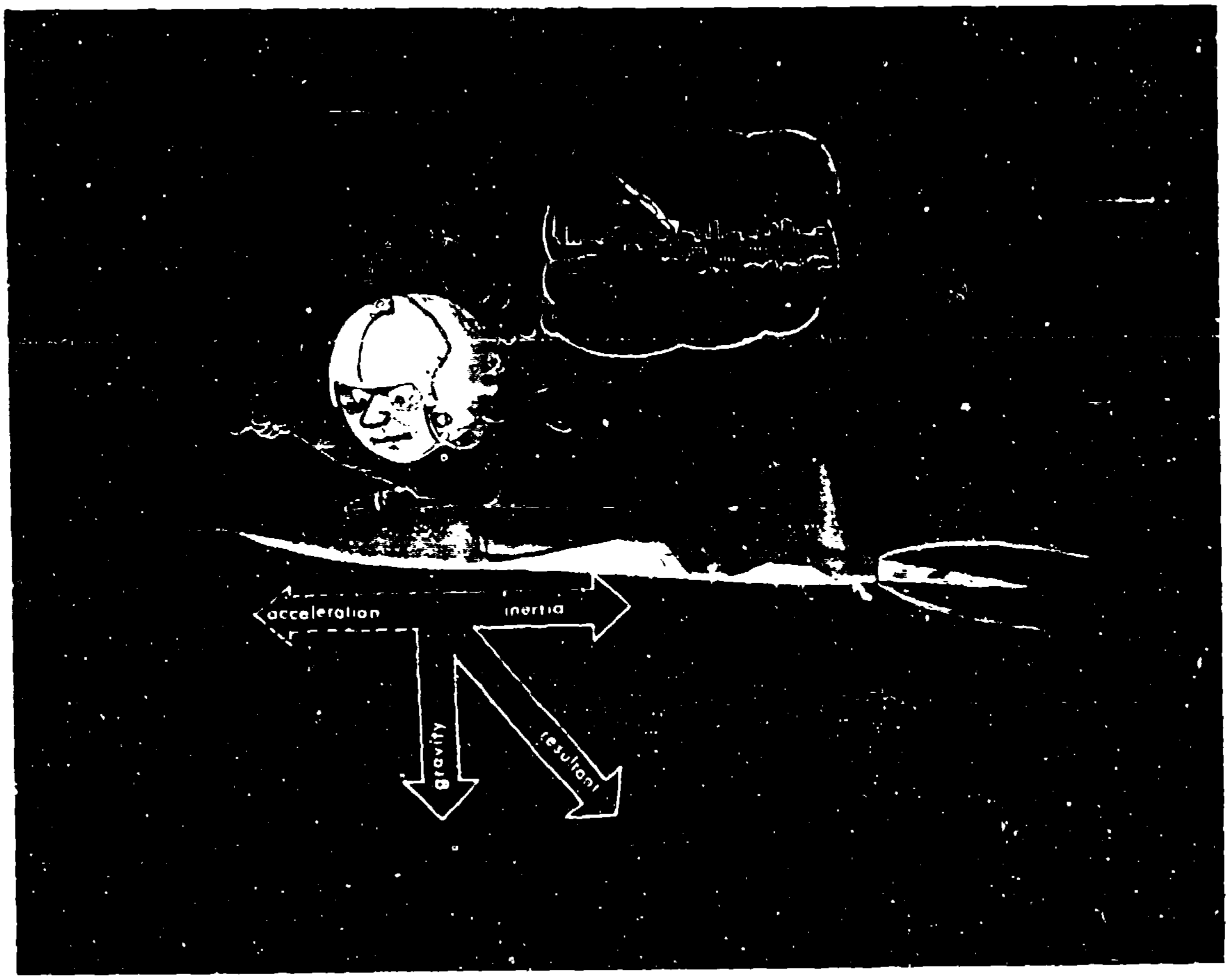


Figure 30. A somatogravic illusion occurring on takeoff. The inertial force resulting from the forward acceleration combines with the force of gravity to create a resultant gravitoinertial force directed down and aft. The pilot, perceiving down to be in the direction of the resultant gravitoinertial force, feels the aircraft is in an excessively nose-high attitude and is tempted to push the stick forward to correct the illusory nose-high attitude.

Do not be misled by the above example into believing that only pilots of high-performance aircraft suffer the somatogravic illusion of pitching up after takeoff. More than a dozen air transport aircraft are believed to have crashed as a result of the somatogravic illusion occurring on takeoff.[31] A relatively slow aircraft, accelerating from 100 to 130 knots over a 10-second period just after takeoff, generates $+0.16\ G_x$ on the pilot. Although the resultant gravitoinertial force is only 1.01 G, barely perceptibly more than the force of gravity, it is directed 9° aft, signifying to the unwary pilot a 9° nose-up pitch attitude. Because many slower aircraft climb out at 6° or less, a 9° downward pitch correction would put such an aircraft into a descent of 3° or more--the same as a normal final-approach slope. In the absence of a distinct external visual horizon or, even worse, in the presence of a false visual horizon (e.g., a shoreline) receding under the aircraft and reinforcing the vestibular illusion, the pilot's temptation to push the nose down can be overwhelming. This type of mishap has happened at one particular civil airport so often that a notice has been placed on navigational charts cautioning pilots flying from this airport to be aware of the potential for loss of attitude reference.

Although the classic graveyard spiral was indicated earlier to be a consequence of the pilot's suffering a somatogyral illusion, it also can be said to result from a somatogravic illusion. A pilot who is flying "by the seat of the pants" applies the necessary control inputs to create a resultant G-force vector having the same magnitude and direction as that which the desired flight path would create. Unfortunately, any particular G vector is not unique to one particular condition of aircraft attitude and motion, and the likelihood that the G vector created by a pilot flying in this mode corresponds for more than a few seconds to the flight condition desired is remote indeed. Specifically, once an aircraft has departed a desired wings-level attitude because of an unperceived roll, and the pilot does not correct the resulting bank, the only way to create a G vector that matches the G vector of the straight and level condition is with a descending spiral. In this condition, as is always the case in a coordinated turn, the centrifugal force resulting from the turn provides a G_y force that cancels the G_y component of the force of gravity that exists when the aircraft is banked. In addition, the tangential linear acceleration associated with the increasing airspeed resulting from the dive provides a $+G_x$ force that cancels the $-G_x$ component of the gravity vector that exists when the nose of the aircraft is pointed downward. Although the vector analysis of the forces involved in the graveyard spiral is somewhat complicated, a skillful pilot can easily manipulate the stick and rudder pedals to cancel all vestibular and other nonvisual sensory indications that the aircraft is turning and diving. In one mishap involving a dark-night takeoff of a commercial airliner, the recorded flight data showed that the resultant G force which the pilot created by his control inputs allowed him to perceive his desired 10° to 12° climb angle and a net G force between 0.9 and 1.1 G for virtually the whole flight, even though he actually leveled off and then descended in an accelerating spiral until the aircraft crashed nearly inverted.

Inversion Illusion

The inversion illusion is a type of somatogravic illusion in which the resultant gravitoinertial force vector rotates backward so far as to be pointing away from rather than toward the earth's surface, thus giving the pilot the false sensation of being upside down. Figure 31 shows how this can happen. Typically, a steeply climbing high-performance aircraft levels off more or less abruptly at the desired altitude. This maneuver subjects the aircraft and pilot to a $-G_z$ centrifugal force resulting from the arc flown just prior to level-off. Simultaneously, as the aircraft changes to a more level attitude, airspeed picks up rapidly, adding a $+G_x$ tangential inertial force to the overall force environment. Adding the $-G_z$ centrifugal force and the $+G_x$ tangential force to the 1-G gravitational force results in a net gravitoinertial force vector that rotates backward and upward relative to the pilot. This stimulates the pilot's otolith organs in a manner similar to the way a pitch upward into an

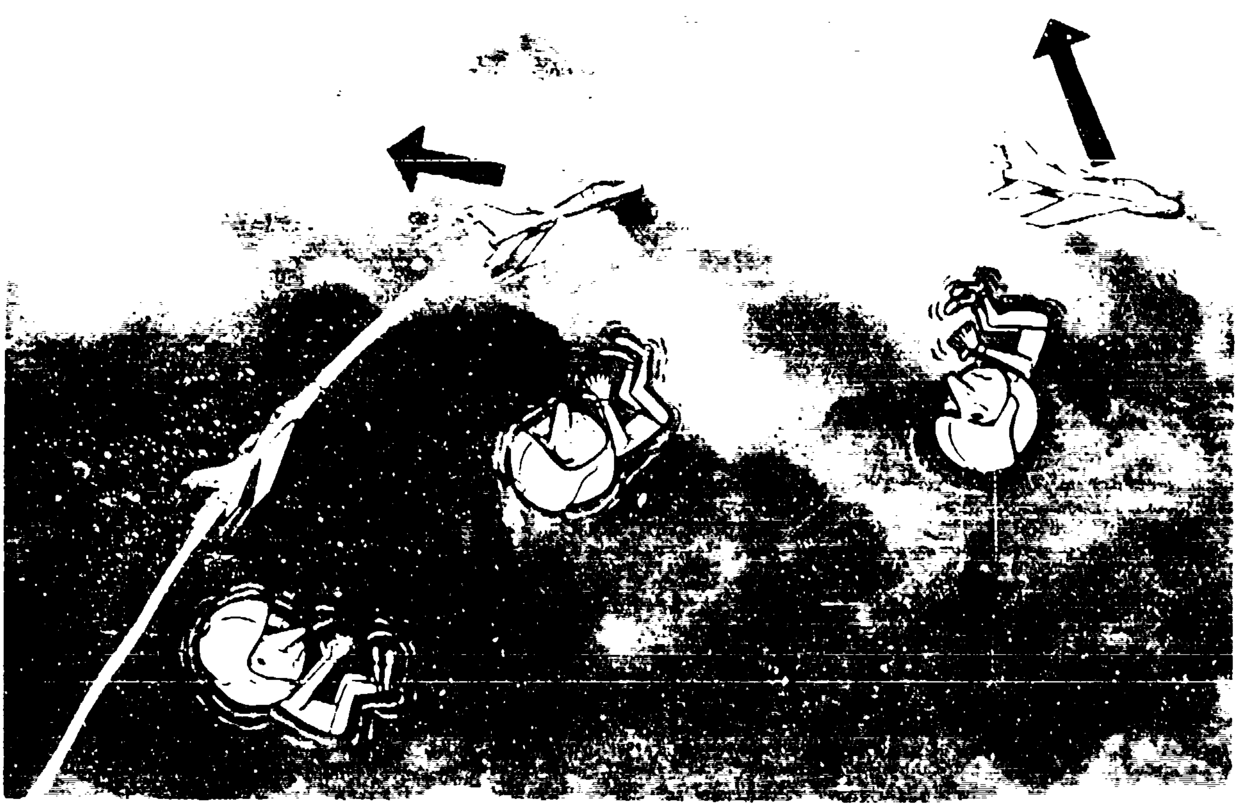


Figure 31. The inversion illusion. Centrifugal and tangential inertial forces during a level-off combine with the force of gravity to produce a resultant gravitoinertial force that rotates backward and upward with respect to the pilot, causing a false percept of suddenly being upside down. Turbulent weather can produce additional inertial forces that contribute to the illusion. (Adapted from Martin and Jones.[32])

inverted position would. Even though the semicircular ducts should respond to the actual pitch downward, for some reason this conflict is resolved in favor of the otolith-organ information, perhaps because the semicircular-duct response is transient while the otolith-organ response persists, or perhaps because the information from the other mechanoreceptors reinforces the information from the otolith organs. The pilot who responds to the inversion illusion by pushing forward on the stick to counter the perceived pitching up and over backward only prolongs the illusion by creating more $-G_z$ and $+G_x$ forces, thus aggravating the situation. Turbulent weather usually contributes to the development of the illusion; certainly, downdrafts are a source of $-G_z$ forces that can add to the net gravitoinertial force producing the inversion illusion. Again, do not assume one must be flying a jet fighter to experience this illusion. Several reports of the inversion illusion involve crews of large airliners who lost control of their aircraft because the pilot lowered the nose inappropriately after experiencing the illusion. Jet upset is the name for the sequence of events that includes instrument weather, turbulence, the inability of the pilot to read the instruments, the inversion illusion, a pitch-down control input, and difficulty recovering the aircraft because of resulting aerodynamic or mechanical forces.[33]

G-Excess Effect

Whereas the somatogravic illusion results from a change in the direction of the net G force, the G-excess effect results from a change in G magnitude. The G-excess effect is a false or exaggerated sensation of body tilt that can occur when the G environment is sustained at greater than 1 G. For a simplistic illustration of this phenomenon, let us imagine a subject is sitting upright in a $+1\ G_z$ environment and then tips the head forward 30° (Fig. 32). As a result of this change in head position, the subject's otolithic membranes slide forward the appropriate amount for a 30° tilt relative to vertical say a distance of x µm. Now suppose that the same subject is sitting upright in a $+2\ G_z$ environment and again tips the head forward 30°. This time, the subject's otolithic membranes slide forward more than x µm because of the doubled gravitoinertial force acting on them. The displacement of the otolithic membranes, however, now corresponds not to a 30° forward tilt in the normal 1-G environment but to a much greater tilt, theoretically as much as 90° ($2 \sin 30° = \sin 90°$). The subject had initiated only a 30° head tilt, however, and expects to perceive no more than that. The unexpected additional perceived tilt is thus referred to the immediate environment; i.e., the subject perceives his or her aircraft to have tilted by the amount equal to the difference between the actual and expected percepts of tilt. The actual perceptual mechanism underlying the G-excess effect is more complicated than the illustration suggests: first, the plane of the utricular maculae is not really horizontal but slopes upward 20-30° from back to front; second, the saccular maculae contribute in an undetermined manner to the net percept of tilt; and third, as is usually the case with vestibular illusions, good visual orientational cues attenuate the illusory percept. But experimental evidence clearly demonstrates the existence of the G-excess effect. Perceptual errors of 10° to 20° are generated at 2 G, and at 1.5 G the errors are about half that amount.[34,35]

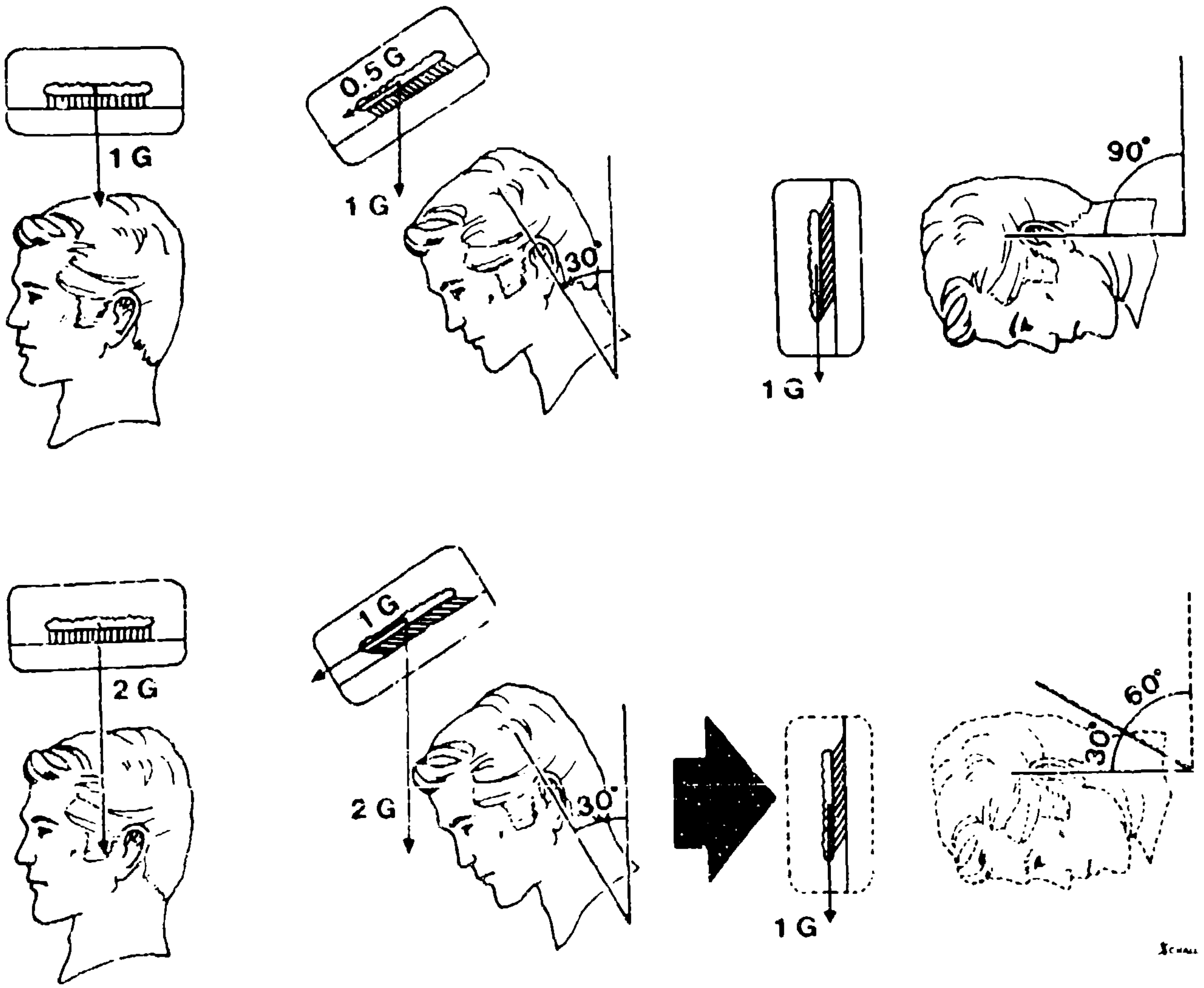


Figure 32. Mechanism of G-excess illusion. In this oversimplified illustration, the subject in a 1-G environment (upper half of figure) experiences the result of a 0.5-G pull on the utricular otolithic membranes when the head is tilted 30° off the vertical, and the result of a 1-G pull when the head is tilted a full 90°. The subject in a 2-G environment (lower half of figure) experiences the result of a 1-G pull when the head is tilted only 30°. The illusory excess tilt perceived by the subject is attributed to external forces (lower right). Note that the actual plane of the utricular macula slopes 20-30° upward.

In fast-moving aircraft, the G-excess illusion can occur as a result of the moderate amount of G force pulled in a turn--a penetration turn or procedure turn, for example. A pilot who has to look down and to the side to select a new radio frequency or to pick up a dropped pencil while in a turn should experience an uncommanded tilt in both the pitch and roll planes due to the G-excess illusion. As noted previously, the G excess illusion may be responsible for the false sensation of pitch and/or roll generally attributed to the Coriolis illusion under such circumstances. The G-excess effect has recently become a suspect in a number of mishaps involving fighter/attack aircraft making 2- to 5.5-G turns at low altitudes in conditions of essentially good visibility. For some reason, the aircraft were overbanked while the pilots were looking out of the cockpit for an adversary, wingman, or some other object of visual attention; and as a result they descended into the terrain. In theory, the G-excess effect causes an illusion of underbank if the pilot's head is either facing the inside of the turn and elevated (Fig. 33) or facing the outside of the turn and depressed. If facing forward, the pilot would have an illusion of pitching up, i.e., climbing, during the turn. Thus, in any of these common circumstances, the pilot who fails to maintain a continuous visual reference to the earth's surface would likely cause the aircraft to descend in response

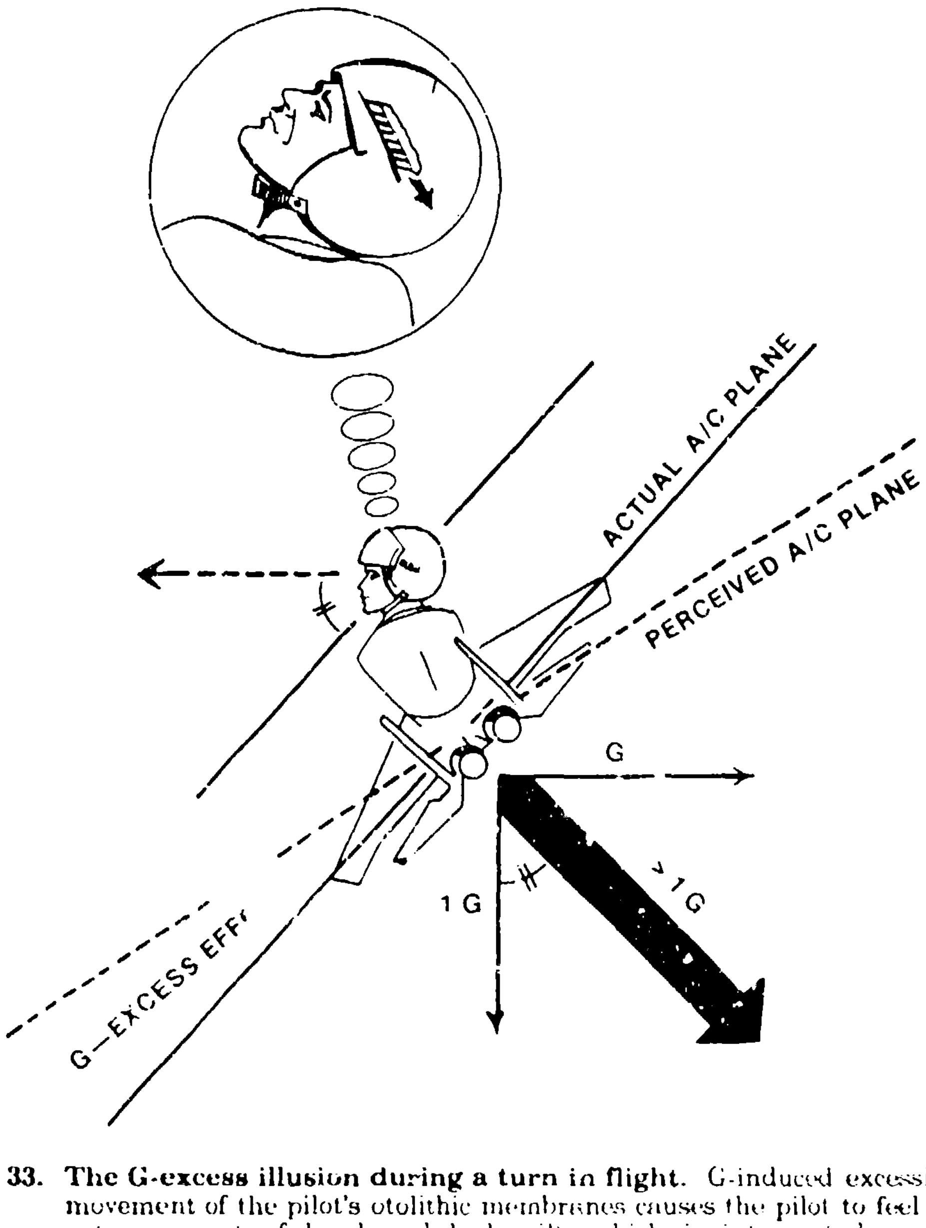


Figure 33. The G-excess illusion during a turn in flight. G-induced excessive movement of the pilot's otolithic membranes causes the pilot to feel an extra amount of head and body tilt, which is interpreted as an underbank of the aircraft when looking up to the inside of the turn. Corre[illegible]g for the illusion, the pilot overbanks the aircraft and it d[illegible]

to the illusory change of attitude caused by the G-excess effect. Perhaps in some of the mishaps mentioned the pilot's view of the spatial environment was inadequate encompassing sky rather than ground, or perhaps G-induced tunnel vision was responsible for loss of ambient visual cues. In any case, it is apparent that the pilots failed to perceive correctly their aircraft attitude, vertical velocity, and height above the ground; i.e., they were spatially disoriented.

The elevator illusion is a special kind of G-excess effect. Because of the way the utricular otolithic membranes are variably displaced with respect to their maculae by increases and decreases in $+G_z$ force, false sensations of pitch and vertical velocity can result even when the head remains in the normal, upright position. When an upward acceleration (as occurs in an elevator) causes the net G_z force to increase, a sensation of climbing and tilting backward can occur. In flight, such an upward acceleration occurs when an aircraft levels off from a sustained descent. This temporary increase in $+G_z$ loading can make pilots feel a pitch up and climb if their views of the outside world are restricted by night, weather, or head-down cockpit chores. Compensating for the illusory pitch up sensation, the pilot would likely put the aircraft back into a descent, all the while feeling that the aircraft is maintaining a constant altitude. In one inflight study of the elevator illusion, blindfolded pilots were told to maintain perceived level flight after a relatively brisk level-off from a sustained 2000-ft/min (10 m/sec) descent; the mean response of the six pilots was a 1300-ft/min (6.6 m/sec) descent.[15] Clearly this tendency to reestablish a descent is especially dangerous during the final stage of a nonprecision instrument approach at night or in weather. Upon leveling off at the published minimum descent altitude, the pilot typically starts a visual search for the runway. In conjunction with failing to monitor the flight instruments during this critical time, the elevator illusion can cause the pilot to unwittingly put the aircraft into a descent, and thus squander the altitude buffer protecting the aircraft from ground impact.

Oculogravic Illusion

The oculogravic illusion can be thought of as a visual correlate of the somatogravic illusion and occurs under the same stimulus conditions.[36] A pilot who is subjected to the deceleration resulting from the application of speed brakes, for example, experiences a nose-down pitch because of the somatogravic illusion. Simultaneously, the pilot observes the instrument panel to move downward, confirming the sensation of tilting forward. The oculogravic illusion is thus the visually apparent movement of an object that is actually fixed relative to the subject during the changing direction of the net gravitoinertial force. Like the oculogyral illusion, the oculogravic illusion probably results from the attempt to maintain visual fixation during a vestibulo-ocular reflex elicited, in this case, by the change in direction of the applied G vector rather than by angular acceleration.

The elevator illusion was originally thought of as a visual phenomenon like the oculogravic illusion, except that the false percept was believed to result from a vestibulo-ocular reflex generated by a change in magnitude of the $+G_z$ force instead of by a change in its direction. When an individual is accelerated upward, as in an elevator, the increase in $+G_z$ force elicits a vestibulo-ocular reflex of otolith-organ origin (the elevator reflex) that drives the eyes downward. Attempting to stabilize visually the objects in a fixed position relative to the observer causes those objects to appear to shift upward when the G force is increased. The opposite effect occurs when the individual is accelerated downward; the reduction in the magnitude of the net gravitoinertial force to less than $+1\ G_z$ causes a reflex upward shift of the direction of gaze, and the immediate surroundings appear to shift downward. (The latter effect also has been called the oculoagravic illusion because of its occurrence during transient weightlessness.) Although the described visual effect undoubtedly contributes to the expression of the elevator illusion, it is not essential for its generation, since the illusion can occur even in the absence of vision, as just noted.

The Leans

By far the most common vestibular illusion in flight is the leans. Virtually every instrument-rated pilot has had or will get the leans in one form or another at some time during his or her flying career. The leans consists of a false percept of angular displacement about the roll axis (i.e., an illusion of bank) and is frequently associated with a vestibulospinal reflex, appropriate to the false percept, that results in the pilot's actually leaning in the direction of the falsely perceived vertical (Fig. 34). The usual explanations of the leans invoke the known deficiencies of both otolith-organ and semicircular-duct sensory mechanisms. As indicated previously, the otolith organs are not reliable sources of information about the exact direction of the true vertical because they respond to the resultant gravitoinertial force, not to gravity alone. Furthermore, other sensory inputs can sometimes override otolith-organ cues and result in a false perception of the vertical, even when the gravitoinertial force experienced is truly vertical. The semicircular ducts provide false inputs in flight by responding accurately to some roll stimuli but not responding at all to others because they are below threshold. For example, a pilot who is subjected to an angular acceleration in roll so that the product of the acceleration and its time of application does not reach some threshold value, say 2°/sec, does not perceive the roll. Suppose that this pilot, who is trying to fly straight and level, is subjected to an unrecognized and uncorrected 2°/sec roll for 10 seconds: a 20° bank results. If the unwanted bank becomes suddenly apparent and is corrected by rolling the aircraft back upright with a suprathreshold rate, the pilot experiences only half of the actual roll motion that took place--the half resulting from the correcting roll. As the aircraft started from a perceived wings-level position, the pilot upon returning to an actual wings-level attitude is left with the illusion of having rolled into a 20° bank in the direction of the correcting roll and experiences the leans. Even though the pilot may be able to fly the aircraft properly by the deliberate and difficult process of forcing the attitude indicator to read correctly, the leans can last for many minutes, seriously degrading flying efficiency during that time.

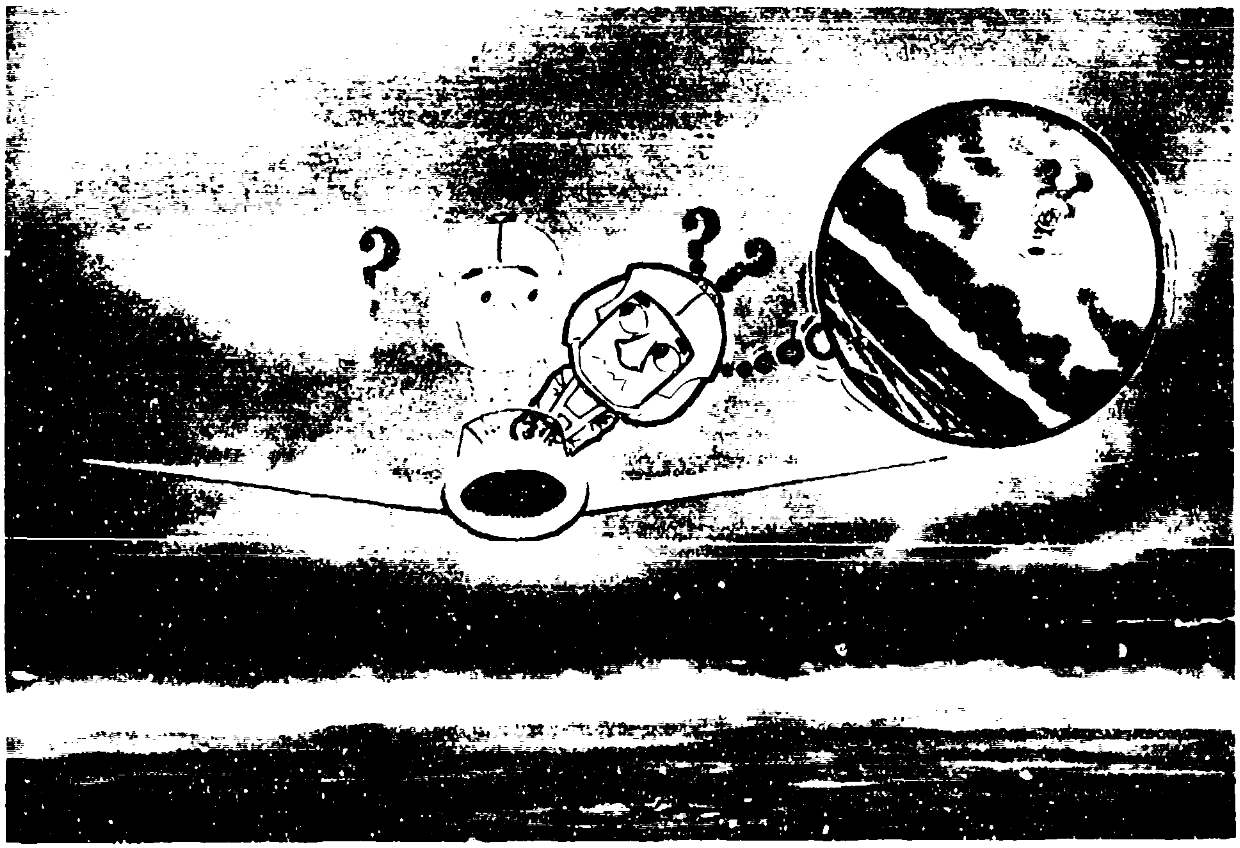


Figure 34. The leans, the most common of all vestibular illusions in flight. Falsely perceived to be in a right bank, but flying the aircraft straight and level by means of the flight instruments, this pilot is leaning to the left in an attempt to assume an upright posture compatible with the illusion of bank.

Interestingly, pilots frequently get the leans after prolonged turning maneuvers and not because of alternating subthreshold and suprathreshold angular motion stimuli. In a holding pattern, for example, the pilot rolls into a 3°/sec standard-rate turn, holds the turn for 1 minute, rolls out and flies straight for 1 minute, turns again for 1 minute, and so on until traffic conditions permit the continuation of the flight toward its destination. During the turning segments, the pilot initially feels the roll into the turn and accurately perceives the banked attitude. But as the turn continues, the percept of being in a banked turn dissipates and is replaced by a feeling of flying straight with wings level, both because the sensation of turning is lost when the endolymph comes up to speed in the semicircular ducts (somatogyral illusion) and because the net G force being directed toward the floor of the aircraft provides a false cue of verticality (somatogravic illusion). Upon rolling out of the turn, the pilot's perception is of a banked turn in the opposite direction. With experience, a pilot learns to suppress this false sensation quickly by paying strict attention to the attitude indicator. Sometimes, however, pilots cannot dispel the illusion of banking--usually when they are particularly busy, unfortunately. The leans also can be caused by misleading peripheral visual orientation cues, as mentioned in the section entitled "Visual Illusions." Roll vection is particularly effective in this regard, at least in the laboratory. One thing about the leans is apparent: there is no single explanation for this illusion. The deficiencies of several orientation-sensing systems in some cases reinforce each other to create the illusion; in other cases, the inaccurate information from one sensory modality for some reason is selected over the accurate information from others to create the illusion. Stories have surfaced of pilots suddenly experiencing the leans for no apparent reason at all, or even of experiencing it voluntarily by imagining the earth to be in a different direction from the aircraft. The point is that one must not think that the leans, or any other illusion for that matter, occurs as a totally predictable response to a physical stimulus: there is much more to perception than stimulation of the end-organs.

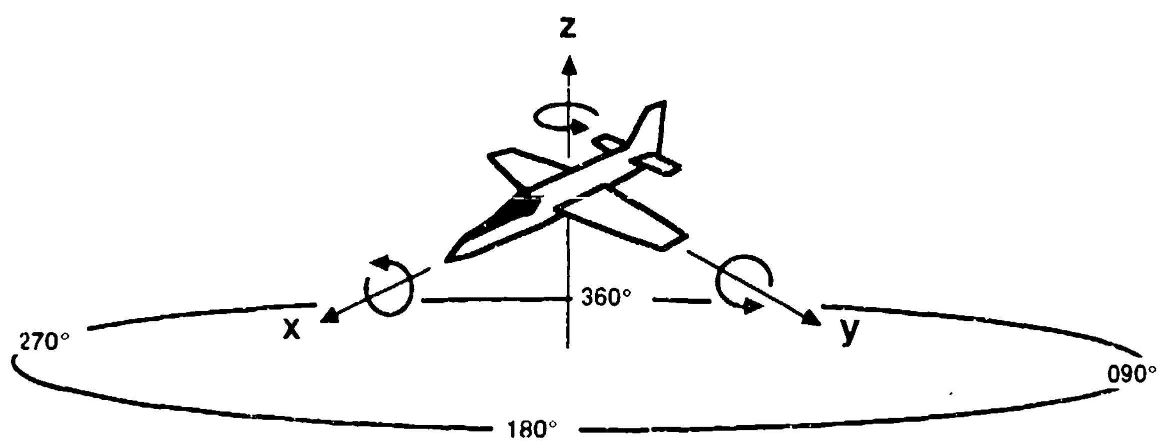
Disorientation

Definitions

An orientational percept is a sense of one's linear and angular position and motion relative to the plane of the earth's surface. It can be primary (i.e., natural), meaning that it is based on ambient visual, vestibular, or other sensations that normally contribute to spatial orientation in our natural environment; or it can be secondary (i.e., synthetic), meaning that it is intellectually constructed from focal visual, verbal, or other symbolic data, such as that presented by flight instruments. While the former type of orientational percept is essentially irrational and involves largely preconscious mental processing, the latter type is rational and entirely conscious. A locational percept, to be distinguished from an orientational percept, is a sense of one's position *in* (as opposed to *relative to*) the plane of the earth's surface. An accurate locational percept is achieved by reading a map or knowing the latitude and longitude of one's location.

Spatial disorientation is a state characterized by an erroneous orientational percept, i.e., an erroneous sense of one's position and motion relative to the plane of the earth's surface. Geographic disorientation, or "being lost," is a state characterized by an erroneous locational percept. These definitions together encompass all the possible positions and velocities, both translational and rotational, along and about three orthogonal earth-referenced axes.

Orientation information includes those parameters that an individual on or near the earth's surface with eyes open can reasonably be expected to process accurately on a sunny day. Lateral tilt, forward-backward tilt, angular position about a vertical axis, and their corresponding first derivatives with respect to time are the angular positions and motions included; height above ground, forward-backward velocity, sideways velocity, and up-down velocity are the linear position and motions included. Absent from this collection of orientation information parameters are the location coordinates, the linear position dimensions in the horizontal plane. In flight, orientation information is described in terms of flight instrument-based parameters (Fig. 35). Angular position is bank, pitch, and heading; and the corresponding angular velocities are roll rate, pitch rate, and turn rate (or yaw rate). The linear position parameter is altitude; and the linear velocity parameters are airspeed (or groundspeed), slip/skid rate, and vertical velocity. Inflight navigation information is composed of linear position dimensions in the horizontal plane, such as latitude and longitude or bearing and distance from a navigation reference point.



AXIS	ANGULAR POSITION	ANGULAR VELOCITY	LINEAR POSITION	LINEAR VELOCITY
x	Bank	Roll rate	*	Airspeed
y	Pitch	Pitch rate	*	Slip/skid rate
z	Heading	Turn rate	Altitude	Vertical velocity

* Navigation parameters

Figure 35. Flight instrument-based parameters of spatial orientation. Spatial disorientation is a state characterized by an erroneous sense of any of these parameters.

United States Air Force Manual 51-37, *Instrument Flying*[37], categorizes flight instruments into three functional groups: control, performance, and navigation. In the control category are the parameters of aircraft attitude (i.e., pitch and bank) and engine power or thrust. In the performance category are airspeed, altitude, vertical velocity, heading, turn rate, slip/skid rate, angle of attack, acceleration (G loading), and flight path (velocity vector). The navigation category includes course, bearing, range, latitude/longitude, time, and similar parameters useful for determining location on the earth's surface. This categorization of flight instrument parameters allows us to construct a useful *operational definition of spatial disorientation*: it is *an erroneous sense of the magnitude or direction of any of the control and performance flight parameters*. Geographic disorientation, in contrast, is thus: an erroneous sense of any of the navigation parameters. The practical utility of these operational definitions is that they can establish a common understanding of what is meant by spatial disorientation among all parties investigating an aircraft mishap, whether they be pilots, flight surgeons, aerospace physiologists, or representatives of some other discipline. If the answer to the question, "Did the pilot not realize the aircraft's actual pitch attitude and vertical velocity (and/or other control or performance parameters)?" is "Yes," then it is obvious that the pilot was spatially disoriented, and the contribution of the disorientation to the sequence of events leading to the mishap is clarified.

Sometimes aircrew tend to be imprecise when they discuss spatial disorientation, preferring to say that they "lost situational awareness" rather than "became disoriented," as though having experienced spatial disorientation stigmatizes them. Situational awareness involves a correct appreciation of a host of conditions, including the tactical environment, location, weather, weapons capability, administrative constraints, [illegible] as well as spatial orientation. Thus, if the situation about which a pilot lacks awareness is the aircraft's position and motion relative to the plane of the earth's surface, the pilot has spatial disorientation, as well as a loss of situational awareness, generally.

Types of Spatial Disorientation

We distinguish three types of spatial disorientation in flight: Type I (unrecognized), Type II (recognized), and Type III (incapacitating). In Type I disorientation, no conscious perception of any of the manifestations of disorientation is present; i.e., the pilot experiences no disparity between natural and synthetic orientational percepts, has no suspicion that a flight instrument (e.g., attitude indicator) has malfunctioned, and does not feel that the aircraft is responding incorrectly to control inputs. In unrecognized spatial disorientation the pilot is oblivious to his or her disoriention, and controls the aircraft completely in accord with and in response to a false orientational percept. To distinguish Type I disorientation from the others, and to emphasize its insidiousness, some pilots and aerospace physiologists call Type I spatial disorientation "misorientation."

In Type II disorientation, the pilot consciously perceives some manifestation of disorientation. Pilots may experience a conflict between what they feel the aircraft is doing and what the flight instruments show that it is doing. Or the pilot may not experience a genuine conflict, but may merely conclude that the flight instruments are incorrect. The pilot also may feel that the aircraft is attempting to assume a pitch or bank attitude counter to the intended one. Type II disorientation is the kind to which pilots are referring when they use the term "vertigo," as in "I had a bad case of vertigo on final approach." Although Type II spatial disorientation is labeled "recognized," this does not mean that pilots necessarily realize they are disoriented: they may only realize that there is a problem in controlling the aircraft, not knowing that the source of the problem is spatial disorientation.

With Type III spatial disorientation, the pilot experiences an overwhelming--i.e., incapacitating--physiologic response to physical or emotional stimuli associated with the disorientation event. For example, the pilot may suffer from "vestibulo-ocular disorganization" due to the presence of vestibular nystagmus, so that the flight instruments cannot be read and a stable view of the outside world cannot be obtained. Or, control of the aircraft may be impeded by strong vestibulospinal reflexes affecting the shoulder and arm muscles. The pilot may even be so incapacitated by fear that rational decisions may be thwarted--e.g., the pilot may freeze on the controls. The important feature of Type III disorientation is that the pilot is disoriented and most likely knows it, but can't do anything about it.

Examples of Disorientation

The last of four F-15 Eagle fighter aircraft took off on a daytime sortie in bad weather, intending to follow the other three in a radar in-trail departure. Because of a navigational error committed by the pilot shortly after takeoff, he was unable to find the other aircraft on his radar. Frustrated, the pilot elected to intercept the other aircraft where he knew they would be in the arc of the standard instrument departure, so he made a beeline for that point, presumably scanning his radar diligently for the blips he knew should be appearing at any time. Meanwhile, after ascending to 4000 ft (1200 m) above ground level, he entered a descent of approximately 2500 ft/min (13 m/sec) as a result of an unrecognized 3° nose-low attitude. After receiving requested position information from another member of the flight, the pilot either suddenly realized he was in danger of colliding with the other aircraft or he suddenly found them on radar, because he then made a steeply banked turn, either to avoid a perceived threat of collision or to join up with the rest of the flight. Unfortunately, he had by this time descended far below the other aircraft and was going too fast to avoid the ground, which became visible under the overcast just before the aircraft crashed. This mishap resulted from an episode of unrecognized, or Type I, disorientation. The specific illusion responsible appears to have been the somatogravic illusion, which was created by the forward acceleration of this high-performance aircraft during takeoff and climb-out. The pilot's preoccupation with the radar task compromised his instrument scan to the point where the false vestibular cues gained access to his perceptual processing. Having unknowingly accepted an inaccurate orientational percept, he controlled the aircraft accordingly until it was too late to recover.

Examples of recognized, or Type II, spatial disorientation are easier to obtain than are examples of Type I because most experienced pilots have anecdotes to tell about how they "got vertigo" and fought it off. Some pilots were not so fortunate, however. One F-15 Eagle pilot, after climbing his aircraft in formation with another F-15 at night, began to experience difficulty in maintaining spatial orientation and aircraft control upon leveling off in clouds at 27,000 ft (8,200 m). "Talk about practice bleeding," he commented to the lead pilot. Having decided to go to another area because of the weather, the two pilots began a descending right turn. At this point, the pilot on the wing told the lead pilot, "I'm flying upside down." Shortly afterward, the wingman considered separating from the formation, saying, "I'm going lost wingman." Then he said, "No, I've got you," and finally, "No, I'm going lost wingman." The hapless wingman then caused his aircraft to descend in a wide spiral, and crashed into the desert less than a minute later, even though the lead pilot advised the wingman several times during the descent to level out. In this mishap, the pilot probably suffered an inversion illusion upon leveling off in the weather, and entered a graveyard spiral after leaving the formation. Although he knew he was disoriented, or at least recognized the possibility, he still was unable to control the aircraft effectively. That pilots can realize being disoriented, see accurate orientation information displayed on the attitude indicator, and still fly into the ground always strains the credulity of nonaviators. Pilots who have had spatial disorientation, who have experienced fighting oneself for control of an aircraft, are less skeptical.

The pilot of an F-15 Eagle, engaged in vigorous air combat tactics training with two other F-15s on a clear day, initiated a hard left turn at 17,000 ft (5,200 m) above ground level. For reasons that have not been established with certainty, his aircraft began to roll to the left at a rate estimated at 150 to 180°/sec. He transmitted, "Out-of-control autoroll," as he descended through 15,000 ft (4,600 m). The pilot made at least one successful attempt to stop the roll, as evidenced by the momentary cessation of the roll at 8,000 ft (2,400 m); then the aircraft began to roll again to the left. Forty seconds elapsed between the time that the rolling began and the time that the pilot ejected--but too late. Regardless of whether the rolling was caused by a mechanical malfunction or was an autoroll induced by the pilot, the likely result of this extreme motion was vestibulo-ocular disorganization, which not only prevented the pilot from reading his instruments but also kept him from orienting with the natural horizon. Thus, Type III disorientation probably prevented him from taking appropriate corrective action to stop the roll and keep it stopped; if not that, it certainly compromised his ability to assess accurately the level to which his situation had deteriorated.

Statistics

Because the fraction of aircraft mishaps caused by or contributed to by spatial disorientation has doubled over the four decades between 1950 and 1990, one might conclude that continuing efforts to educate pilots about spatial disorientation and the hazard it represents have been to no avail. Fortunately, the total number of major mishaps and the number of major mishaps per million flying hours have dropped considerably over the same period (at least in the United States), so it appears that such flying safety education efforts actually have been effective.

A number of statistical studies of spatial disorientation mishaps in the United States Air Force provide an appreciation of the magnitude of the problem in military aviation. In 1956, Nuttall and Sanford[38] reported that, in one major air command during the period of 1954 to 1956, spatial disorientation was responsible for 4% of all major aircraft mishaps and 14% of all fatal aircraft mishaps. In 1969, Moser[39] reported a study of aircraft mishaps in another major air command during the four-year period from 1964 through 1967: He found that spatial disorientation was a significant factor in 9% of major mishaps and 26% of fatal mishaps. In 1971, Barnum and Bonner[40] reviewed the Air Force mishap data from 1958 through 1968 and found that in 281 (6%) of the 4679 major mishaps, spatial disorientation was a causative factor; fatalities occurred in 211 of those 281 accidents, accounting for 15% of the 1462 fatal mishaps. A comment by Barnum and Bonner summarizes some interesting data about the "average pilot" involved in a spatial disorientation mishap: "He will be around 30 years of age, have 10 years in the cockpit, and have 1500 hours of first pilot/instructor-pilot time. He will be a fighter pilot and will have flown approximately 25 times in the three months prior to his accident." In an independent 1973 study, Kellogg[41] found the relative incidence of spatial disorientation mishaps in the years 1968 through 1972 to range from 4.8% to 6.2% and confirmed the high proportion of fatalities in mishaps resulting from spatial disorientation. The major (Class A) Air Force mishaps over the ten-year period from 1980 through 1989 were reviewed by Freeman (personal communication, 1990). He found that 81 (13%) of the 633 major mishaps during that period, and 115 (14%) of the 795 fatalities, were due to spatial disorientation. If we consider only the mishaps caused by operator error, disorientation accounted for approximately one-fourth of these (81 out of 356). If we only consider the Air Force's front-line fighter/attack aircraft, the F-15 and F-16, nearly one-third (26 of 86) of the losses of these aircraft resulted from spatial disorientation. The cost of the Air Force aircraft destroyed each year in disorientation mishaps until the decade of the 1980s was on the order of $20 million per year. From 1980 through 1989, over $500 million dollars worth of Air Force resources were lost as a result of spatial disorientation. Currently, the average annual dollar cost of spatial disorientation to the Air Force is on the order of $100 million; but occasional losses of particularly expensive aircraft result in much higher figures in some years.

Regarding the fractions of the disorientation-related mishaps for which the various types of spatial disorientation are responsible, the conventional wisdom is that more than half of the mishaps involve Type I disorientation, most of the remainder involve Type II, and very few involve Type III. The same wisdom suggests that the source of the disorientation is visual illusions in about half of the mishaps, and vestibular/somatosensory illusions in the other half, with combined visual and vestibular illusions accounting for at least some of the mishaps. An analysis of Air Force aircraft mishaps in 1988 in which spatial disorientation was suspected by the investigating flight surgeon revealed that all 8 involved Type I; 2 apparently resulted from visual illusions, 3 from vestibular illusions, and 3 from mixed visual and vestibular illusions.[42]

The recent experience of the United States Navy with spatial disorientation is also instructive.[43] During the years 1980 through 1989, 112 Class A flight mishaps involved spatial disorientation as a definite, probable, or possible causal factor. Of the 40 mishaps in the "definite" category, 20 occurred in daytime and 20 happened at night; 17 occurred during flight over land, and 23 resulted during flight over water. Thirty-two aircraft, including 15 fighter/attack aircraft, 6 training aircraft, and 11 helicopters, were destroyed; and 38 lives were lost in the 13 fatal mishaps out of the 40 Class A mishaps. The mean experience for the Navy pilots involved in spatial disorientation mishaps was 1488 hours (median: 1152 hours), nearly the same as that for Air Force pilots. Surprisingly, the incidence of spatial disorientation-related mishaps for the Air Force, Navy, and Army have been remarkably similar over the years, even though the flying missions of the several military services are somewhat different.[44,45]

One problem with the mishap statistics related above is that they are conservative, representing only those mishaps in which disorientation was stated to be a possible or probable factor by the Safety Investigation Board. In actuality, many mishaps resulting from spatial disorientation were not identified as such because other factors--such as distraction, task saturation, and poor crew coordination--initiated the chain of events resulting in the mishap; these factors were considered more relevant or more amenable to correction than the disorientation that followed and ultimately caused the pilot to fly the aircraft into the ground or water. In the Air Force from 1980 through 1989, 263 mishaps and 425 fatalities, at a cost of over two billion dollars, resulted from "loss of situational awareness" (Freeman, J.E.; personal communication, 1990). It is apparent that the great majority of those mishaps would not have happened if the pilots had at all times correctly assessed their pitch/bank attitude, vertical velocity, and altitude--i.e., if they had not been spatially disoriented. Thus we can infer that spatial disorientation causes considerably more aircraft mishaps than the disorientation-specific incidence statistics would lead us to believe, probably two or three times as many.

Although statistics indicating the relative frequency of spatial disorientation mishaps in air-carrier operations are not readily available, it would be a serious mistake to conclude that there have been no air-carrier mishaps caused by spatial disorientation. Fourteen such mishaps occurring between 1950 and

1969 were reportedly due to somatogravic and visual illusions that resulted in the so-called "dark-night takeoff accident."[31] In addition, 26 commercial airliners were involved in jet-upset incidents or accidents during the same period.[33] Spatial disorientation also is a problem in general (nonmilitary, nonair-carrier) aviation. Kirkham and colleagues[46] reported in 1978 that although spatial disorientation was a cause or factor in only 2.5% of all general aviation aircraft accidents in the United States, it was the third most common cause of fatal general aviation accidents. Of the 4012 fatal general aviation mishaps occurring in the years 1970 through 1975, 627 (15.6%) involved spatial disorientation as a cause or factor. Notably, 90% of general aviation mishaps in which disorientation was a cause or factor were fatal.

Dynamics of Spatial Orientation and Disorientation

Part of the process of learning how to fly solely by reference to flight instruments, as opposed to flying by visual reference to the outside world, involves acquiring an ability to select and process information and to deselect unreliable information cues. Visual dominance and vestibular suppression are concepts of how this ability is manifested.

The lack of adequate orientation cues and conflicts between competing sensory modalities are only a partial explanation of disorientation mishaps, however. Why so many disoriented pilots, even those who know they are disoriented, are unable to recover their aircraft has mystified aircraft accident investigators for decades. One possibility is that the psychologic stress of disorientation results in a disintegration of higher-order learned behavior, including flying skills. Another is a complex psychomotor effect of disorientation that causes the pilot to feel the aircraft itself is misbehaving.

Visual Dominance

It is naive to assume that a certain pattern of physical stimuli always elicits a particular veridical or illusory perceptual response. Certainly, when a pilot has a wide, clear view of the horizon, ambient vision supplies virtually all necessary orientation information, and potentially misleading linear or angular acceleratory motion cues do not result in spatial disorientation (unless, of course, they are so violent as to cause vestibulo-ocular disorganization). When a pilot's vision is compromised by night or bad weather conditions, the same acceleratory motion cues can cause spatial disorientation, but the pilot usually avoids it by referring to the aircraft instruments for orientation information. If the pilot is unskilled at interpreting the instruments, if the instruments fail, or, as frequently happens, if the pilot neglects to look at the instruments, those misleading motion cues inevitably cause disorientation. Such is the character of visual dominance, the phenomenon in which one incorporates visual orientation information into a percept of spatial orientation to the exclusion of vestibular and nonvestibular proprioceptive, tactile, and other sensory cues. Visual dominance falls into two categories: the congenital type, in which ambient vision provides dominant orientation cues through natural neural connections and functions, and the acquired type, in which orientation cues are gleaned through focal vision and are integrated as a result of training and experience into an orientational percept. The functioning of the proficient instrument pilot illustrates acquired visual dominance: such an individual has learned to decode with foveal vision the information on the attitude indicator and other flight instruments and to reconstruct that information into a concept of what the aircraft is doing and where it is going, which is then used in controlling the aircraft. This complex skill must be developed through training and maintained through practice, and its fragility is one of the factors that make spatial disorientation such a hazard.

Vestibular Suppression

The term vestibular suppression often is used to denote the active process of visually overriding undesirable vestibular sensations or reflexes of vestibular origin. An example of this aspect of visual dominance is seen in well-trained figure skaters who, with much practice, learn to abolish the postrotatory dizziness, nystagmus, and postural instability that normally result from the high angular decelerations associated with suddenly stopping rapid spins on the ice.[16] But even these individuals, when deprived of vision by eye closure or darkness, have the very dizziness, nystagmus, and falling that we would expect to result from the acceleratory stimuli produced.[17] In flight, the ability to suppress unwanted vestibular sensations and reflexes is developed with repeated exposure to the linear and angular accelerations of flight. As is the case with the figure skaters, however, the pilot's ability to prevent vestibular sensations and reflexes is compromised when visual orientation cues are disrupted by night, weather, and inadequate flight instrument displays.

Opportunism

Opportunism on the part of the primary (ambient visual and vestibular) orientation-information processing systems refers to the propensity of those systems to fill an orientation-information void swiftly and surely with natural orientation information. When a pilot flying in instrument weather looks away from the artificial horizon for a mere few seconds, this is usually long enough for erroneous ambient visual or vestibular information to break through and become incorporated into the pilot's orientational percept. In fact, conflicts between focal visual and ambient visual or vestibular sources of orientation information tend to resolve themselves very quickly in favor of the latter without providing the pilot an opportunity to evaluate the information. It is logical that any orientation information reaching the vestibular nuclei--whether vestibular, other proprioceptive, or ambient visual--should have an advantage in competing with focal visual cues for expression as the pilot's sole orientational percept, because the vestibular nuclei are primary terminals in the pathways for reflex orientational responses and are the initial level of integration for any eventual conscious spatial orientation percept. In other words, although acquired visual dominance can be maintained by diligent attention to synthetic orientation cues, the challenge to this dominance presented by the processing of natural orientation cues through primitive neural channels is very potent and ever present.

Disintegration of Flying Skill

The disintegration of flying skill perhaps begins with the pilot's realization that spatial orientation and control over the motion of the aircraft have been compromised. Under such circumstances, the pilot pays more heed to whatever orientation information is naturally available, monitoring it more and more vigorously. Whether the brain stem reticular activating system or the vestibular efferent system, or both, are responsible for the resulting heightened arousal and enhanced vestibular information flow can only be surmised; the net effect, however, is that more erroneous vestibular information is processed and incorporated into the pilot's orientational percept. This, of course, only makes matters worse. A positive-feedback situation is thus encountered, and the vicious circle can now be broken only with a precisely directed and very determined effort by the pilot. Unfortunately, complex cognitive and motor skills tend to be degraded under conditions of psychologic stress such as occur during Type II or Type III spatial disorientation. First, there is a coning of attention; pilots who have survived severe disorientation have reported that they were concentrating on one particular flight instrument instead of scanning and interpreting the whole group of them in the usual manner. Pilots also have reported that they were unaware of radio transmissions to them while they were trying to recover from disorientation. Second, there is the tendency to revert to more primitive behavior, even reflex action, under conditions of severe psychologic stress. The highly developed, relatively newly acquired skill of instrument flying can give way to primal protective responses during disorientation stress, making appropriate recovery action unlikely. Third, it is suggested that disoriented pilots may become totally immobilized--frozen to the aircraft controls by fear or panic--as the disintegration process reaches its final state.

Giant Hand

The giant hand phenomenon described by Malcolm and Money[33] undoubtedly explains why many pilots have been rendered hopelessly confused and ineffectual by spatial disorientation, even though they knew they were disoriented and should have been able to avoid losing control of their aircraft. The pilot suffering from this effect of disorientation perceives falsely that the aircraft is not responding properly to control inputs, because every attempt to bring the aircraft to the desired attitude, seemingly is resisted by its tendency to fly back to another, more stable attitude. A pilot experiencing disorientation about the roll axis (e.g., the leans or graveyard spiral) may feel a force--like a giant hand--trying to push one wing down and hold it there (Fig. 36), whereas the pilot with pitch-axis disorientation (e.g., the classic somatogravic illusion) may feel the airplane subjected to a similar force trying to hold the nose down. The phenomenon is not rare: one report states that 15% of pilots responding to a questionnaire on spatial disorientation had experienced the giant hand.[47] Pilots who are unaware of the existence of this phenomenon and experience it for the first time can be very surprised and confused by it, and may not be able to discern the exact nature of their problem. A pilot's radio transmission that the aircraft controls are malfunctioning should not, therefore, be taken as conclusive evidence that a control malfunction caused a mishap: spatial disorientation could have been the real cause.

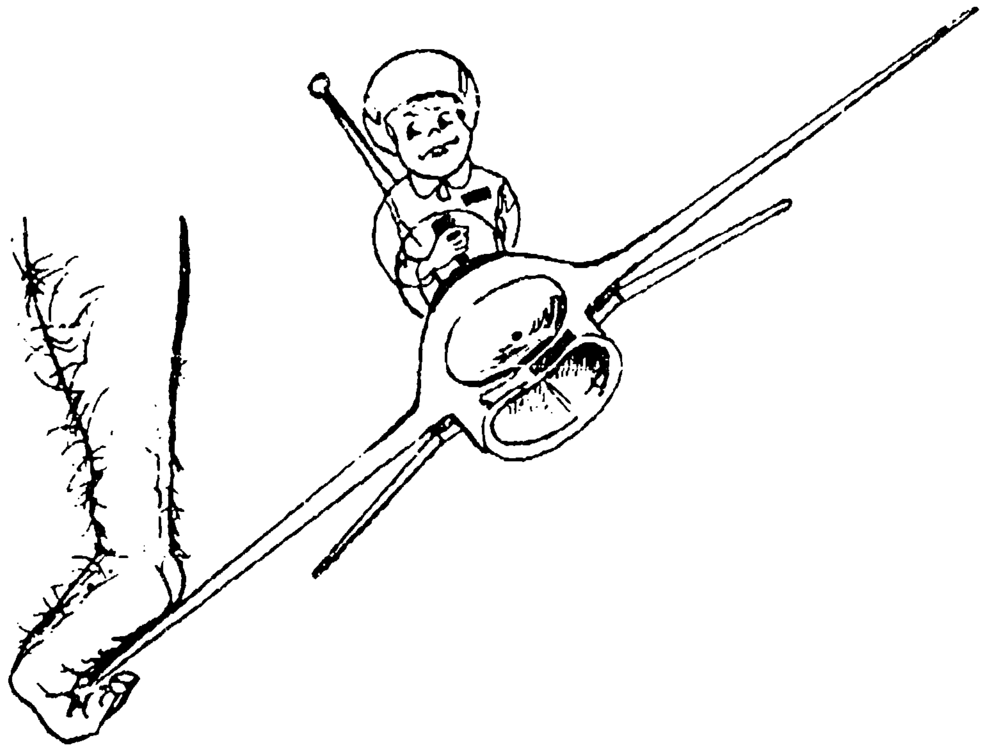


Figure 36. The giant hand phenomenon. This pilot, who is disoriented with respect to roll attitude (bank angle), feels the aircraft is resisting the attempt to bring it to the desired attitude according to the flight instruments, as though a giant hand is holding it in the desired attitude according to the erroneous sense of bank angle.

What mechanism could possibly explain the giant hand? To try to understand this phenomenon, we must first recognize that an individual's perception of orientation results not only in the conscious awareness of position and motion but also in a preconscious percept needed for the proper performance of voluntary motor activity and reflex actions. A conscious orientational percept can be considered rational, in that one can subject it to intellectual scrutiny, weigh the evidence for its veracity, conclude that it is inaccurate, and to some extent modify the percept to fit facts obtained from other than the primary orientation senses. In contrast, a preconscious orientational percept must be considered irrational, in that it consists only of an integration of data relayed to the brain stem and cerebellum by the primary orientation senses and is not amenable to modification by reason. So what happens when pilots know they have become disoriented and try to control their aircraft by reference to a conscious, rational percept of orientation that is at variance with a preconscious, irrational one? Because only the data comprising one's preconscious orientational percept are available for the performance of orientational reflexes (e.g., postural reflexes) and skilled voluntary motor activity (e.g., walking, bicycling, flying), it is to be expected that the actual outcome of these types of actions will deviate from the rationally intended outcome whenever the orientational data on which they depend are different from the rationally perceived orientation. The disoriented pilot who consciously commands a roll to recover aircraft control may experience a great deal of difficulty in executing the command, because the informational substrate in reference to which the body functions indicates that such a move is counterproductive or even dangerous. Or the pilot may discover that the roll, once accomplished, must be reaccomplished repeatedly, because of the automatic tendency to return the aircraft to its original flight attitude in response to the preconsciously perceived orientational threat resulting from his or her conscious efforts and actions to regain control. Thus, the preconscious orientational percept influences Sherrington's "final common pathway" for both reflex and voluntary motor activity, and the manifestation of this influence on the act of flying during an episode of spatial disorientation is the giant hand phenomenon. To prevail in this conflict between will and skill, the pilot must decouple voluntary acts from automatic flying behavior. It has been suggested that using the thumb and forefinger to move the control stick, rather than using the whole hand, can effect the necessary decoupling and thereby facilitate recovery from the giant hand.[47]

The salient features of the dynamics of spatial orientation and disorientation are diagrammed in Figure 37 to ease the student's burden of assimilating the rather abstract concepts discussed above. In particular, the relations between the conscious and preconscious orientational percepts, visual dominance, vestibular suppression, opportunism, giant hand, disintegration of flying skill, and other aspects of orientation information flow are presented.

Conditions Conducive to Disorientation

From knowledge of the physical bases of the various illusions of flight, the reader can readily infer many of the specific environmental factors conducive to spatial disorientation. Certain visual phenomena produce characteristic visual illusions such as false horizons and vection. Prolonged turning at a constant rate, as in a holding pattern or procedure turn, can precipitate somatogyral illusions or the leans. Relatively sustained linear accelerations, such as occur on takeoff, can produce somatogravic illusions, and head movements during G-pulling turns can elicit G-excess illusions.

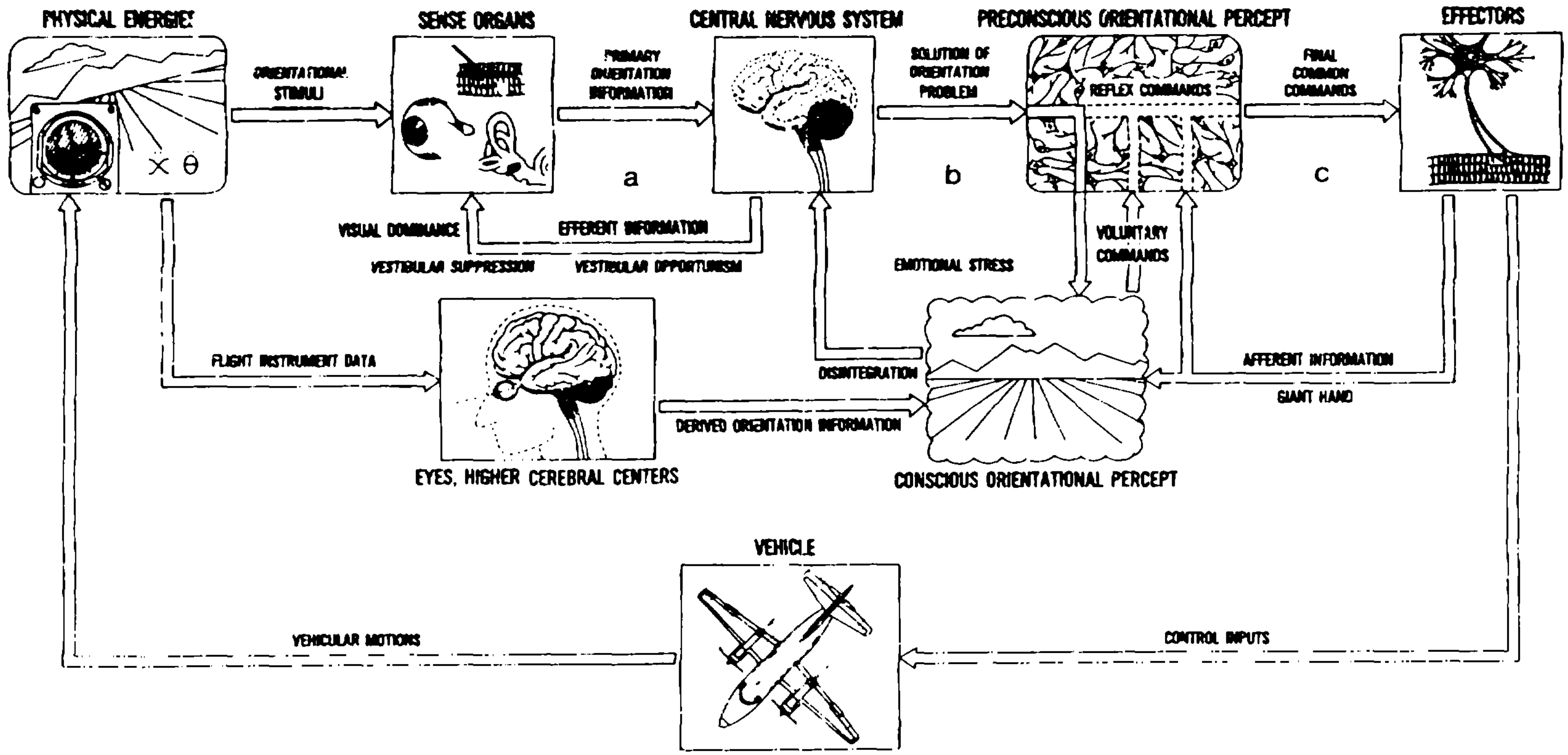


Figure 37. **Flow of orientation information in flight.** The primary information-flow loop involves: stimulation of the visual, vestibular, and other orientation senses by visual scenes and linear and angular accelerations; processing of this primary orientation information by brain stem, cerebellum, and cerebral centers; incorporating the solution into a data base for reflexive and skilled voluntary motor activity (preconscious orientational percept); and effecting control inputs, which produce aircraft motions that result in additional orientational stimuli. A secondary path of information flow involves the processing of symbolic data from flight instruments into derived orientation information by higher cerebral centers. Subloop **a** provides for feedback from various components of the nervous system, and includes efferent system influences on sensory end-organs. The phenomena of visual dominance, vestibular suppression, and vestibular opportunism occur in conjunction within the functioning of this loop. Subloop **b** generates conscious perception of orientation, both from the body's naturally obtained solution of the orientation problem and from orientation information derived from flight instrument data. Voluntary control commands arise in response to conscious orientational percepts; and the psychic stress resulting from conflicting orientation information or from apparently aberrantly responding effectors can influence the manner in which orientation information is processed, leading ultimately to disintegration of flying skill. Subloop **c** incorporates feedback from muscles, tendons, and joints involved in making control inputs, and provides a basis for the giant hand phenomenon.

But what are the regimes of flight and activities of the pilot that seem most likely to allow these potential illusions to manifest themselves? Certainly, instrument weather and night flying are primary factors. Especially likely to produce disorientation, however, is the practice of switching back and forth between the instrument flying mode and the visual, or contact, flying mode; pilots are far less likely to become disoriented if they get on the instruments as soon as out-of-cockpit vision is compromised and stay on the instruments until continuous contact flying is again assured. In fact, any event or practice requiring the pilot to break an instrument cross-check is conducive to disorientation. In this regard, avionics control switches and displays in some aircraft are located where pilots must interrupt their instrument cross-checks for more than just a few seconds to interact with them, and are thus known as "vertigo traps." Some of these vertigo traps require substantial movements of the pilot's head during the time of cross-check interruption, thereby providing both a reason and an opportunity for spatial disorientation to strike.

Formation flying in adverse weather conditions is probably the most likely of all situations to produce disorientation; indeed, some experienced pilots get disoriented every time they fly wing or trail in weather. A pilot who has little if any opportunity to scan the flight instruments while flying formation on the lead aircraft in weather is essentially isolated from any source of accurate orientation information, and misleading vestibular and ambient visual cues arrive unchallenged into the pilot's sensorium.

Of utmost importance to a pilot in preventing spatial disorientation is competency and currency in instrument flying. A noninstrument-rated pilot who penetrates instrument weather is virtually assured of developing spatial disorientation within a matter of seconds, just as the most competent instrument pilot would develop it while flying in weather without functioning flight instruments. Regarding instrument flying skill, one must "use it or lose it," as they say. For that reason, it is inadvisable and usually illegal for one to act as a pilot in command of an aircraft in instrument weather without a certain amount of recent instrument flying experience.

Even the most capable instrument pilot is susceptible to spatial disorientation when attention is diverted away from the flight instruments and the primary task of flying the airplane is neglected. This can happen when other duties, such as navigation, communication, operating weapons, responding to malfunctions, and managing inflight emergencies, place excessive demands on the pilot's attention and lead to "task saturation." In fact, virtually all aircraft mishaps involving Type I spatial disorientation occur as a result of the pilot's failure to prioritize several competing tasks properly. "First, fly the airplane; then do other things as time allows," is always good advice for pilots, especially for those faced with a high mental workload. Not to prioritize in this manner can result in disorientation and disaster.

Finally, conditions affecting the pilot's physical or mental health must be considered capable of rendering the pilot more susceptible to spatial disorientation. The unhealthy effect of alcohol ingestion on neural information processing is one obvious example; however, the less well-known ability of alcohol to produce vestibular nystagmus (positional alcohol nystagmus) for many hours after its more overt effects have disappeared is probably of equal significance. Use of other drugs, such as barbiturates, amphetamines, and especially the illegal "recreational" drugs (marijuana, cocaine, etc.) certainly could contribute to the development of disorientation and precipitate aircraft mishaps. Likewise, physical and mental fatigue, as well as acute or chronic emotional stress, can rob pilots of the ability to concentrate on the instrument cross-check and can, therefore, have deleterious effects on their resistance to spatial disorientation.

Prevention of Disorientation Mishaps

Spatial disorientation can be attacked in several ways. Theoretically, each link in the physiologic chain of events leading to a disorientation mishap can be broken by a specific countermeasure (Fig. 38). Many times, spatial disorientation can be prevented by modifying flying procedures to avoid those visual or vestibular motion and position stimuli that tend to create illusions in flight. Improving the capacity of flight instruments to translate aircraft position and motion information into readily assimilable orientation cues will help the pilot to avoid disorientation. Through repeated exposure to the environment of instrument flight, the pilot becomes proficient in instrument flying; this proficiency involves developing perceptual processes that result in accurate orientational percepts rather than orientational illusions. If a pilot who experiences an illusion has relegated primary control of flight parameters to an autopilot rather than having maintained active control of the aircraft, the existence of an orientational illusion is essentially irrelevant (i.e., the pilot has spatial unorientation rather than disorientation). But use of an autopilot can not only help prevent disorientation, it can also help the pilot recover from it: the disoriented pilot can engage the autopilot and ride as a passenger until able safely to reclaim primary control of the aircraft. (Indeed, some fighter aircraft have a special "panic switch" which the disoriented pilot can activate to bring the aircraft back to a wings-level attitude.) A pilot who has developed spatial disorientation and who can be made to recognize the symptoms, is well along the road to recovery. Recognizing disorientation is not necessarily easy, however. First, the pilot must be aware of a problem holding altitude or heading; this cannot be done if the pilot is concentrating on something other than the flight instruments--the radar scope, for instance. Only through proper flight training can the appreciation of the need for appropriate task prioritization and the discipline of continuously performing the instrument cross-check be instilled. Second, the pilot must recognize that the difficulty in controlling the aircraft is a result of spatial disorientation. This ability is promoted through physiological training. Finally, a pilot's ability to cope with the effects of disorientation on control inputs to the aircraft comes through effective flight instruction, proper physiological training, and experience in controlling an actual or simulated aircraft in an environment of conflicting orientation cues; simply being aware of one's disorientation by no means ensures survival.

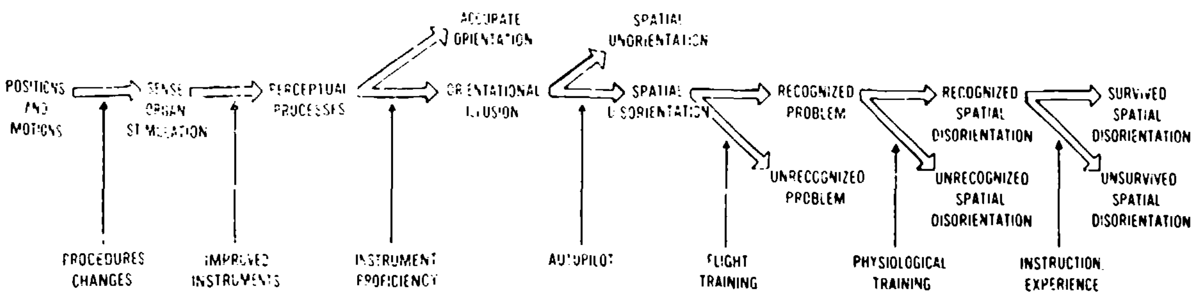


Figure 38. The chain of events leading to a spatial disorientation mishap, and where the chain can be attacked and broken. From the left: Flight procedures can be altered to generate less confusing sensory inputs. Improved instrument presentations can aid in the assimilation of orientation cues. Proficiency in instrument flying helps to assure accurate orientational percepts. In the event the pilot suffers an orientational illusion, putting the aircraft under autopilot control avoids disorientation by substituting unorientation. Flight training helps in prioritizing various tasks properly so the pilot can recognize quickly that the aircraft is not flying the desired flight path. Once a problem surfaces, physiological training helps the pilot realize that this problem is spatial disorientation. With appropriate instruction and/or firsthand experience, the pilot with recognized spatial disorientation can apply the correct control forces to recover the aircraft and survive the disorientation incident.

Education and Training

Physiological training is the main weapon against spatial disorientation at the disposal of the flight surgeon and aerospace physiologist. This training ideally should consist of both didactic material and demonstrations. There is no paucity of didactic material on the subject of disorientation: numerous films, videocassette tapes, slide sets, handbooks, and chapters in books and manuals have been prepared for the purpose of informing the pilot about the mechanisms and hazards of spatial disorientation. Although the efforts to generate information on spatial disorientation are commendable, there has been a tendency for such didactic material to dwell too much on the mechanisms and effects of disorientation without giving much practical advice on how to deal with it.[48]

We now emphasize to pilots a two-stage approach to preventing disorientation mishaps. First, minimize the likelihood of spatial disorientation by monitoring frequently and systematically the critical flight parameters (bank, pitch, vertical velocity, altitude) displayed by the flight instruments or a valid natural reference; conversely, expect to become disoriented if attention to these flight parameters is allowed to lapse as a result of misprioritizing the tasks at hand. Second, when disorientation does occur, recognize it as such and act. In the past, the standard advice was "Believe the instruments." Now we feel this message by itself is inadequate, because pilots in a stressful, time-critical situation need to know what to do to extricate themselves from their predicament, not how to analyze it. If told "make the instruments read right, regardless of your sensation," the pilot has simple, definite instructions on how to bring the aircraft under control when disorientation strikes. We strongly advise that every presentation to pilots on the subject of spatial disorientation emphasize (1) the need to avoid disorientation by making frequent instrument cross-checks, and (2) the need to recover from disorientation by making the instruments read right.

The traditional demonstration accompanying lectures to pilots on spatial disorientation is a ride in a Barany chair or some other smoothly rotating device. The subject, sitting in the device with eyes closed, is accelerated to a constant angular velocity and asked to signal with the thumbs his or her perceived direction of turning. After a number of seconds (usually from 10 to 20) at constant angular velocity, the subject loses the sensation of rotation and signals this fact to the observers. The instructor then suddenly stops the rotation, whereupon the subject immediately reports a sense of turning in the direction opposite to the original direction of rotation. The subject usually is asked to open the eyes during this part of the demonstration and is amazed to see that the chair is actually stationary, despite the strong vestibular sensation of rotation. After the described demonstration of somatogyral illusions, the subject is again rotated at a constant velocity with the eyes closed, this time with the head facing the floor. After indicating when the sensation of turning has ceased, the subject is asked to raise the head abruptly so as to face the wall. The Coriolis illusion resulting from this maneuver is one of a very definite roll to one side; startled subjects may exhibit a protective postural reflex and may open their eyes to help visually orient during this falsely perceived upset. The message delivered with these demonstrations is not that such illusions will be experienced in flight in the same manner, but that the vestibular sense can be fooled, i.e., is unreliable, and that only the flight instruments provide accurate orientation information.

Over the years, at least a dozen different training devices have been developed to augment or supplant the Barany chair for demonstrating various vestibular and visual illusions and the effects of disorientation in flight. These devices fall into two basic categories: orientational illusion demonstrators and spatial disorientation demonstrators. The majority are illusion demonstrators, in which the trainee rides passively and experiences one or more of the following: somatogyral, oculogyral, somatogravic, oculogravic, Coriolis, G-excess, vection, false horizon, and autokinetic illusions. In an illusion demonstrator, trainees typically are asked to record or remember the magnitude and direction of the orientational illusion and then are told or otherwise allowed to experience their true orientation. A few devices actually put trainees in the motion control loop and allow them to experience the difficulty in controlling the attitude and motion of the device while being subjected to various vestibular and visual illusions. Figure 39 shows two such spatial disorientation demonstrators presently in use.

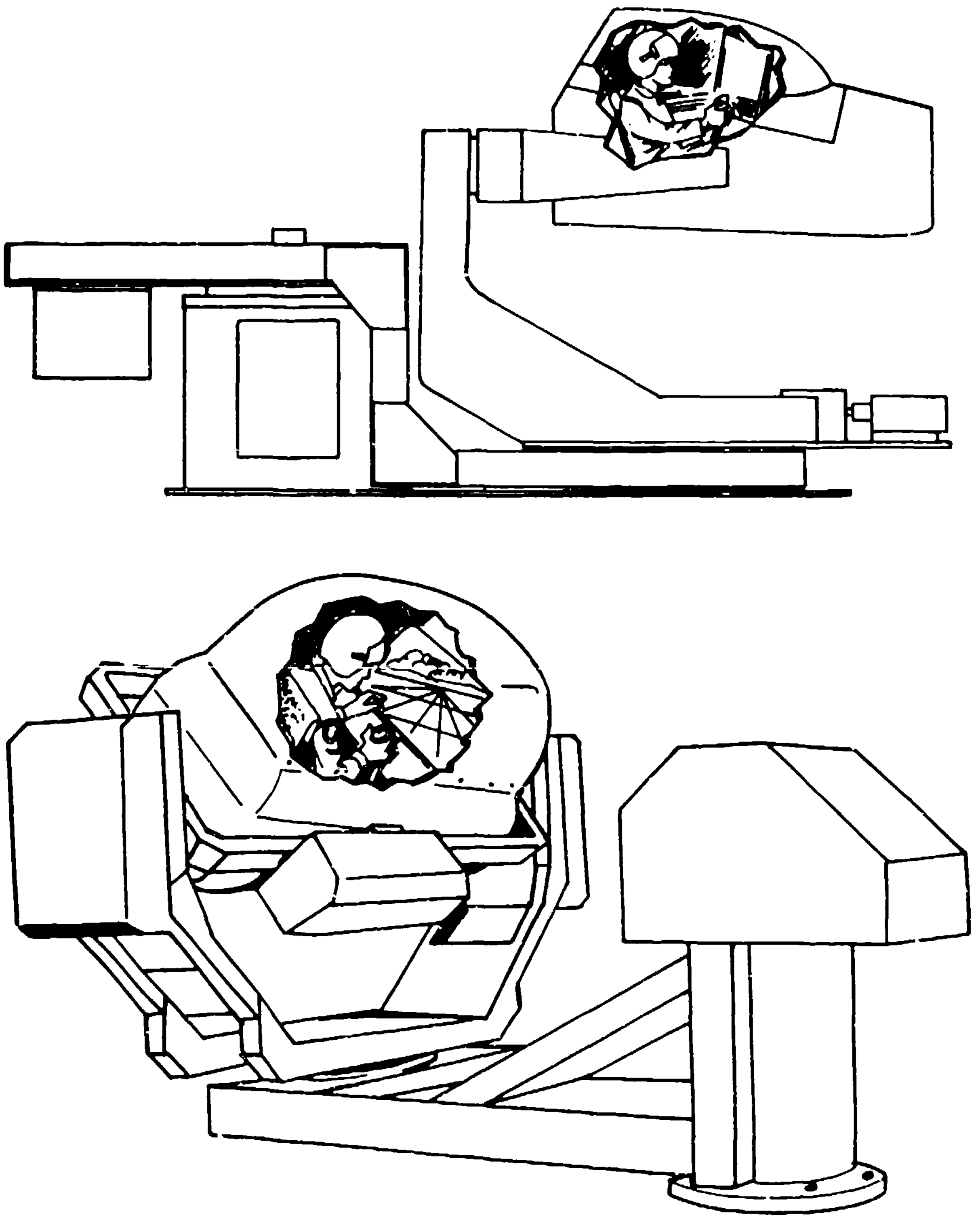


Figure 39. Two spatial disorientation demonstrators marketed for physiological training--the Model 2400 Vertifuge (above) and the Gyrolab GL-1000 (below). Both devices use somatogyral, somatogravic, and other vestibular illusions, as well as focal and ambient visual illusions, to create disorientation in the trainee, who "flies" the cockpit by reference to flight instruments.

Although the maximal use of ground-based spatial disorientation training devices in the physiological training of pilots is to be encouraged, it is important to recognize the great potential for misuse of such devices by personnel not thoroughly trained in their theory and function. Several devices have aircraft-instrument tracking tasks for the trainee to perform while experiencing orientational illusions but not actually controlling the motion of the trainer. The temptation is very strong for unsophisticated operating personnel to tell trainees that they are "fighting disorientation" if they perform well on the tracking task while being subjected to the illusion-generating motions. Because the trainee's real orientation is irrelevant to the tracking task, any orientational illusion is also irrelevant, and the trainee experiences no conflict between visual and vestibular information in acquiring cues used in performing the task. This situation, of course, does not capture the essence of disorientation in flight, and trainees who are led to believe they are fighting disorientation in such a ground-based demonstration may develop a false sense of security about their ability to combat disorientation in flight. The increasing use of spatial disorientation demonstrators, in which the subject must control the actual motion of the trainer by referring to true-reading instruments while under the influence of orientational illusions, will reduce the potential for misuse and improve the effectiveness of presentations to pilots on the subject of spatial disorientation.

Flight training provides a good opportunity to instruct pilots about the hazards of spatial disorientation. Inflight demonstrations of vestibular illusions are included in most formalized pilot training curricula, although the efficacy of such demonstrations is highly dependent on the motivation and skill of the individual flight instructor. Somatogyral and somatogravic illusions and illusions of bank attitude usually can be induced in a student pilot by a flight instructor who either understands how the vestibular system works or knows from experience which maneuvers consistently produce illusions. The vestibular-illusion demonstrations should not be confused with the unusual-attitude-recovery demonstrations in the typical pilot training syllabus: the objective of the former is for the student to experience orientational illusions and recognize them as such, whereas the objective of the latter is for the student to learn to regain control of an aircraft in a safe and expeditious manner. In both types of demonstration, however, control of the aircraft should be handed over to the student pilot with the instruction, "Make the instruments read right."

Part of flight training is continuing practice to maintain flying proficiency, and the importance of such practice in reducing the likelihood of having a disorientation mishap cannot be overemphasized. Whether flying on instruments, flying in formation, or engaged in aerobatic maneuvering, familiarity with the environment--based on recent exposure to it--and proficiency at the flying task--based on recent practice at it--result not only in a greater ability to avoid or dispel orientational illusions but also in a greater ability to cope with disorientation when it does occur.

Inflight Procedures

If a particular inflight procedure frequently results in spatial disorientation, it stands to reason that modifying or eliminating that procedure should help to reduce aircraft mishaps due to disorientation. Night formation takeoffs and rejoins are examples of inflight procedures that are very frequently associated with spatial disorientation, and the United States Air Force wisely has officially discouraged these practices in most of its major commands.

Another area of concern is the "lost wingman" procedure, which is used when a pilot has lost sight of the lead aircraft. Usually the loss of visual contact is due to poor visibility and occurs after a period of vacillation between formation flying and instrument flying; this, of course, invites disorientation. The lost wingman procedure must, therefore, be made as uncomplicated as possible while still allowing safe separation from the other elements of the flight. Maintaining a specified altitude and heading away from the flight until further notice is an ideal lost wingman procedure in that it avoids frequent or prolonged disorientation-inducing turns and minimizes cognitive workload. Often, a pilot flying wing in bad weather does not lose sight of the lead aircraft but suffers so much disorientation stress as to make the option of going lost wingman seem safer than that of continuing in the formation. A common practice in this situation is for the wingman to take the lead position in the formation, at least until the disorientation disappears. This procedure avoids the necessity of having the disoriented pilot make a turn away from the flight to go lost wingman, a turn that could be especially difficult and dangerous because of the disorientation. One should question the wisdom of having a disoriented pilot leading a flight, however, and some experts in the field of spatial disorientation are adamantly opposed to this practice, with good reason.

Verbal communications can help keep a pilot from becoming disoriented during formation flying in weather, when workload is high and the pilot's visual access to the flight instruments is by necessity infrequent. The leader of the flight should report periodically to the wingman what the flight is doing; i.e., announce the lead aircraft's pitch and bank attitude, altitude, vertical velocity, heading, and airspeed as necessary to allow a mental image of the wingman's own spatial orientation to be constructed. If the wingman has already become disoriented, the lead pilot still needs to tell the wingman the correct orientation information, but also needs to provide some potentially life-saving advice about what to do. Unfortunately, no clear-cut procedure exists for ensuring appropriate communications. Should the pilot be hounded mercilessly with verbal orders to get on the instruments or should the pilot be left relatively undistracted to solve the orientation problem? The extremes of harassment and neglect are definitely not appropriate; a few forceful, specific, action-oriented commands probably represent the best approach. "Make the attitude indicator read wings level!" is an example of such a command. One must remember that the pilot suffering from spatial disorientation may be either so busy or so functionally compromised that complex instructions may fall on deaf ears. Simple, emphatic directions may be the only means of penetrating the disoriented pilot's consciousness.

To illustrate how official recommendations regarding inflight procedures are disseminated to pilots in an effort to prevent spatial disorientation mishaps, a message from a major United States Air Force command headquarters to field units is excerpted here:

> . . . Review SD procedures in [various Air Force manuals] . . . Discuss the potential for SD during flight briefings prior to flight involving night, weather, or conditions where visibility is significantly reduced . . . Recognize the [SD] problem early and initiate corrective actions before aircraft control is compromised.
>
> A. Single ship:
>
> (1) Keep the head in the cockpit. Concentrate on flying basic instruments with frequent reference to the attitude indicator. Defer nonessential cockpit chores.
>
> (2) If symptoms persist, bring aircraft to straight and level flight using the attitude indicator. Maintain straight and level flight until symptoms abate--usually 30 to 60 seconds. Use autopilot if necessary.
>
> (3) If necessary, declare an emergency and advise air traffic control. Note: It is possible for SD to proceed to the point where the pilot is unable to see, interpret, or process information from the flight instruments. Aircraft control in such a situation is impossible. A pilot must recognize when physiological/psychological limits have been exceeded and be prepared to abandon the aircraft.
>
> B. Formation flights:
>
> (1) Separate aircraft from the formation under controlled conditions if the weather encountered is either too dense or turbulent to insure safe flight.
>
> (2) A flight lead with SD will advise his wingmen that he has SD and he will comply with procedures in Paragraph A. If possible, wingmen should confirm straight and level attitude and provide verbal feedback to lead. If symptoms do not abate in a reasonable time, terminate the mission and recover the flight by the simplest and safest means possible.
>
> (3) Two-ship formation. Wingman will advise lead when he experiences significant SD symptoms.
>
> (a) Lead will advise wingman of aircraft attitude, altitude, heading, and airspeed.

(b) The wingman will advise lead if problems persist. If so, lead will establish straight and level flight for at least 30 to 60 seconds.

(c) If the above procedures are not effective, lead should transfer the flight lead position to the wingman while in straight and level flight. Once assuming lead, maintain straight and level flight for 60 seconds. If necessary, terminate the mission and recover by the simplest and safest means possible.

(4) More than two-ship formation. Lead should separate the flight into elements to more effectively handle a wingman with persistent SD symptoms. Establish straight and level flight. The element with the SD pilot will remain straight and level while other element separates from the flight.

Cockpit Layout and Flight Instruments

One of the most notorious vertigo traps is the communications-transceiver frequency selector or transponder code selector located in an obscure part of the cockpit. To manipulate this selector requires the pilot not only to look away from the flight instruments, which interrupts an instrument scan, but also to tilt the head to view the readout, which potentially leads to G-excess and possibly Coriolis illusions. Aircraft designers are now aware that easy accessibility and viewing of such frequently used devices minimize the potential for spatial disorientation; accordingly, most modern aircraft have communications frequency and transponder code selectors and readouts located in front of the pilot near the flight instruments.

The location of the flight instruments themselves is also very important. They should be clustered directly in front of the pilot, and the attitude indicator--the primary provider of orientation cuing and the primary instrument by which the aircraft is controlled--should be in the center of the cluster (Fig. 40). When this principle is not respected, the potential for spatial disorientation is increased. One modern fighter aircraft, for example, was designed to have pilots sitting high in the cockpit to enhance their field-of-view during air-to-air combat in conditions of good visibility. This design relegates the attitude indicator to a position more or less between the pilot's knees. As a result, at night and during instrument weather, the pilot is subjected to potentially disorienting peripheral visual motion and position cuing by virtue of being surrounded by a vast expanse of canopy, while trying to glean with central vision the correct orientation information from a relatively small, distant attitude indicator. The net effect is an unusually difficult orientation problem for the pilot, and a greater risk of developing spatial disorientation in this aircraft than in others with a more advantageously located attitude indicator.

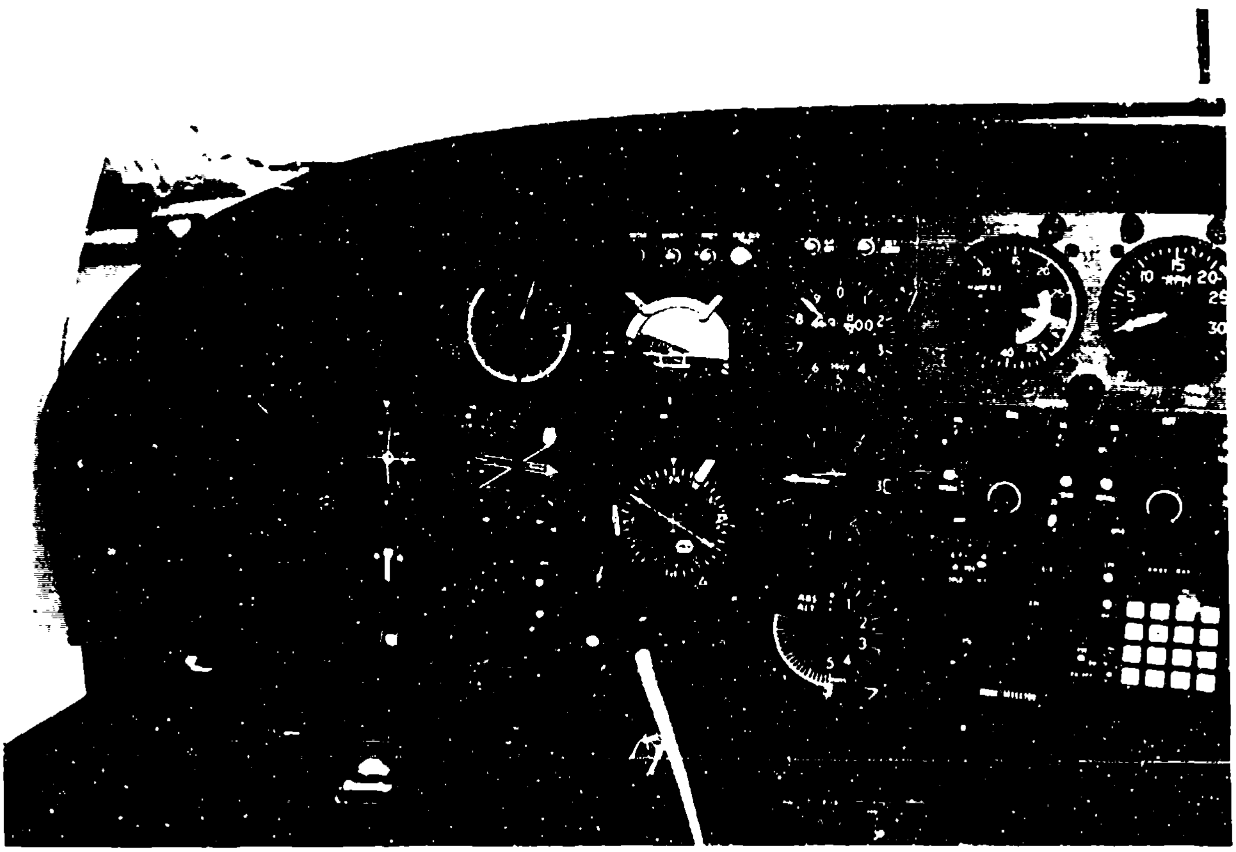


Figure 40. A well-designed instrument panel, with the attitude indicator located directly in front of the pilot and the other flight instruments clustered around it. Radios and other equipment requiring frequent manipulation and viewing are placed close to the flight instruments to minimize interruption of the pilot's instrument scan and to obviate the need to make head movements that could precipitate spatial disorientation

The verisimilitude of the flight instruments is a major factor in their ability to convey readily assimilable orientation information. The old "needle, ball, and airspeed" indicators (a needle pointer showing the direction and rate of turn, a ball showing whether the turn is being properly coordinated with the rudders, and an airspeed indicator showing whether the airplane is climbing or diving) required a lot of interpretation for the pilot to perceive the aircraft's orientation through them; nevertheless, this combination sufficed for nearly a generation of pilots. When the attitude indicator (also known as the gyro horizon, artificial horizon, or attitude gyro) was introduced, it greatly reduced the amount of work required to spatially orient during instrument flying because the pilot could readily imagine the artificial horizon line to be the real horizon. In addition to becoming more reliable and more versatile over the years, it became even easier to interpret: the face was divided into a gray or blue "sky" half and a black or brown "ground" half, with some models even having lines of perspective converging to a vanishing point in the lower half. Such a high degree of similarity to the real world has made the attitude indicator (which includes an added flight director function and the attitude director indicator, or ADI) the mainstay of instrument flying today.

A relatively new concept in flight instrumentation, the head-up display (HUD), projects numeric and other symbolic information to the pilot from a combining glass near the windscreen, so that the pilot can be looking forward out of the cockpit and simultaneously monitoring flight and weapons data. When the pilot selects the appropriate display mode, the pitch and roll of the aircraft are observed on the "pitch ladder" or "climb-dive ladder" (Fig. 41), with heading, altitude, airspeed, and other parameters being numerically displayed elsewhere on the HUD. Its up-front location and its close-together arrangement of most of the required aircraft control and performance data make the HUD a possible improvement over the conventional cluster of instruments with regard to minimizing the likelihood of spatial disorientation.

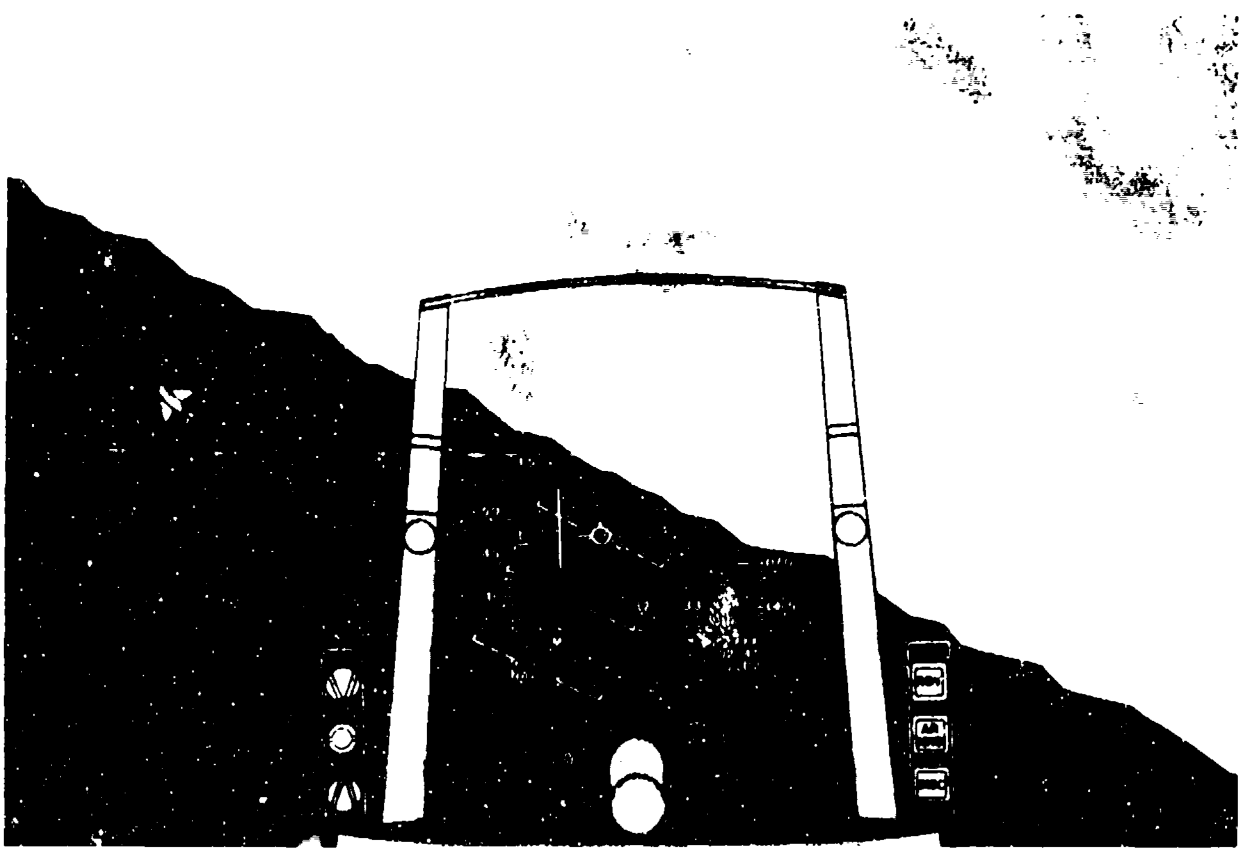


Figure 41. A typical head-up display (HUD). The pitch ladder in the center of the display provides pitch and roll attitude information.

Pilot acceptance and use of the HUD for flying in instrument weather has not been universal, however. Many pilots prefer to use the HUD under conditions of good outside visibility and use the conventional instruments for flying at night and in weather. This approach is understandable, because in some ways the HUD is inferior to the conventional flight instruments in being able to provide spatial orientation information that can readily be assimilated. One reason is that the HUD presents such a narrow view of the outside world--a "vernier" view with high resolution--while the conventional attitude indicator gives an expansive, "global" view of the spatial environment. Another reason is that the relative instability of the HUD pitch ladder and the frequency with which the zero-pitch line (horizon) disappears from view make the HUD difficult to use during moderately active maneuvering, as would be necessary during an unusual-attitude recovery attempt. A third reason may be that the horizon on the conventional attitude instrument looks more like the natural horizon than does the zero-pitch line on the HUD pitch ladder. Nevertheless, at the time of this writing, the HUD is the sole source of primary (aircraft control and performance) flight information in at least one aircraft (the US Navy F/A-18 Hornet), and the United States Air Force is planning to approve the use of the HUD as the primary flight reference in its HUD-equipped aircraft. Attempts to eliminate the potpourri of HUD symbologies and arrive at a maximally efficient, standardized display are also being made.

As good as they are, both the attitude indicator and the HUD leave much to be desired as flight instruments for assuring spatial orientation. Both suffer from the basic design deficiency of presenting visual spatial orientation information to the wrong sensory system--the focal visual system. Two untoward effects result. First, the pilot's focal vision not only must serve to process numeric data from a number of instruments but also must take on the task of spatially orienting the pilot. Thus, the pilot has to employ focal vision in a somewhat inefficient manner during instrument flight, with most of the time spent viewing the attitude indicator or pitch ladder, while ambient vision remains unutilized (or worse, is being bombarded with misleading orientational stimuli). Second, the fact that focal vision is not naturally equipped to provide primary spatial orientation cues causes difficulty for pilots in interpreting the artificial horizon directly: there is a tendency, especially among novice pilots, to sense the displayed deviations in bank and pitch backward and to make initial bank and pitch corrections in the wrong direction.

Several approaches have been taken to try to improve the efficiency of the pilot's acquisition of orientation information from the attitude indicator and associated flight instruments. One has been to make the artificial horizon stationary but to roll and pitch the small aircraft on the instrument display to indicate the motion of the real aircraft (the so-called "outside-in" presentation, as opposed to the "inside-out" presentation of conventional attitude displays). Theoretically, this configuration relieves pilots of having to orient themselves before trying to fly the aircraft: they merely fly the small aircraft on the attitude instrument and the real aircraft follows. Another approach involves letting the artificial horizon provide pitch information but having the small aircraft on the attitude instrument provide bank information (e.g., the Crane Flitegage). Neither of these approaches, however, frees foveal vision from the unnatural task of processing spatial orientation information. Another concept, the peripheral vision display (PVD, also known as the Malcolm horizon), attempts to give pitch and bank cues to the pilot through peripheral vision, thus sparing foveal vision for tasks requiring a high degree of visual discrimination.[49,50] The PVD projects across the instrument panel a long, thin line of light representing the true horizon; this line of light moves directly in accordance with the relative movement of the true horizon. The PVD has been incorporated into at least one military aircraft, but its limited pitch display range and certain other characteristics have prevented an enthusiastic acceptance of this display concept.

A potentially better approach to solving the spatial disorientation problem lies in head-mounted or helmet-mounted display (HMD) technology. The revolution in computer image-generation capability and advances in optical and acoustic techniques will ultimately allow the display of a synthesized representation of the natural spatial environment over the full visual field at optical infinity and in three dimensions of auditory space (Fig. 42). HMDs are already being used in military aircraft to provide targeting and basic flight control and performance information. Further development is needed, however, to reach the point where an electronically enhanced visual and auditory spatial environment is displayed superimposed on the real world, so that the pilot can spatially orient using synthetically created cues in a perceptually natural fashion.

Other Sensory Phenomena

Flicker vertigo, fascination, and target hypnosis are traditionally described in conjunction with spatial disorientation, although, strictly speaking, these entities involve alterations of attention rather than aberrations of perception. Nor is the break-off phenomenon related directly to spatial disorientation, although the unusual sensory manifestations of this condition make a discussion of it appropriate here.

Flicker Vertigo

As most people are aware from personal experience, viewing a flickering light or scene can be distracting, annoying, or both. In aviation, flicker is sometimes created by helicopter rotors or idling airplane propellers interrupting direct sunlight or, less frequently, by such things as several anticollision lights flashing in nonunison. Pilots report that such conditions are indeed a source of irritation and distraction, but there is little evidence that flicker induces either spatial disorientation or clinical vertigo in normal aircrew. In fact, one authority insists there is no such thing as flicker vertigo and that the original reference to it was merely speculation.[51] Certainly, helicopter rotors or rotating beacons on aircraft can produce angular vection illusions because they create revolving shadows or revolving areas of illumination; however, vection does not result from flicker, per se. Symptoms of motion sickness also can conceivably result from the sensory conflict associated with angular vection; but again, these symptoms would be produced by revolving lights and shadows and not by flicker.

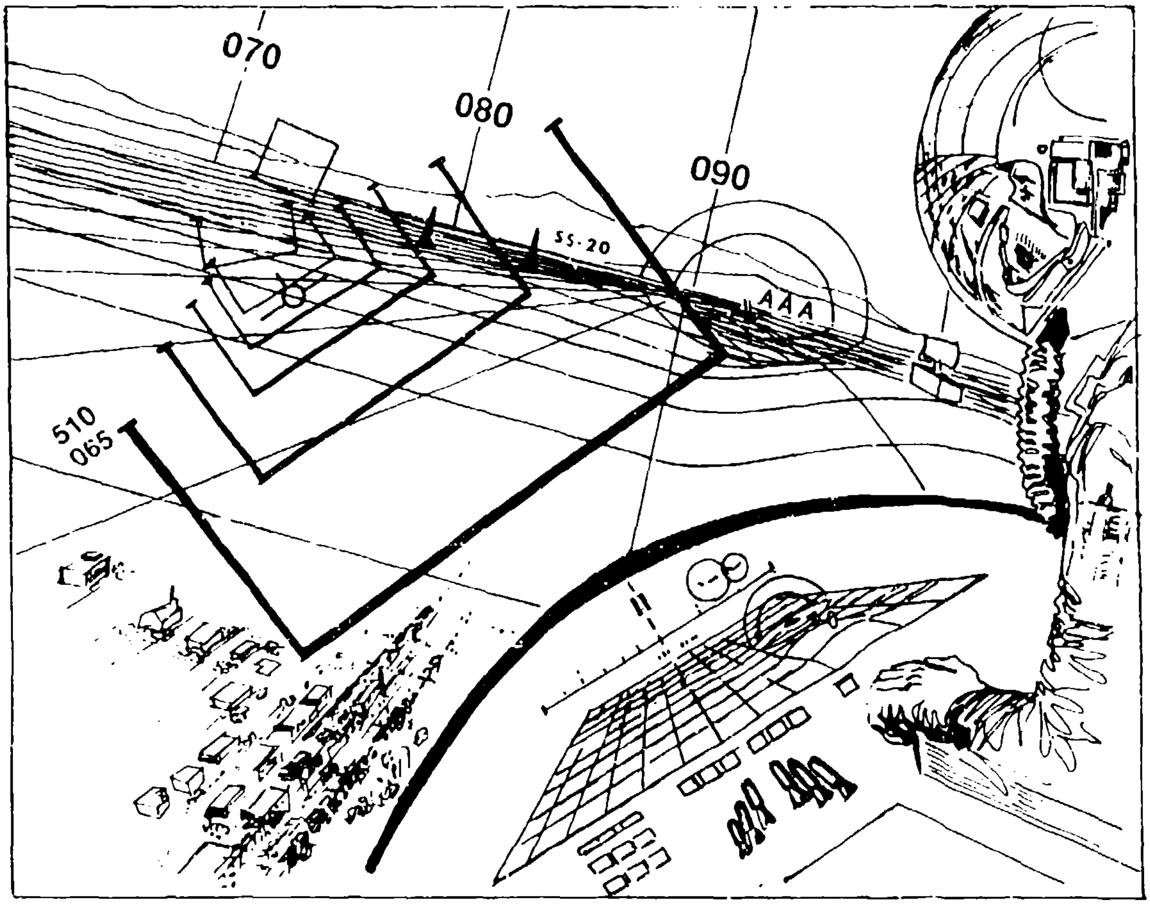


Figure 42. Artist's concept of an advanced helmet-mounted display. A computer-generated image of the plane of the earth's surface and other critical flight information are displayed on the helmet visor at optical infinity, superimposed on the real world.

Nevertheless, one should be aware that photic stimuli at frequencies in the 8- to 14-Hz range--i.e., the range of the electroencephalographic alpha rhythm--can produce seizures in those rare individuals who are susceptible to flicker-induced epilepsy. Although the prevalence of this condition is very low (less than 1 in 20,000), and the number of pilots affected are very few, some helicopter crashes are thought to have been caused by pilots suffering from flicker-induced epilepsy.

Fascination

Coning of attention is something everyone experiences every day, but it is especially likely to occur when one is stressed by the learning of new skills or by the relearning of old ones. Pilots are apt to concentrate on one particular aspect of the flying task to the relative exclusion of others when that aspect is novel or unusually demanding. If this concentration is of sufficient degree to cause the pilot to disregard important information that should be responded to, it is termed fascination. An extreme example of fascination is when a pilot overly intent on delivering weapons to the target ignores the obvious cues of ground proximity and flies into the ground. Mishaps of this sort are said to result from target hypnosis; no actual hypnotic process is suspected or should be inferred, however. Other examples of fascination in aviation are: (1) the monitoring of one flight instrument rather than cross-checking during particularly stressful instrument flight; (2) paying so much attention to flying precise formation that other duties are neglected; and (3) the aviator's most ignominious act of negligence, landing an airplane with the landing gear up despite the clearly perceived warning from the gear-up warning horn. These examples help us to appreciate the meaning of the original definition of fascination by Clark and colleagues: "a condition in which the pilot fails to respond adequately to a clearly defined stimulus situation in spite of the fact that all the necessary cues are present for a proper response and the correct procedure is well known to him."[52] From the definition and the examples given, it is clear that fascination can involve either a sensory deficiency or an inability to act, or perhaps both. It also is known that fascination, at least the type involving sensory deficiency, occurs not only under conditions of relatively high work load but also can occur when work load is greatly reduced and tedium prevails. Finally, the reader should understand that coning of attention, such as occurs with fascination, is not the same thing as tunneling of vision, which occurs with G stress: even if all pertinent sensory cues could be made accessible to foveal vision, the attentional lapses associated with fascination still could prevent those cues from being perceived or eliciting a response.

Break-off

In 1957, Clark and Graybiel[53] reported a condition that is perhaps best described by the title of their paper: "The break-off phenomenon--a feeling of separation from the earth experienced by pilots at high altitude." They found that 35% of 137 United States Navy and Marine Corps jet pilots interviewed by them had had feelings of being detached, isolated, or physically separated from the earth when flying at high altitudes. The three conditions most frequently associated with the experience were high altitude (15,000 to 45,000 ft, with a median of 33,250 ft; or approximately 5,000, 15,000, and 11,000 m, respectively), being alone in the aircraft, and not being particularly busy with operating the aircraft. The majority of the pilots interviewed found the break-off experience exhilarating, peaceful, or otherwise pleasant; over a third, however, felt anxious, lonely, or insecure. No operational importance could be ascribed to the break-off phenomenon; specifically, it was not considered to have a significant effect on a pilot's ability to operate the aircraft. The authors nevertheless suggested that the break-off experience might have significant effects on a pilot's performance when coupled with preexisting anxiety or fear, and, for that reason, the phenomenon should be described to pilots before they go alone to high altitudes for the first time. Break-off may, on the other hand, have a profound, positive effect on the motivation to fly. Who could deny the importance of this experience to John Gillespie Magee, Jr., who gave us "High Flight," the most memorable poem in aviation?

> "Oh, I have slipped the surly bonds of earth . . .
> Put out my hand, and touched the face of God."

MOTION SICKNESS

Motion sickness is a perennial aeromedical problem, with pathogenetic origins in the spatial orientation senses. So closely entwined are the mechanisms of spatial orientation and those of motion sickness that "orientation sickness" is sometimes (and legitimately) used as the general term for the category of related conditions that are commonly referred to as motion sickness.

Definition, Description, and Significance of Motion Sickness

Motion sickness is a state of diminished health characterized by specific symptoms that occur in conjunction with and in response to unaccustomed conditions existing in one's motional environment. These symptoms usually progress from lethargy, apathy, and stomach awareness to nausea, pallor, and cold eccrine perspiration, then to retching and vomiting, and finally to total prostration if measures are not taken to arrest the progression. The sequence of these major symptoms is generally predictable; and vestibular scientists have devised a commonly used scale, consisting of five steps from malaise I through frank sickness, to quantify the severity of motion sickness according to the level of symptoms manifested.[54] Under some conditions, however, emesis can occur precipitously, i.e., without premonitory symptoms. Other symptoms sometimes seen with motion sickness are headache, increased salivation and swallowing, decreased appetite, eructation, flatulence, and feeling warm. Although vomiting provides temporary relief from the symptoms of motion sickness, the symptoms usually will return if the offending motion or other condition continues, and the vomiting will be replaced by nonproductive retching, or "dry heaves." A wide variety of motions and orientational conditions qualify as offensive, so there are many species of the generic term motion sickness. Among them are seasickness, airsickness, car sickness, train sickness, amusement-park-ride sickness, camel sickness, motion-picture sickness, flight-simulator sickness, and the most recent addition to the list, space motion sickness.

Military Experience

Armstrong[55] has provided us with some interesting statistics on airsickness associated with the World War II military effort:

> . . . it was learned that 10 to 11 percent of all flying students became air sick during their first 10 flights, and that 1 to 2 percent of them were eliminated from flying training for that reason. Other aircrew members in training had even greater difficulty and the air sickness rate among them ran as high as 50 percent in some cases. It was also found that fully trained combat crews, other than pilots, sometimes became air sick which affected their combat efficiency. An even more serious situation was found to exist among air-borne troops. Under very unfavorable conditions as high as 70 percent of these individuals became air sick and upon landing were more or less temporarily disabled at a time when their services were most urgently needed.

More recent studies of the incidence of airsickness in United States and British military flight training reveal that approximately 40% of aircrew trainees become airsick at some time during their training. In student pilots, there is a 15 to 18% incidence of motion sickness that is severe enough to interfere with control of the aircraft. Airsickness in student aviators occurs almost exclusively during the first several training flights, during spin training, and during the first dual aerobatic flights. The adaptation of which most people are capable is evidenced by the fact that only about 1% of military pilot trainees are eliminated from flight training because of intractable airsickness. The percentage of other aircrew trainees eliminated because of airsickness is considerably higher, however.

Although trained pilots almost never become airsick while flying the aircraft themselves, they surely can become sick while riding as a copilot or as a passenger. Other trained aircrew, such as navigators and weapon systems operators, are likewise susceptible to airsickness. Particularly provocative for these aircrew are flights in turbulent weather, low-level "terrain-following" flights, and flights in which high G forces are repeatedly experienced, as in air combat training and bombing practice. Both the lack of foreknowledge of aircraft motion, which results from not having primary control of the aircraft, and the lack of a constant view of the external world, which results from having duties involving the monitoring of in-cockpit displays, are significant factors in the development of airsickness in these aircrew.

Simulator Sickness

Flight-simulator sickness is getting increased attention now as aircrew spend more and more time in flight simulators capable of ever greater realism. Currently used high-quality military flight simulators are reported to elicit symptoms in 40 to 70% of trainees.[56,57,58] Generally, these symptoms are the usual drowsiness, perspiration, and nausea that occur in other forms of motion sickness; vomiting rarely occurs because simulated flights can readily be terminated prior to reaching the point of emesis. Symptoms associated with eyestrain (headache, blurring of vision) are also quite common. But of particular aeromedical interest is the fact that simulator exposure also frequently results in postflight disturbances of posture and locomotion, transient disorientation, involuntary visual flashbacks, and other manifestations of acute sensory rearrangement. Simulator sickness is more likely to occur in simulators that employ wide-field-of-view, optical-infinity, computer-generated, ambient visual displays--both with and without motion bases--than in those providing less realistic visual stimulation. Helicopter simulators are especially likely to generate symptoms, probably because of the greater freedom of movement available to these aircraft at low altitudes. Interestingly, simulator sickness is more likely to occur in pilots having considerable experience in the aircraft that the simulator is simulating than in pilots without such experience. Symptoms usually disappear within several hours after termination of the simulated flight, but a small percentage of subjects have symptoms of disequilibrium persisting as long as one day after exposure. Because of the possibility of transient sensory and motor disturbances following intensive training in a flight simulator, it is recommended that aircrew not resume normal flying duties in real aircraft until the day after training in simulators known to be capable of inducing simulator sickness. As is the case with other motion environments, repeated exposure to the simulated motion environment usually renders aircrew less susceptible to its effects.

Civil Experience

The incidence of airsickness in the flight training of civilians can only be estimated, but is probably somewhat less than that for their military counterparts because the training of civil pilots usually does not include spins or other aerobatics. Very few passengers in today's commercial air-transport aircraft become airsick, largely because the altitudes at which these aircraft generally fly are usually free of turbulence. This cannot be said, however, for passengers of most of the lighter, less capable, general aviation aircraft, who often must spend considerable portions of their flights at the lower, "bumpier" altitudes.

Space Motion Sickness

The challenge of space flight includes coping with space motion sickness, a form of motion sickness experienced first by cosmonaut Titov and subsequently by approximately 50% of spacecrew. The incidence of space motion sickness has been significantly greater in the larger space vehicles (e.g., Skylab, Shuttle), in which crewmembers make frequent head and body movements, than in the smaller vehicles (e.g., Apollo), in which such movements were more difficult. Although space motion sickness resembles other forms of motion sickness, the emesis occurring in space vehicles often is not associated with the customary prodromal nausea and cold sweat, but occurs precipitously. This same phenomenon can occur, however, in other novel orientational environments when the level of stimulation is very low but prolonged or very intense but sudden. Because of the similarity between the sudden vomiting associated with space flight and the "projectile" vomiting frequently seen in patients with increased intracranial pressure, a theory was proposed that the sickness precipitated by space flight was due to a cephalad fluid shift resulting from the zero-G environment. This fluid shift theory is no longer popular, having been replaced by the more conservative consensus that the symptoms generated by space flight have the same origin as those of ordinary motion sickness--hence the commonly accepted terminology, "space motion sickness."

The time course of space motion sickness symptom development and resolution is presented graphically in Figure 43.[59] Symptoms usually appear within minutes to several hours after exposure, plateau for hours to several days, and rapidly resolve by 36 hours on average. One feature of space motion sickness that bears special mention is a characteristic adynamic ileus, evidenced by a profound lack of bowel sounds. Because of this absence of normal gastrointestinal activity, nutrition is compromised until adaptation occurs. As a consequence of their adaptation to the zero-G environment, some spacecrew again experience motion sickness upon their return to Earth, although the severity and duration of symptoms tend to be less than they were during the initial exposure to space. Spacecrew are also reported to be especially resistant to other forms of motion sickness (airsickness, seasickness) for up to several weeks after returning from space.

Space motion sickness has a definite negative effect on the efficiency of manned space operations, with on the order of 10% of crewmembers being affected to the point that their performance is significantly impaired. Thus, the potential impact of space motion sickness on manned space operations must be minimized by appropriate mission planning. If possible, duties involving less locomotion should be scheduled early in the flight. Because of the possibility of space motion sickness-induced emesis into a space suit and the consequent risk to life and mission success, extravehicular activity (EVA) should not be undertaken before the third day of a space mission. By that time, adaptation to the novel environment is largely complete and the head and body movements concomitant with EVA are much less likely to provoke symptoms than they would have been prior to adaptation. (Of interest is the fact that pitching motions of the head are the most provocative, followed by rolling and yawing motions, and that such motions are more provocative with eyes open than with eyes closed. These observations suggest that otolith-organ-mediated changes in vestibulo-ocular reflex gain during altered gravitational states constitute at least part of the underlying mechanism of space motion sickness.[60])

Another type of space motion sickness will be encountered in the event that large space stations are rotated to generate G loading for the purpose of alleviating the fluid shift, cardiovascular deconditioning, and skeletal demineralization that occur in the zero-G environment. Vestibular Coriolis effects created in occupants of such rotating systems are very potent producers of motion sickness and would be expected to plague the occupants for several days after arrival. Of course, after the space station personnel have become adapted to the rotating environment, they would be disadapted to the nonrotating one and would suffer from motion sickness upon returning to Earth.

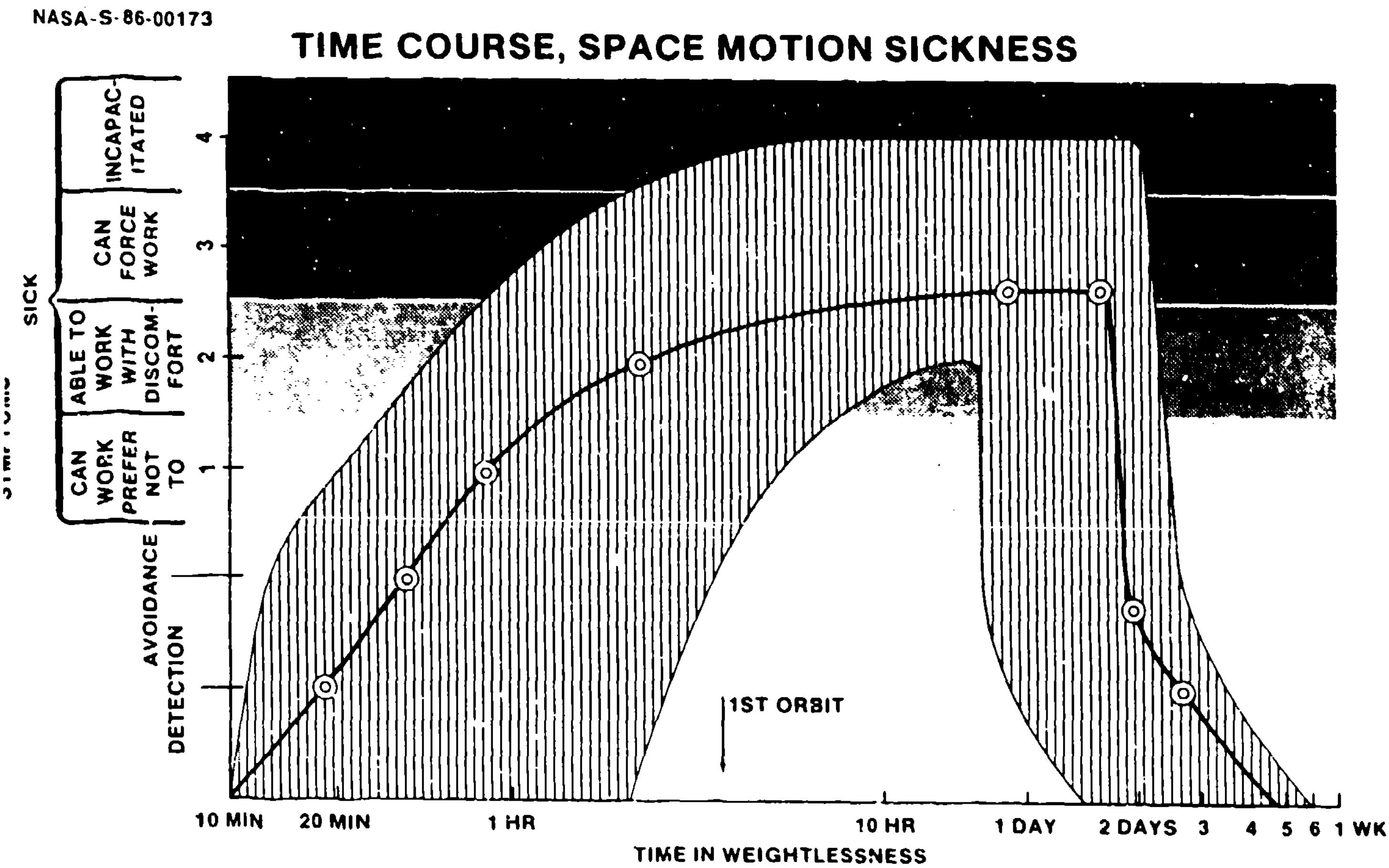


Figure 43. **Time course of space motion sickness symptoms.** The shaded area represents the range of symptoms experienced by Space Shuttle crewmembers. (From Thornton et al.[59])

Etiology of Motion Sickness

Humans have speculated about the causes of and reasons for motion sickness for thousands of years. Largely because of the scientific interest in motion sickness that has been generated by naval and aerospace activities of the present century, we may now have a satisfactory explanation for this puzzling malady.

Correlating Factors

As already mentioned, motion sickness occurs in response to conditions in one's motional environment to which one is not accustomed. Motional environment means all of the linear and angular positions, velocities, and accelerations that are directly sensed or secondarily perceived as determining one's spatial orientation. The primary quantities of relevance here are mechanically (as opposed to visually) sensed linear and angular acceleration--those stimuli that act on the vestibular end-organs. Certainly, the pitching, rolling, heaving, and surging motions of ships in bad weather are clearly correlated with motion sickness, as are the pitching, rolling, yawing, and positive and negative G-pulling of aircraft during maneuvering. Abnormal stimulation of the semicircular ducts alone, as with a rotating chair, can result in motion sickness. So, too, can abnormal stimulation of the otolith organs alone--as occurs in an elevator or a four-pole swing--lead to motion sickness. Whether the stimulation provided is complex, as is usually the case on ships and in aircraft, or simple, such as that generated in the laboratory, the important point is that abnormal labyrinthine stimulation is associated with the production of motion sickness. Not only is a modicum of abnormal vestibular stimulation sufficient to cause motion sickness, but some amount of vestibular stimulation is also necessary for motion sickness to occur. Labyrinthectomized experimental animals and humans without functioning vestibular end-organs (so-called "labyrinthine defectives") are completely immune to motion sickness.

The visual system can play two very important roles in the production of motion sickness. First, self-motion sensed solely through vision (i.e., vection) can make some people sick. Examples of this phenomenon are: motion-picture sickness, in which wide-screen movies of rides on airplanes, roller-coasters, and ships in rough seas are provocative; microscope sickness, in which susceptible individuals cannot tolerate viewing moving microscope slides; and flight-simulator sickness, in which wide-field-of-view visual motion systems create motion sickness in the absence of any mechanical motion. Abnormal stimulation of ambient vision rather than focal vision appears to be the essential feature of visually induced motion sickness. The fact that orientation information processed through the ambient visual system converges on the vestibular nuclei helps to reconcile the phenomenon of visually induced motion sickness with the necessity for functioning vestibular end-organs. The second role of vision in the etiology of motion sickness is illustrated by the well-known fact that the absence of an outside visual reference makes persons undergoing abnormal motion more likely to become sick than they would be if an outside visual reference were available. Good examples of this are the sailor who becomes sick below deck but prevents the progression of motion sickness by coming topside to view the horizon, and the aircrewman who becomes sick while attending to duties inside the aircraft (e.g., radarscope monitoring) but alleviates the symptoms by looking outside.

Other sensory systems capable of providing primary spatial orientation information also are capable of providing avenues for motion-sickness-producing stimuli. The auditory system, when stimulated by a revolving sound source, is responsible for audiogenic vertigo, audiokinetic nystagmus, and concomitant symptoms of motion sickness. Nonvestibular proprioceptors may contribute to the development of motion sickness when the pattern of stimulation of these senses by linear and angular accelerations is unfamiliar. Perhaps more important than the actual sensory channel employed or the actual pattern of stimulation delivered, however, is the degree to which the spatial orientation information received deviates from that which is anticipated. The experience with motion sickness in various flight simulators bears witness to the importance of unexpected patterns of motion and unfulfilled expectations of motion. Instructor pilots in the 2-FH-2 helicopter hover trainer, for example, were much more likely to become sick in the device than were student pilots.[61] It is postulated that imperfections in flight simulation are perceived by pilots who, as a result of their experience in the real aircraft, expect certain orientational stimuli to occur in response to certain control inputs. Pilots without time in the real aircraft, on the other hand, have no such expectations, and therefore notice no deviations from them in the simulator. Another example of the role played by the expectation of motion in the generation of motion sickness is seen in the pilot who does not become sick when controlling the airplane, but does become sick when another pilot is flying the same maneuvers in the same airplane. In this case, the expectation of motion is always fulfilled when the pilot in question controls the airplane but is not fulfilled when someone else is flying.

Several other variables not primarily related to spatial orientation seem to correlate well with motion sickness susceptibility. Age is one such variable: susceptibility increases with age until puberty and then decreases thereafter. Sex is another: women are more susceptible to motion sickness than men (two-thirds more women than men become seasick on ocean-going ferry boats, for example). In concordance with popular opinion, there is some scientific evidence that having eaten just prior to motion exposure tends to increase motion sickness susceptibility. There is also evidence suggesting that a high level of aerobic conditioning increases one's susceptibility to motion sickness, possibly as a result of increased parasympathetic tone. The personality characteristics of emotional lability and excessive rigidity are also positively correlated with motion sickness susceptibility. Whether one is mentally occupied with a significant task during exposure to motion or is free to dwell on orientation cues and the state of one's stomach seems to affect susceptibility--the latter, more introverted state is more conducive to motion sickness. Likewise, anxiety, fear, and insecurity, either about one's orientation relative to the ground or about one's likelihood of becoming motion sick, seem to enhance susceptibility. We must be careful, however, to distinguish between sickness caused by fear and sickness caused by motion: a paratrooper who vomits in an aircraft while waiting to jump into battle may be suffering either from fear or from motion sickness, or both. Finally, it must be recognized that many things, such as mechanical stimulation of the viscera and malodorous aircraft compartments, do not in themselves cause motion sickness even though they are commonly associated with conditions that result in such sickness.

An uncommon but potentially devastating phenomenon is conditioned motion sickness. Just as Pavlov's canine subjects learned to salivate at the sound of a bell, student pilots and other aircrew who encounter repeated exposure to the conditioning stimulus of sickness-producing aircraft motion can eventually develop the autonomic response of motion sickness to the conditioned stimulus of being in or even just seeing an aircraft (Fig. 44). For this reason, it is advisable to initiate aircrew gradually to the abnormal motions of flight and to provide pharmacologic prophylaxis against motion sickness, if necessary, in the early instructional phases of flight.

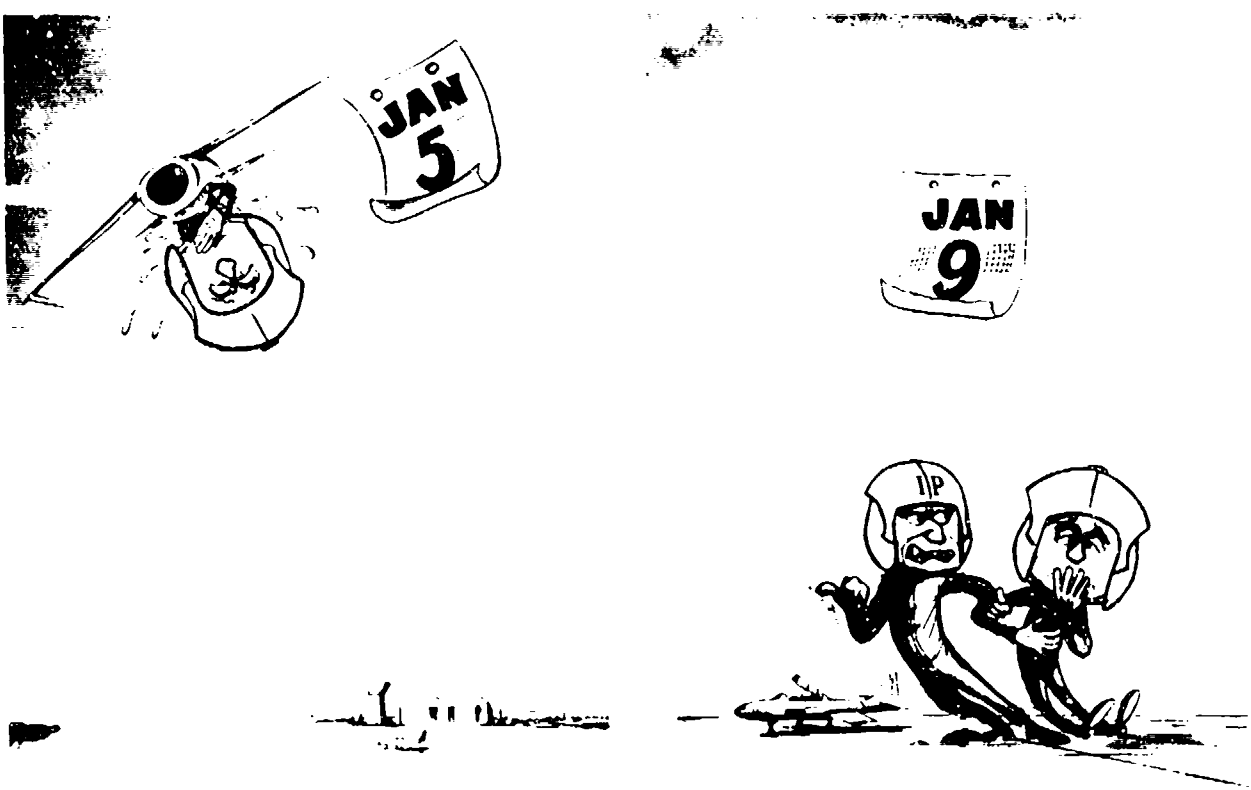


Figure 44. Conditioned motion sickness. A student aviator who repeatedly gets airsick during flight can become conditioned to develop symptoms in response to the sight or smell of an aircraft even before flight. Use of antimotion-sickness medication until the student adapts to the novel motion can prevent conditioned motion sickness.

Unifying Theory

Current thinking regarding the underlying mechanism of motion sickness has focused on the "sensory conflict," or "neural mismatch," hypothesis proposed originally by Claremont in 1931.[62] In simple terms, the sensory conflict hypothesis states that motion sickness results when incongruous orientation information is generated by various sensory modalities, one of which must be the vestibular system. In virtually all examples of motion sickness, one can, with sufficient scrutiny, identify a sensory conflict. Usually the conflict is between the vestibular and visual senses or between different components of the vestibular system, but conflicts between vestibular and auditory or vestibular and nonvestibular proprioceptive systems are also possible. A clear example of sickness resulting from vestibular-visual conflict is that which occurs when experimental subjects wear reversing prism goggles so that their visual perception of self-motion is exactly opposite in direction to their vestibular perception of it. Another example is motion-picture sickness, the conflict being between visually perceived motion and vestibularly perceived stationarity. Airsickness and seasickness are most often a result of vestibular-visual conflict: the vestibular signals of linear and angular motion are not in agreement with the visual percept of being stationary inside the vehicle. Vestibular-visual conflict need not even be in relation to motion but can be in relation to static orientation: some people become sick in "antigravity" houses, which are built in such a way that the visually apparent vertical is quite different from the true gravitational vertical.

Intravestibular conflict is an especially potent means of producing motion sickness. When vestibular Coriolis effects cause the semicircular ducts to signal falsely that angular velocity about a nonvertical axis is occurring, and the otolith organs do not confirm a resulting change in angular position, the likelihood of developing motion sickness is great. In a zero-gravity environment, when an individual makes head movements, the semicircular ducts sense rotation but the otolith organs cannot sense any resulting change of angular position relative to a gravity vector; many scientists believe the generation of this intravestibular conflict to be the underlying mechanism of space motion sickness. Conceptually similar is the "otolith-organ tilt-translation reinterpretation" hypothesis, which postulates that space motion sickness results from a visual-vestibular conflict that occurs until one learns to interpret otolith-organ stimulation in the zero-G condition correctly (i.e., as resulting from linear accelerations rather than from the force of gravity). This model is the basis of a promising scheme to preadapt astronauts to the conflictual sensory effects of the weightless environment.[63] Another hypothesis is that the altered gain of vestibulo-ocular reflexes in microgravity creates conflicts between visually perceived orientation and that perceived through the vestibular sense, or even between the anticipated and the actually experienced visual orientations. A more subtle hypothesis is that asymmetry of morphology and/or functioning of the left and right otolith organs, for which compensation has occurred in the one-G environment, results in conflicting vestibular orientation information in other than the one-G environment. Whatever explanation of space motion sickness eventually prevails, sensory conflict will likely remain a central theme.

What determines whether orientation information is conflicting or not? It is one's prior experience in the motional environment and the degree to which orientation information expected on the basis of that experience agrees with the actual orientation information received. The important sensory conflict is thus not so much an absolute discrepancy between information from the several sensory modalities as it is between anticipated and actual orientation information.[64] Evidence of this can be seen in the gradual adaptation to sustained abnormal motional environments, such as the sea, space, slowly rotating rooms, and the wearing of reversing prisms, and in the readaptation to the normal environment that must take place upon returning to it. It can also be seen that being able to anticipate orientation cues confers immunity to motion sickness, as evidenced by the fact that pilots and automobile drivers almost never make themselves sick and by the fact that we actively subject ourselves to many motions (jumping, dancing, acrobatics) that would surely make us sick if we were subjected to them passively. It appears, then, that the body refers to an internal model of orientational dynamics, both sensory and motor, to effect voluntary and involuntary control over orientation.[19] When transient discrepancies between predicted and actual orientation data occur, corrective reflex activity is initiated and/or the internal model is updated. But when sustained discrepancies occur, motion sickness can be the result.

Neurophysiology

The neurophysiology of motion sickness remains an enigma, although some progress in this area has been made recently. We now know that the chemoreceptive emetic trigger zone (CTZ) in the lower brain stem is not essential for motion-induced vomiting in experimental animals, as was once believed. Thus, there is more than one pathway to the medullary vomiting center, one subserving the motion sickness mechanism and another involving the CTZ. A popular hypothesis has been that motion sickness results mainly from a stimulated imbalance of lower brainstem neuronal activity which is normally in a state of dynamic balance between muscarinic cholinergically activated (parasympathetic) effects and norepinephrine-activated (sympathetic) effects. The focus of attention thus has been on the vestibular nuclei, reticular formation, and autonomic control centers of the lower brain stem. Appearing to support this hypothesis have been the observations that scopolamine, a muscarinic cholinergic receptor blocker, and dextroamphetamine, a compound that stimulates norepinephrine release, are highly effective pharmacologic agents for controlling motion sickness, especially in combination. But neuropharmacologic studies have not demonstrated significant lower brainstem sites of activity of these drugs; accordingly, there has been productive speculation that other anatomic structures, in particular the limbic system and basal ganglia, are of critical importance in the development and treatment of motion sickness. Kohl[65] points out that limbic structures are very important in the selection of sensory systems in the mechanisms of attention; he argues that the sensory conflict which is an essential feature of motion sickness pathogenesis, as well as the profound dependence on vision which develops with adaptation to a conflict-generating motional environment, both strongly suggest that limbic attentional mechanisms are heavily involved in the production and resolution of motion sickness. Kohl also argues that the known effects of scopolamine on limbic structures (particularly the septohippocampal tract) and the ability of dextroamphetamine to enhance dopamine transmission (particularly in the nigrostriatal and mesolimbic systems) constitute evidence that limbic structures and the basal ganglia are involved in motion sickness pathogenesis. Kohl and Lewis[66] believe that those structures subserve "a higher sensory integrative process that acts upon sensory discordance and suppresses or activates reflexes which produce autonomic symptomatology." Although the neurophysiology and neuropharmacology of motion sickness and its treatment have not been determined definitively, some recent speculation removes the important sites of action from the vestibular end-organs and lower brain stem and places them in higher subcortical regions.

Teleology

Even if the mechanism of motion sickness could be described completely in terms of cellular and subcellular functions, the question would remain: "What purpose, if any, does motion sickness serve?" The idea that a chance mutation rendered countless generations of vertebrates potential victims of motion sickness, and that the relatively recent arrival of transportation systems gave expression to that otherwise innocuous genetic flaw, strains credulity. A more satisfactory answer is that of Treisman[67], who proposed that the orientation senses (in particular the vestibular system) serve an important function in the emetic response to poisons. When an animal ingests a toxic substance and experiences its effects on the central nervous system--namely, deterioration of the finely tuned spatial orientation senses and consequent degraded predictability of sensory responses to motor activity--reflex vomiting occurs and the animal is relieved of the poison. The positive survival value of such a mechanism to eliminate ingested poisons is obvious. The essentiality of the vestibular end-organs and certain parts of the cerebellum, and the role of sensory conflict as manifested through the functioning of those structures, are provided a rational basis in Treisman's theory. And there is experimental support for Treisman's theory: labyrinthectomized animals, in addition to being immune to motion sickness, exhibit marked impairment of the emetic response to certain naturally occurring poisons.[68]

Prevention and Treatment of Motion Sickness

The variety of methods at our disposal for preventing and treating motion sickness is less an indication of how easy motion sickness is to control than it is of how incompletely effective each method can be. Nevertheless, logical medical principles are generally applicable. Several specific treatments have survived the test of time and become traditionalized, and some newer approaches appear to have great potential.

Physiologic Prevention

An obvious way to prevent motion sickness is to avoid the environments that produce it. For most individuals in today's world, however, this is neither possible nor desirable. The most common and ultimately most successful way is to adapt to the novel motional environment through constant or repeated exposure to it. The rapidity with which adaptation occurs is highly variable, depending mainly on the strength of the challenge and on the adaptability of the individual involved. Usually, several days of sustained exposure to mild orientational challenges (like sea and space travel) or several sessions of repeated exposure to vigorous challenges (like aerobatics or centrifuge riding) will confer immunity. The use of antimotion-sickness medications to prevent symptoms during the period of adaptation does not appear to compromise the process of adaptation and is recommended where practicable.

An important concept that must be considered when attempting to preadapt passengers or crew to a novel orientational environment is that adaptation to motion appears to have both a general and a specific component.[69] Thus, the greater the similarity of the stimuli used in the preadaptation regimen to the stimuli expected in the novel environment, the greater the probability of successful adaptation. As a case in point, exposure to high-G aerobatics prior to zero-G space flight might help increase resistance to space motion sickness because of a general effect, but it could have the opposite outcome as a result of a specific effect. A possibly more efficacious procedure would involve head movements and locomotion during zero-G parabolic flights in aircraft or training in a device specifically designed to promote otolith-organ tilt-translation reinterpretation, as the stimuli would be more like those encountered in space flight.

The selection of individuals resistant to motion sickness, or screening out those unusually susceptible to it, has been considered as a method for reducing the likelihood of motion sickness in certain operations, such as military aviation training. The fact that susceptibility to motion sickness is so complex a characteristic makes selection less efficacious a means of prevention than might be supposed. At least three separate factors are involved in motion sickness susceptibility: (1) receptivity, the degree to which a given orientational information conflict is perceived and the intensity with which it is experienced and responded to; (2) adaptability, the rate at which one adjusts to a given abnormal orientational environment as evidenced by one's becoming less and less symptomatic; and (3) retentivity, the ability to remain adapted to the novel environment after leaving it.[70] These factors appear to be independent. This means that a particular prospective aviator with high receptivity also might adapt very rapidly and remain adapted for a long time, so that it would be unwise to eliminate that person from flying training on the basis of a history of motion sickness or even a test of susceptibility. Nevertheless, although the great majority of aircrew trainees do adapt to the aerial environment, use of vestibular stimulation tests[71] and motion sickness questionnaires[72] reveals that sensitivity to motion sickness tends to be inversely related to success in flight training. Furthermore, sound judgment dictates that an attempt to select against crewmembers with a high probability of becoming motion sick is appropriate for some of the more critical and expensive aerospace operations.

Some promising results have been obtained with biofeedback-mediated behavior modification and other methods for desensitizing fliers with chronic airsickness. Cowings and Toscano[73] have reported that subjects receiving autogenic-feedback training (AFT), a biofeedback-based autonomic conditioning procedure, were able to adjust significantly more rapidly to nauseogenic vestibular Coriolis stimulation than were control subjects not provided with AFT. But can biofeedback be used to rehabilitate aircrew suffering from refractory airsickness? Apparently so, as Levy et al.[74] found that the use of relaxation training and biofeedback in the treatment of highly motivated aircrew who were disabled by recurrent airsickness yields an 84% rate of return to duty. This rate is substantially better than the 45-50% rate for a comparable group of aircrew not provided with the biofeedback treatment.

Physiologic Treatment

Once symptoms of motion sickness have developed, the first step to bring about recovery is to escape from the environment that is producing the symptoms. If this is possible, relief usually follows rapidly; symptoms can still progress to vomiting, however, and nausea and drowsiness can sometimes persist for many hours, even after termination of the offending motion. If escape is not possible, assuming a supine position or just stabilizing the head seems to offer some relief. As mentioned previously, passengers subjected to motion in enclosed vehicles can help alleviate symptoms by obtaining a view of the natural horizon. One of the most effective physiologic remedies is turning over control of the vehicle to the symptomatic crewmember. Generations of flight instructors have used this technique to avert motion sickness in their students, even though they were probably unable to explain how it works in terms of reducing conflict between anticipated and actual orientational cues. Another procedure that has proved useful in practice is to cool the affected individual with a blast of air from the cabin air vent; such thoughtfulness on the part of their instructors has saved many student pilots from having to clean up the cockpit.

Pharmacologic Prevention

The most effective single medication for prophylaxis against motion sickness is scopolamine, 0.3 to 0.6 mg, taken orally 30 minutes to 2 hours before exposure to motion. Unfortunately, the side effects of scopolamine when taken in orally effective doses (i.e., drowsiness, dry mouth, pupillary dilation, and paralyzed visual accommodation) make the routine oral administration of this drug to aircrew highly inadvisable. When prophylaxis is needed for prolonged exposure to abnormal motion (e.g., an ocean voyage), oral scopolamine can be administered every 4 to 6 hours; again, the side effects are troublesome and may preclude repeated oral administration. One approach to the problem of prolonged prophylactic administration of scopolamine is the transdermal therapeutic system (TTS), in which 0.5 mg of scopolamine is delivered transcutaneously over a 3-day period from a small patch worn on the skin behind the ear. For maximum effectiveness, the patch should be applied at least 8 hours prior to exposure to the environment that causes sickness. The cognitive, mood, and visual side effects associated with this route of administration are considerably less than with oral scopolamine.

The antimotion-sickness preparation most useful for aircrew is the "scop-dex" combination, which is 0.6 mg of scopolamine and 5 or 10 mg of dextroamphetamine taken orally 2 hours prior to exposure to motion. A second dose of scopolamine, 0.6 mg, and dextroamphetamine, 5 mg, can be given after several hours if needed. Not only is this combination of drugs more effective than scopolamine alone, but the stimulant effect of dextroamphetamine counteracts the drowsiness side effect of the scopolamine. Another useful oral combination is 25 mg of promethazine and 50 mg of ephedrine, taken approximately 1 hour before exposure. Because the individual response to the several effective antimotion-sickness preparations is variable, it may be worthwhile to perform individual assessments of different drug combinations and dosages to obtain the maximum benefit.

Pharmacologic Treatment

If motion sickness progresses to the point of nausea, and certainly if vomiting occurs, oral medication is useless. If the prospect of returning soon to the accustomed motion environment is remote, it is important to treat the condition to prevent the dehydration and electrolyte loss that result from protracted vomiting. The intramuscular injection of scopolamine, 0.5 mg, or promethazine, 50 mg, is recommended: intramuscular promethazine has, in fact, been used with a high degree of success in treating space motion sickness on Space Shuttle flights. Scopolamine administered intravenously or even by nasal spray or drops is also effective. Promethazine rectal suppositories are used to control vomiting in many clinical situations, and their use in the treatment of motion sickness also should be successful. If the parenteral administration of scopolamine or promethazine does not provide relief from vomiting, sedation with intravenous phenobarbital may be necessary to prevent progressive deterioration of the patient's condition. Of course, fluid and electrolyte losses must be replaced in patients who have been vomiting for prolonged periods.

Aeromedical Use of Antimotion-Sickness Preparations

As mentioned previously, the routine use of antimotion-sickness drugs in aircrew is not appropriate because of the undesirable side effects of these drugs. Prophylactic medication can be very useful, however, in helping the student aviator cope with the novel motions that can cause sickness during flight training--thus promoting better conditions for learning, and preventing the development of conditioned motion sickness. Prophylaxis also can help reduce a student's anxiety over becoming motion sick, which can develop into a self-fulfilling vicious circle. After using medication, if necessary, for two or three dual training sorties (usually at the beginning of flight training and again during the introduction to aerobatics), student pilots should no longer need antimotion-sickness drugs. The use of drugs for solo flight should absolutely be forbidden. A more liberal approach can perhaps be taken with other aircrew trainees, such as navigators, because of their greater propensity to become motion sick and their less critical importance to flight safety. Trained aircrew, as a rule, should not use antimotion-sickness drugs. An exception to this rule is made for spacecrew, whose exposure to the zero-gravity condition of space flight is usually very infrequent and whose premission adaptation by other means cannot be assured. Spacecrew also should be expected to need prophylaxis for reentry into the normal gravitational environment of Earth after a prolonged stay at zero gravity. Airborne troops, who must arrive at the battle zone fully effective, are also candidates for antimotion-sickness prophylaxis under certain circumstances, such as prolonged low-level flight in choppy weather. In all such cases, the flight surgeon must weigh the risks associated with developing motion sickness against the risks associated with the side effects of antimotion-sickness drugs before arriving at a judgment of whether to medicate.

CONCLUSION

Thus, we see how the recent transition of humans into the motional environment of aerospace has introduced them not only to new sensations but also to new sensory demands. By failing to appreciate the fallibility of our natural orientation senses in this novel environment, pilots can succumb to spatial disorientation. By recognizing our innate limitations, however, pilots can meet the demands of the flight environment and function effectively in it. We see also how our phylogenetic heritage, by means of orientational mechanisms, renders us susceptible to motion sickness. That same heritage, however, enables us to adapt to new motional environments. The profound and pervasive influence of our orientation senses in aerospace operations cannot be denied or ignored; through knowledge and understanding, however, it can be controlled.

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