AEROMEDICAL REVIEWS

A PRIMER OF VESTIBULAR FUNCTION, SPATIAL DISORIENTATION, AND MOTION SICKNESS

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A PRIMER OF VESTIBULAR FUNCTION, SPATIAL DISORIENTATION, AND MOTION SICKNESS

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USAF School of Aerospace Medicine
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A PRIMER OF VESTIBULAR FUNCTION, SPATIAL DISORIENTATION, AND MOTION SICKNESS

Equilibrium and orientation are maintained mainly through the use of three sensory modalities: the visual sense, the vestibular sense, and the proprioceptive (subcutaneous-kinesthetic) sense. The role of vision in the maintenance of equilibrium and orientation is obvious, but not so obvious are the mechanisms of vestibular function and proprioception. Despite their obscurity, these sensory functions are nevertheless quite important to the Air Force from an operational standpoint, as the serious problem of spatial disorientation is generated by the inadequacies of the vestibular and proprioceptive senses, and motion sickness originates from stimulation of the vestibular organs. We shall first discuss the anatomy and physiology of the vestibular and proprioceptive organs; then the causes and significances of spatial disorientation and motion sickness will be described.

REVIEW OF VESTIBULAR FUNCTION

Anatomy

The vestibular apparatus is a tiny organ located in the petrous portion of the temporal bone (fig. 1). Each temporal bone is canalized so as to form three distinct portions (fig. 2): (1) the vestibule proper; (2) the semicircular canals; and (3) the cochlea. These three excavations into the temporal bone comprise the bony labyrinth, which is filled with a fluid, perilymph, much like cerebrospinal fluid. Within the bony labyrinth and the perilymph is the membranous labyrinth, filled with another fluid, the endolymph (fig. 3). The membranous labyrinth (fig. 4) conforms roughly in shape to the surrounding bony labyrinth and is also composed of three parts: (1) the otolith organs (utricle and saccule); (2) the semicircular canals; and (3) the cochlear end-organ. The utricle and saccule fit within the vestibule proper

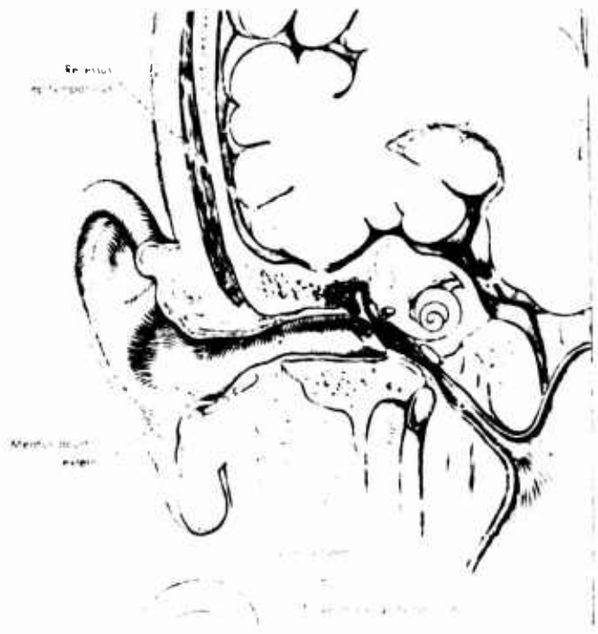


FIGURE 1

Coronal section of human head, revealing the semicircular canals, vestibule, and cochlea situated in the petrous portion of the temporal bone.

and are concerned with the monitoring of linear accelerations. The membranous semicircular canals, of which there are three in each vestibular apparatus, fit within the bony semicircular canals and are concerned with the monitoring of angular accelerations. The cochlear end-organ is the organ of hearing and need not concern us here.

The utricle and saccule can be likened to tiny boxes with the nervous epithelia (known as maculae) lining one or two contiguous inner surfaces of these boxes. Each macula has lying upon it an otolithic membrane, a gelatinous structure containing numerous calcium carbonate granules, which can slide a short distance over the nervous epithelium (fig. 5). As the otolithic membrane slides over the macula, the hairs (cilia) projecting into the otolithic

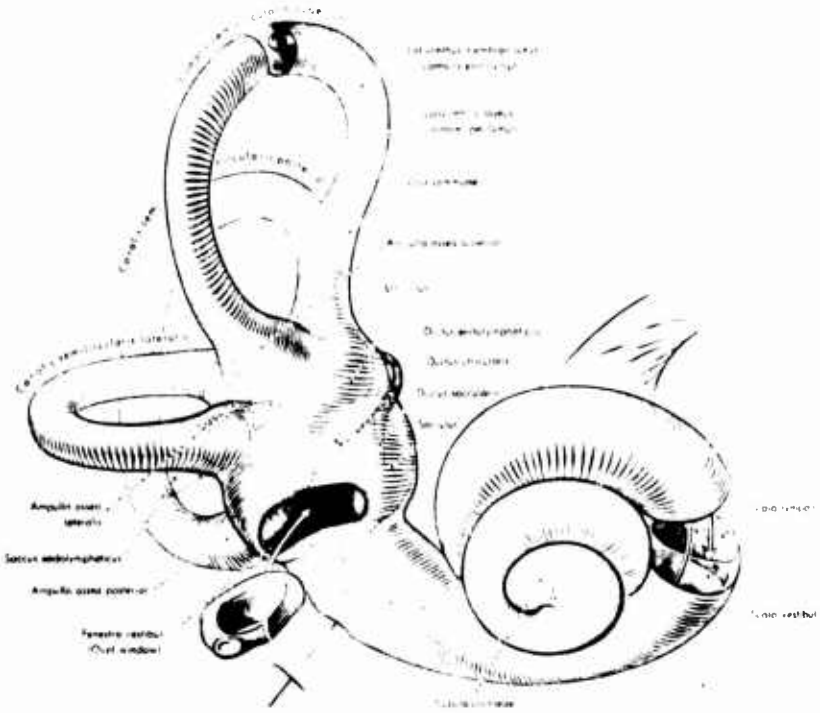


FIGURE 2

The bony labyrinth. The perilymph and membranous labyrinth are contained within its walls.

membrane from the nervous epithelium (hair cells) are bent, and this bending of the cilia results in generation of neural impulses by the hair cells.

The nervous epithelia of the semicircular canals lie in the ampullae and are called cristae ampullares. The hair cells of each crista project their cilia toward the opposite side of the ampulla in a gelatinous structure called the cupula (fig. 6). When the cupula is deviated (as during an angular acceleration), the cilia are bent, and the hair cells generate nervous impulses in the same way as do the hair cells in the otolith organs.

From the utricle and saccule come the utricular and saccular nerves, which coalesce with the ampullary nerves of the semicircular canals to form the vestibular portion of the eighth cranial

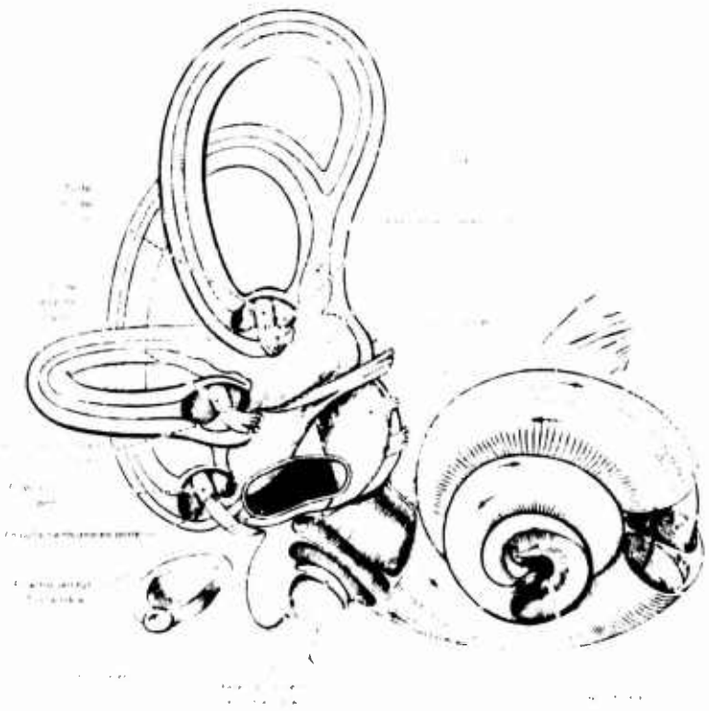


FIGURE 3

The membranous labyrinth. The endolymph flows within this structure. The three ampullae have been opened to show their cristae.

nerve (fig. 7). The cell bodies for the primary afferent neurons of the vestibular nerve lie in the vestibular (Scarpa's) ganglion. These afferent neurons synapse in four vestibular nuclei in the medulla and pons. From the four (bilaterally, eight) vestibular nuclei (the superior, the medial, the lateral, and the inferior) are five primary projections or nervous pathways (fig. 8). The first projection is to the spinal cord via the inferior vestibular nucleus, and this pathway is primarily responsible for postural reflexes. The second pathway is to the cerebellum, which structure has the primary responsibility for coordinating orientation information. The third pathway is to the reticular nuclei of the midbrain, where arousal (attention) reflexes are generated. The fourth projection is to the oculomotor nuclei via the medial longitudinal fasciculus, and it is through this pathway that compensatory eye movements

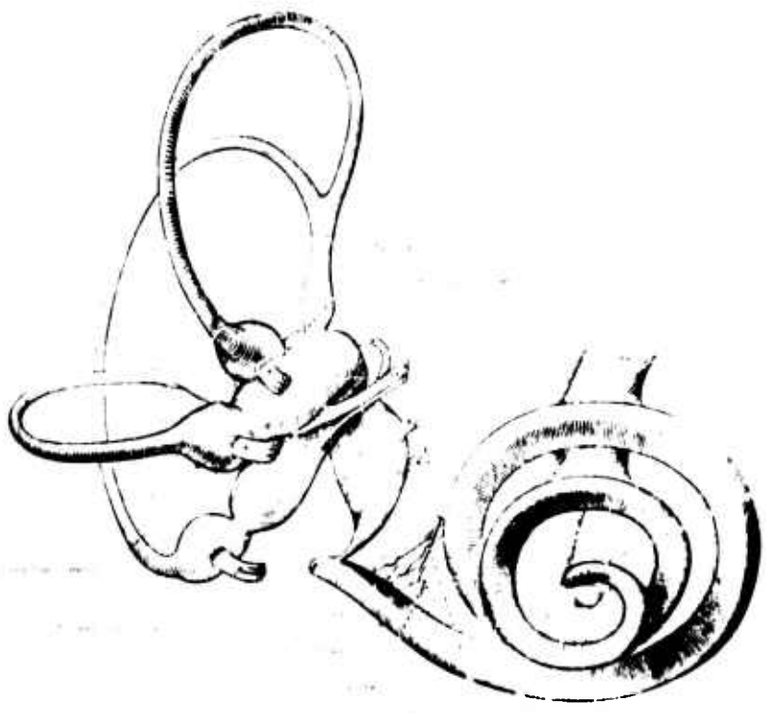


FIGURE 4

The membranous labyrinth dissected free from surrounding bone. Note the mutually perpendicular planes of the semicircular canals, and identify the utricle and saccule.

such as nystagmus and counterrolling are effected. A pathway leading eventually to an area of the cerebral cortex responsible for perception of motion has been proposed and in all likelihood exists. Another component, the vestibular efferent system, which goes from the central nervous system peripherally to the vestibular end-organ, has recently been demonstrated; and it is assumed that this system exerts some form of regulation on the sensory information arising from the vestibular end-organ.

Physiology

To understand the physiology of the vestibular end-organs, one must have a perfect understanding of what is meant by acceleration and velocity; in addition, an appreciation of the difference

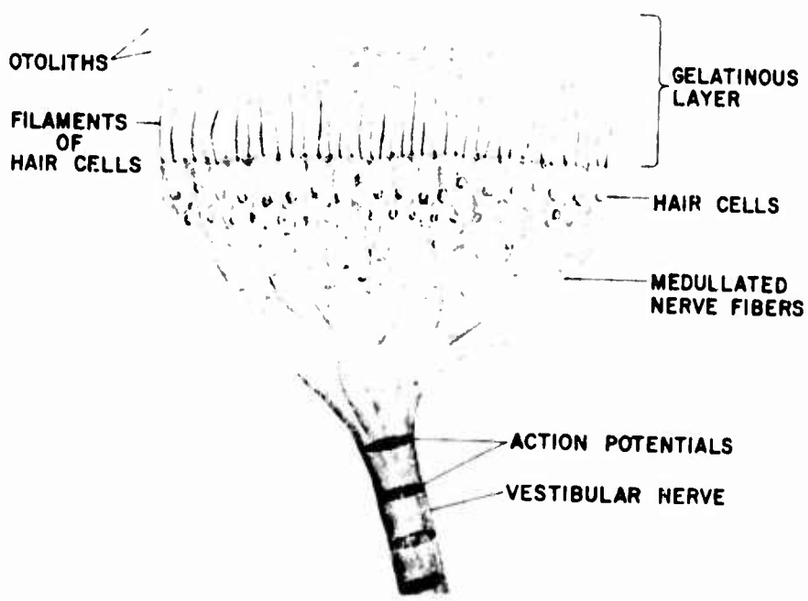


FIGURE 5

Semischematic microscopic cross section of the utricular macula, showing the important structures.

between angular and linear motion is mandatory. A *velocity* is a constant rate of speed. This constant rate of speed can refer to *linear* speed which is measured in feet per second, centimeters per second, miles per hour, and other such units that measure linear distance per unit time. *Angular* velocity, on the other hand, is measured in degrees per second, radians per second, revolutions per minute, or other such units representing constant rotatory movement. An *acceleration* is a change in velocity, linear or angular. If, for example, we go from a speed of 0 feet per second to 10 feet per second in 1 second, we have undergone a linear velocity change, or *linear acceleration*, of 10 feet per second in 1 second, which is written 10 feet per second^2. Likewise, if we go from 0 revolutions per minute to 10 revolutions per minute in 1 second, we have undergone an angular velocity change, or *angular acceleration*, of 10 revolutions per minute per second (which converts to

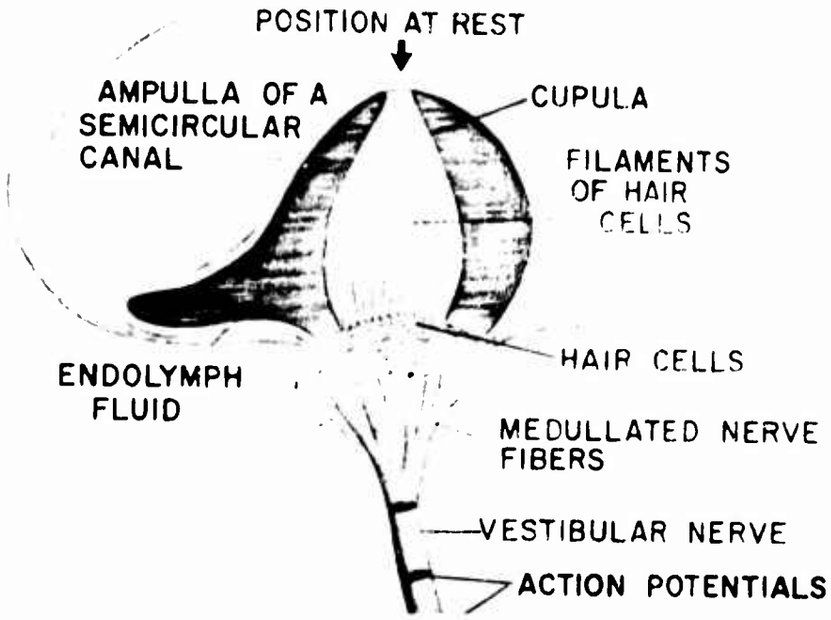


FIGURE 6

Semischematic cross section of the ampulla of a semicircular canal, showing the crista and cupula. Note the structural similarity: (1) between a cupula and an otholithic membrane; (2) between a crista and a macula.

60 degrees per second^2). Simply stated, linear acceleration is the rate of change of linear velocity, and angular acceleration is the rate of change of angular velocity; and all linear acceleration measurements can be converted to centimeters per second^2, just as all angular accelerations can be converted to degrees per second^2. We often hear people talk about linear accelerations in terms of "g's." When one speaks of g units, he refers to the fact that 1 g equals 980 centimeters per second^2: thus, a linear acceleration of 9.8 centimeters per second^2 is equal to $^1/_{100}$ of a g. G units refer only to rate of change of linear velocity: we do *not* use g's to measure angular acceleration.

Do not be confused by the fact that *radial* or *centripetal acceleration*, which is a form of linear motion, is generated during conditions of constant angular velocity, as in a centrifuge. The

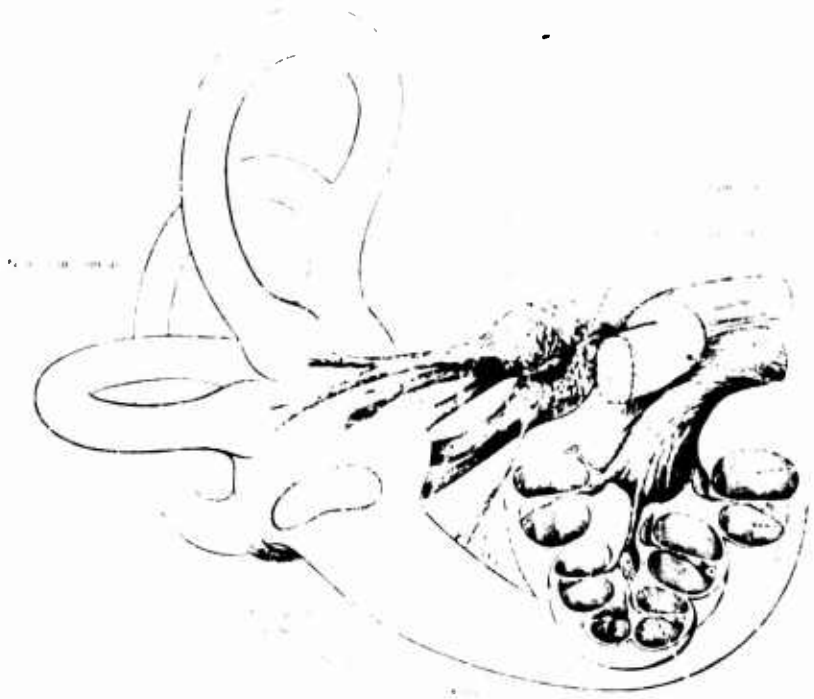


FIGURE 7

The vestibular nerve combines with the cochlear nerve to form cranial nerve VIII.

only angular accelerations that are generated in a centrifuge occur when the centrifuge changes angular speed, as when it goes from 0 r.p.m. to maximum angular speed or when it goes from maximum angular speed to 0 r.p.m. While the centrifuge is rotating at a constant angular velocity, it is generating a radial (linear) acceleration (measured in g's) at the end of the centrifuge arm by virtue of the fact that the end of the centrifuge is constantly being deviated from a straight-line path.

The emphasis on the distinction between acceleration and velocity and angular vs. linear motion is necessary for the following reasons (fig. 9): (1) *the utricle and saccule are stimulated by linear acceleration;* and (2) *the semicircular canals are stimulated by angular acceleration.*

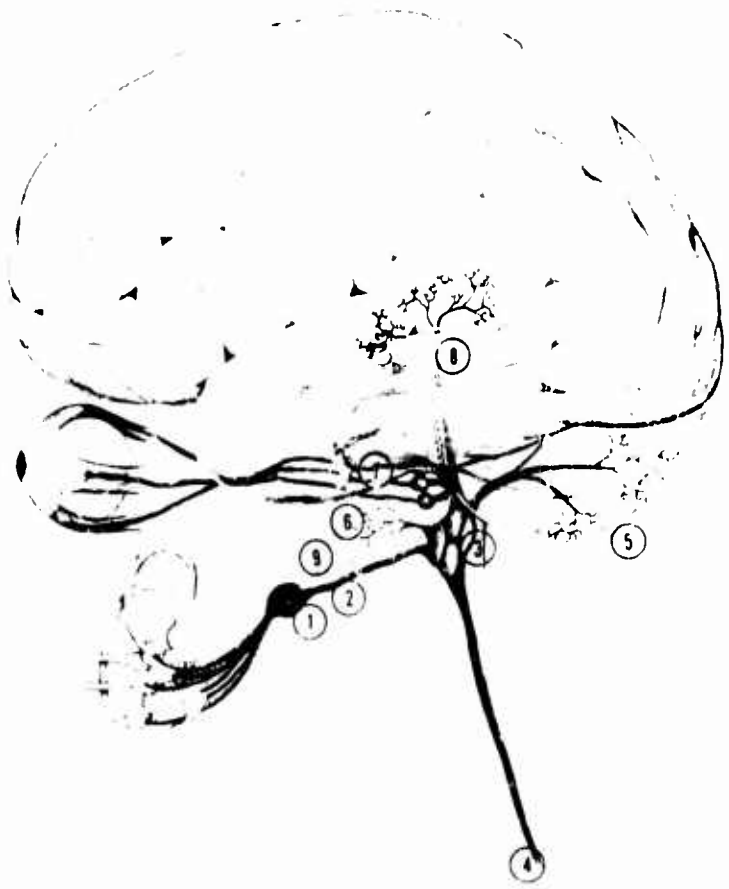


FIGURE 8

Neural projections of the vestibular end-organs. **1**, *Vestibular ganglion.* **2**, *Vestibular nerve.* **3**, *Vestibular nuclei.* **4**, *Spinal cord.* **5**, *Cerebellum.* **6**, *Reticular formation.* **7**, *Oculomotor nuclei.* **8**, *Cortical projection.* **9**, *Vestibular efferent fibers.*

When a person has his head upright and a linear acceleration of 1 g (the force of gravity) is acting upon the otolithic membranes of his utricles and saccules, then a given otolithic membrane (because of the relatively high density of the included calcium carbonate granules) displaces endolymph and slides to the lowest possible position on its macula. When the otolithic membrane occupies a particular position with respect to its macula, the hairs (cilia) of the hair cells are bent in a particular pattern, and the action

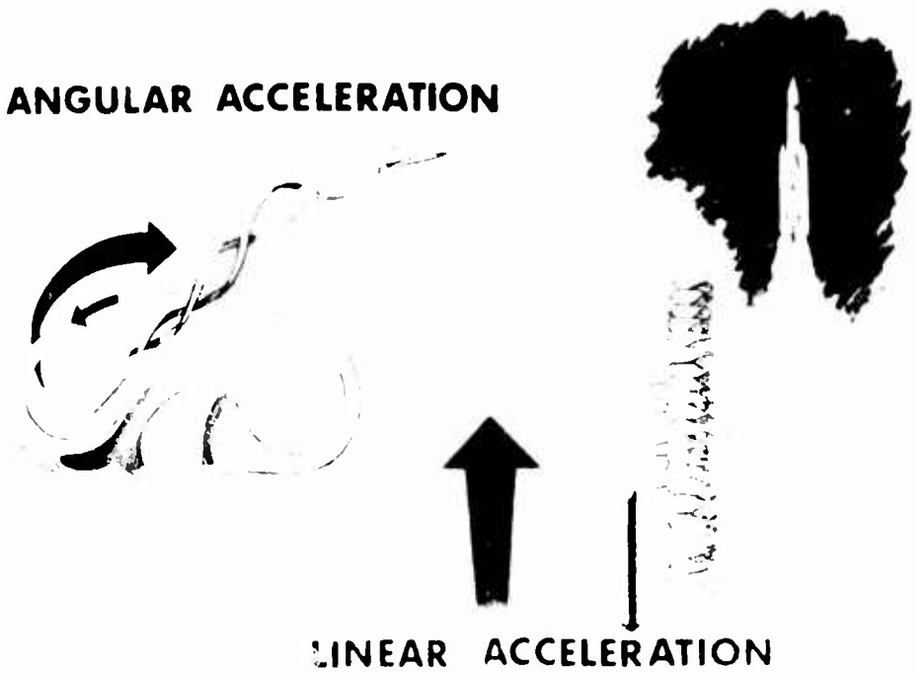


FIGURE 9

Remember: angular accelerations stimulate the semicircular canals; linear accelerations stimulate the otolith organs.

potentials generated by this particular pattern of bent cilia indicate to the central nervous system that a particular direction and intensity of linear acceleration is being applied to the head. In the above example, the hair cells of the maculae are stimulated in such a way as to indicate to the central nervous system the fact that a linear acceleration of 1 g is being applied in the vertical direction. As the head is tipped forward, the otolithic membranes slide over the maculae to new forward and downward positions, bending the cilia of the hair cells in a different direction. This results in a different pattern of nervous activity originating in the otolith organs, which new pattern indicates the new direction of the 1-g acceleration vector. In fact, whenever the head is tipped off of the vertical in any direction, or the gravity (acceleration) vector is otherwise changed with respect to the head, this change in the orientation and intensity of the gravity vector relative to the head is signaled to the brain via the utricular and saccular

hair cells and the vestibular nerve (fig. 10). The structures of the utricle and saccule complement each other in such a way as to allow these organs to monitor linear accelerations in nearly all directions.

The absolute thresholds of otolith organ function are measured in two ways: (1) a change of $1\frac{1}{2}$ degrees in the direction of linear acceleration acting upon the otolith organs can be perceived under ideal conditions; and (2) a change of 0.01 g (9.8 centimeters per second^2) in the length of the linear acceleration vector acting upon the otolith organs has been reported to be perceptible.

The semicircular canals respond to angular accelerations: they do not respond to angular velocity per se, nor do they respond to linear velocity or acceleration. The three canals in each ear are situated so that each canal lies in a plane perpendicular to the planes of the other two; thus, an angular acceleration occurring in any spatial plane can be perceived, provided it is above threshold.

When an angular acceleration is applied to the head, the endolymph within the semicircular canals in the plane of rotation lags behind the accelerated canal walls, and bends the cupulae in the direction opposite the imposed acceleration. As long as angular acceleration continues, the cupulae, with the embedded cilia of the hair cells, remain deviated. When angular acceleration ceases and a constant velocity persists, then the cupulae gradually return to their upright, resting positions. During the time in which a given cupula is deviated, nerve impulses arising from the hair cells signal the brain that angular motion is occurring (fig. 11).

The cupular transducers operate under physiologic conditions to monitor angular acceleration stimuli and transform these stimuli into angular velocity information, which is then relayed to the central nervous system. At physiologic stimulus frequencies (i.e., between 0.1 and 5.0 cps) the cupular end-organ acts primarily as a velocity meter and sends true information to the brain regarding angular velocity. At very low stimulus frequencies (as occasioned during prolonged angular accelerations), and at very high stimulus frequencies, the cupular end-organ responds more as an accelerometer than a velocity meter; and because of this shortcoming, it is prone to relay false information to the brain whenever the stimulating motion is outside the frequency response range of the vestibular transducer.

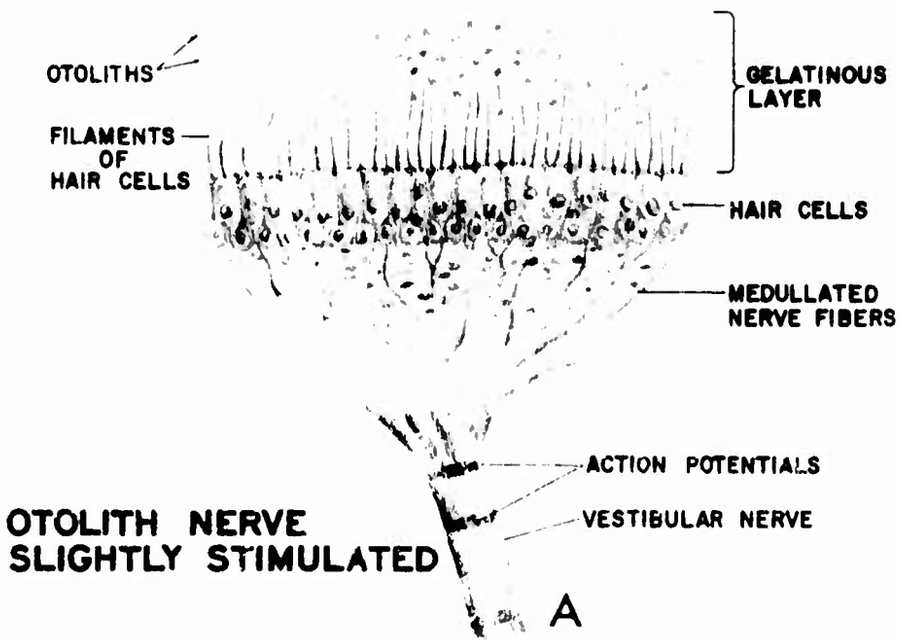


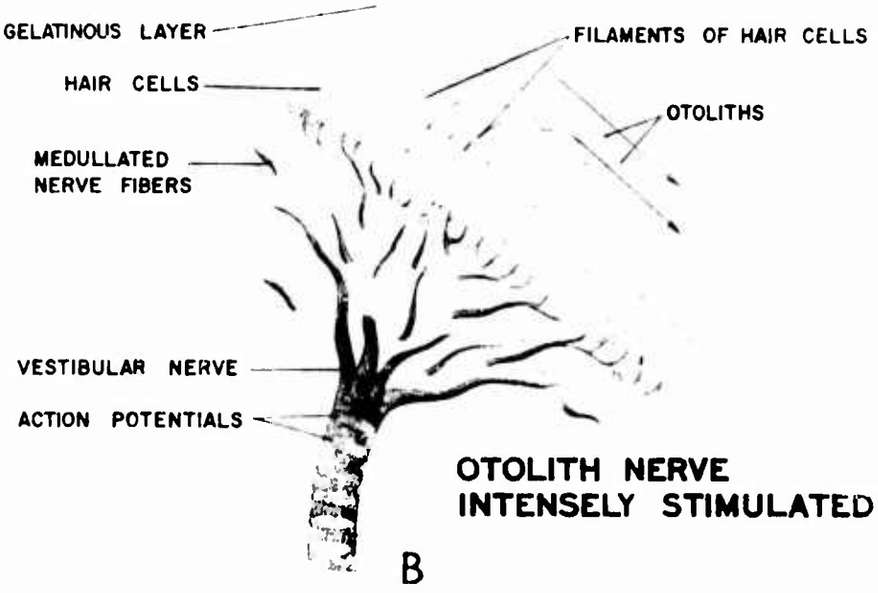
FIGURE 10

Action of the otolith organs. When a person holds his head upright, a "resting" frequency of neural discharge is generated by the hair cells. As the head is tilted, the resting frequency is altered to inform the brain of the new position of the head relative to the earth.

A. *Otolith organ in upright position.*

B. *Otolith organ in aft-tilt.*

C. *Otolith organ in fore-tilt.*


GELATINOUS LAYER
FILAMENTS OF HAIR CELLS
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MEDULLATED NERVE FIBERS
VESTIBULAR NERVE
ACTION POTENTIALS
OTOLITH NERVE INTENSELY STIMULATED
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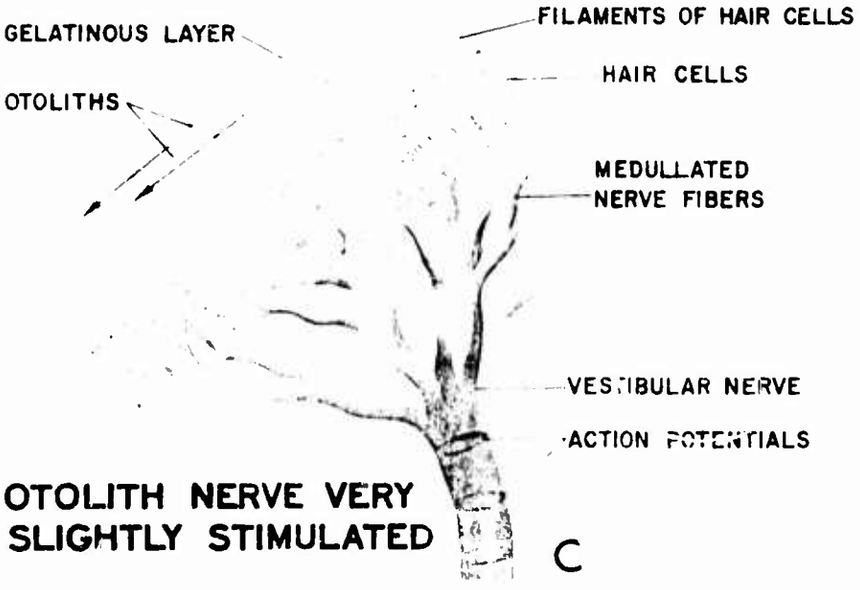
GELATINOUS LAYER
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OTOLITHS
MEDULLATED NERVE FIBERS
VESTIBULAR NERVE
ACTION POTENTIALS
OTOLITH NERVE VERY SLIGHTLY STIMULATED
C

Under ideal conditions, the limits of perception of angular motion (angular acceleration) are dependent upon two factors: (1) the angular acceleration applied; and (2) the time over which the angular acceleration is applied. In general, for an angular acceleration to be sensed by the horizontal semicircular canals, the product of the acceleration and the time of application of the acceleration must be equal to or greater than approximately 2.5 degrees per second. Thus, if a person were subjected to a horizontal angular acceleration (yaw) of 2.5 degrees per second^2 for a 1-second period, he would barely be able to perceive angular motion. If, however, the angular acceleration were 5.0 degrees per second^2, it would require only $^1/_2$ second of this acceleration to enable the person to perceive angular motion. On the other hand, if he were subjected to a 0.25 degree per second^2 acceleration, it would require at least 10 seconds of this acceleration for him to be able to perceive motion. This concept is referred to as Mulder's law, and in equation form is

$$\alpha T = 2.5^\circ/\text{sec.}$$

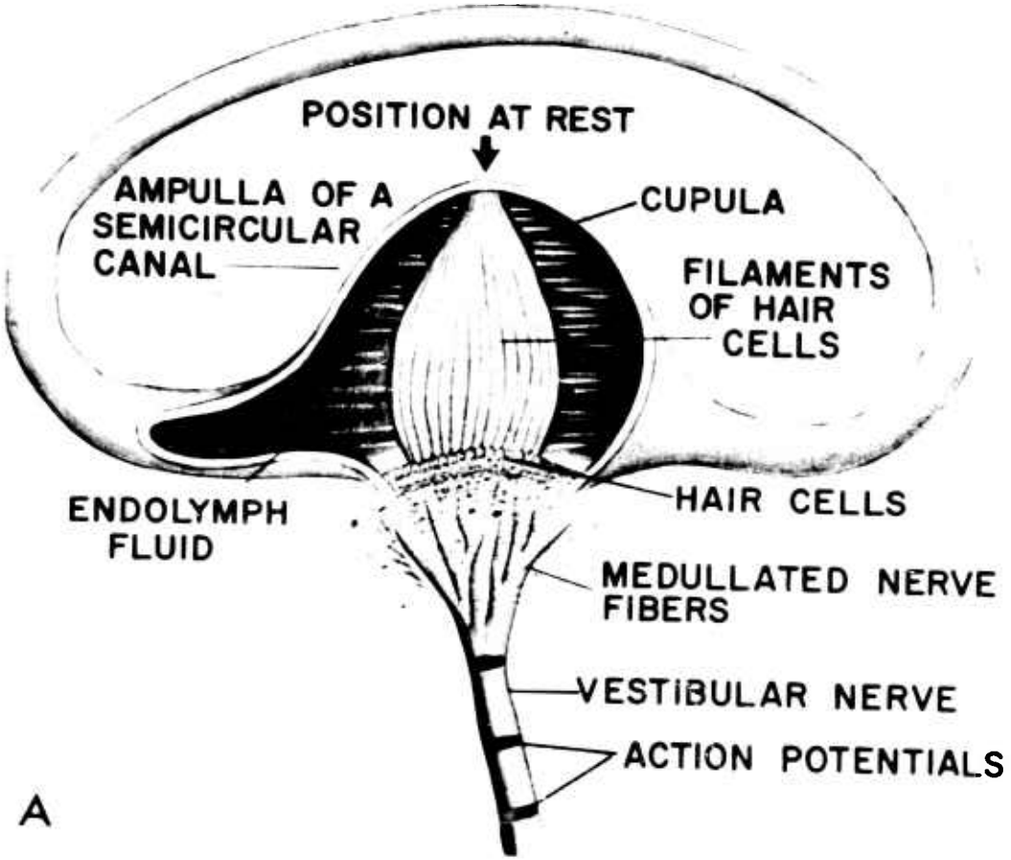
The absolutely minimum acceleration that can be perceived by the horizontal canals, when a theoretically infinite time of application is allowed, is equal to 0.035 /sec.^{2} It is generally believed that the vertical semicircular canals are somewhat more sensitive than the horizontal, and under those circumstances

$$\alpha T < 2.5^\circ/\text{sec.}$$

for the vertical canals. We must always remember, however, that Mulder's constant (2.5 sec.) holds true only under certain ideal conditions (i.e., in situations similar to the experimental conditions

FIGURE 11

Function of a semicircular canal during angular acceleration and deceleration. Note that with these relatively long stimulus durations, the vestibular information sent to the brain is for the most part erroneous as angular velocity measurement. Such is not the case when short-duration stimuli are applied, as during walking, running, falling, turning the head, etc.: under physiologic conditions the semicircular canal integrates angular acceleration stimuli into angular velocity information with no appreciable error.


POSITION AT REST
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ACTION POTENTIALS
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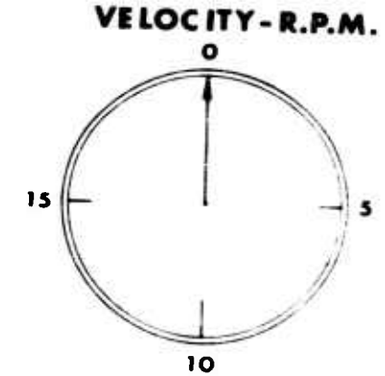
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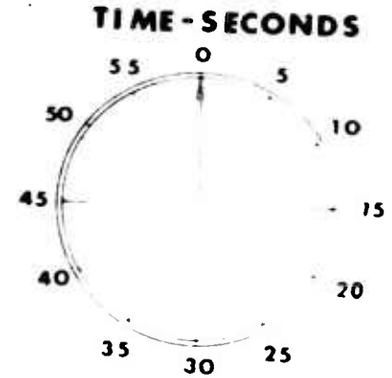
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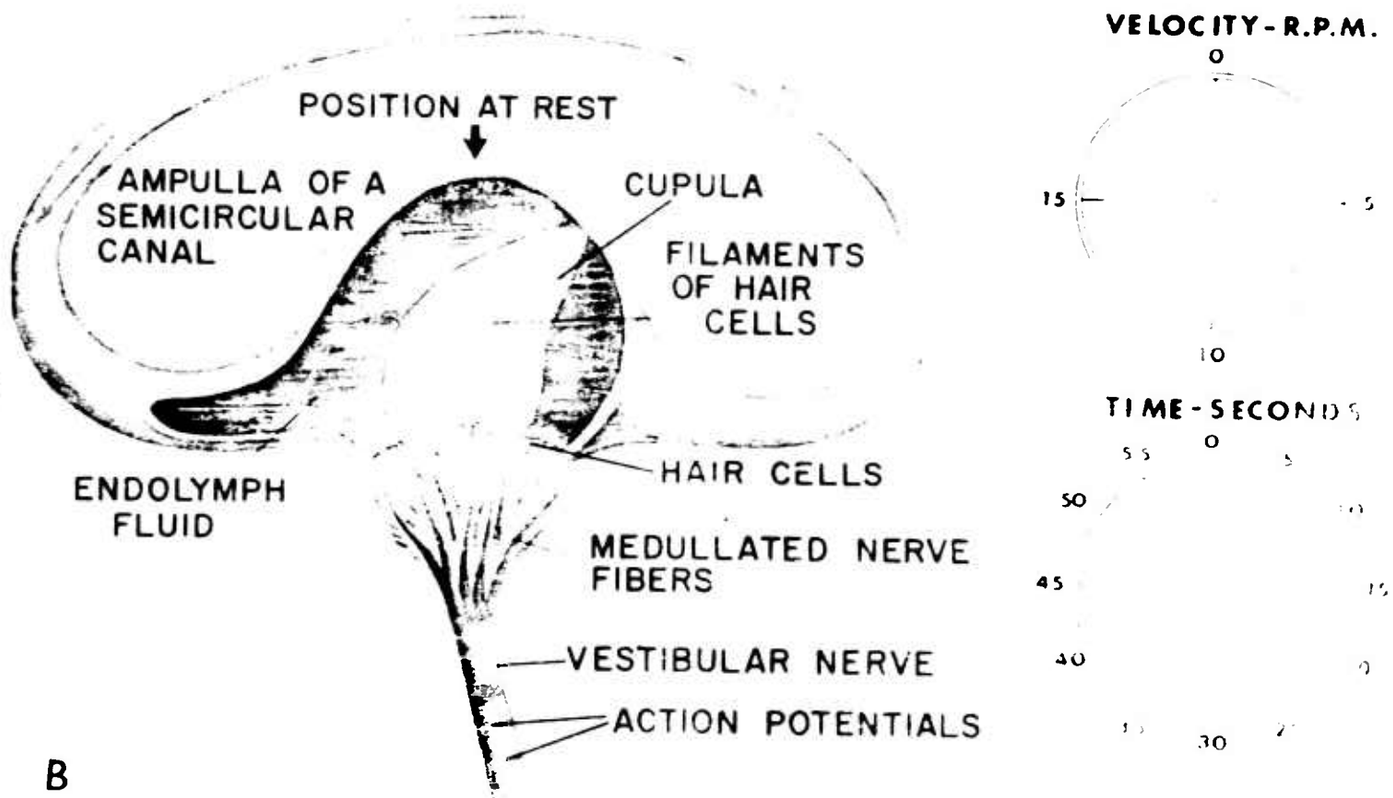
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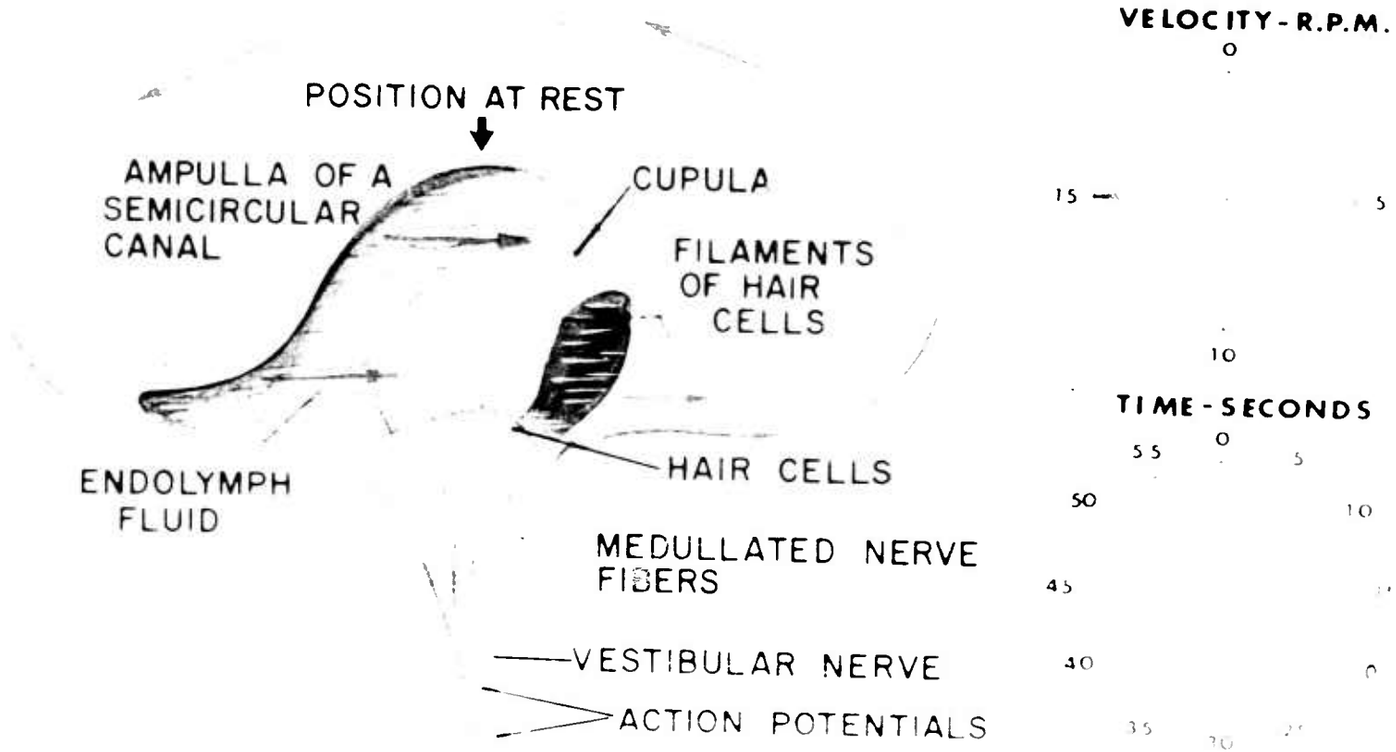
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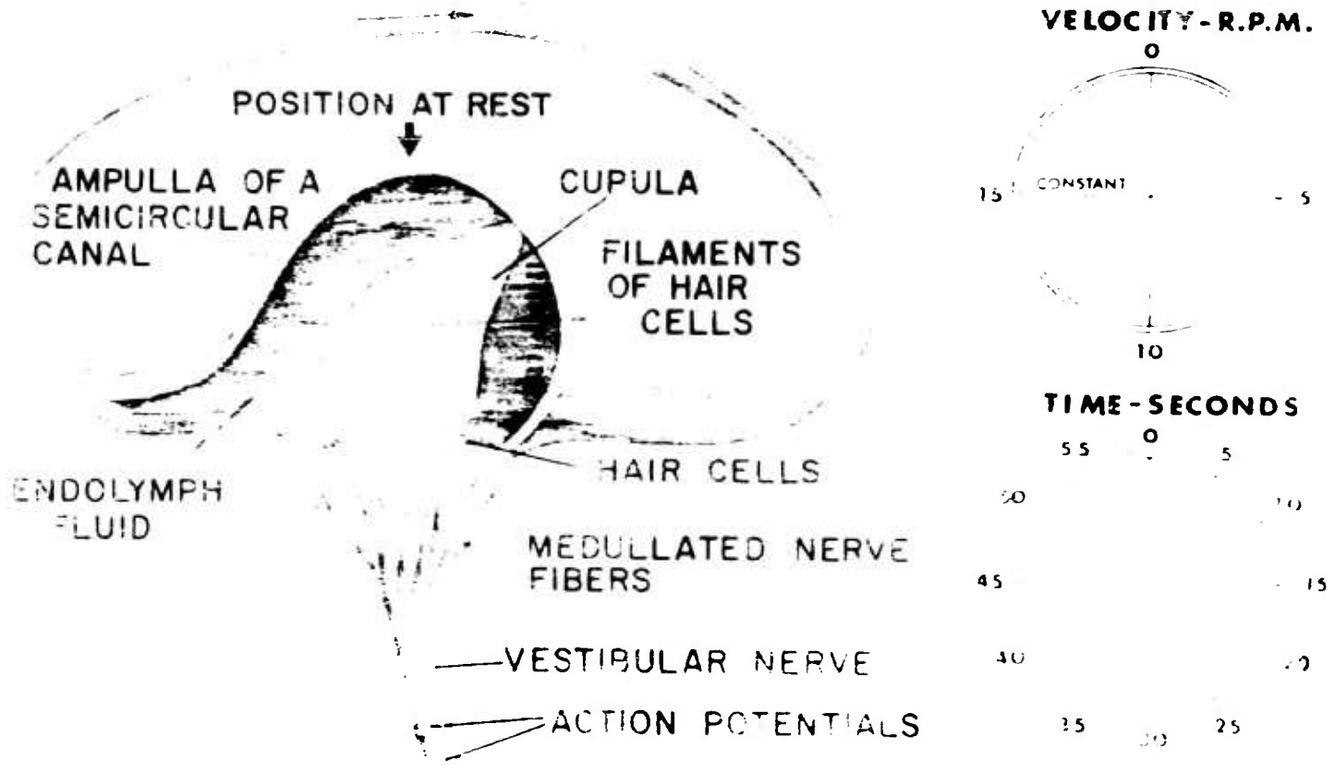
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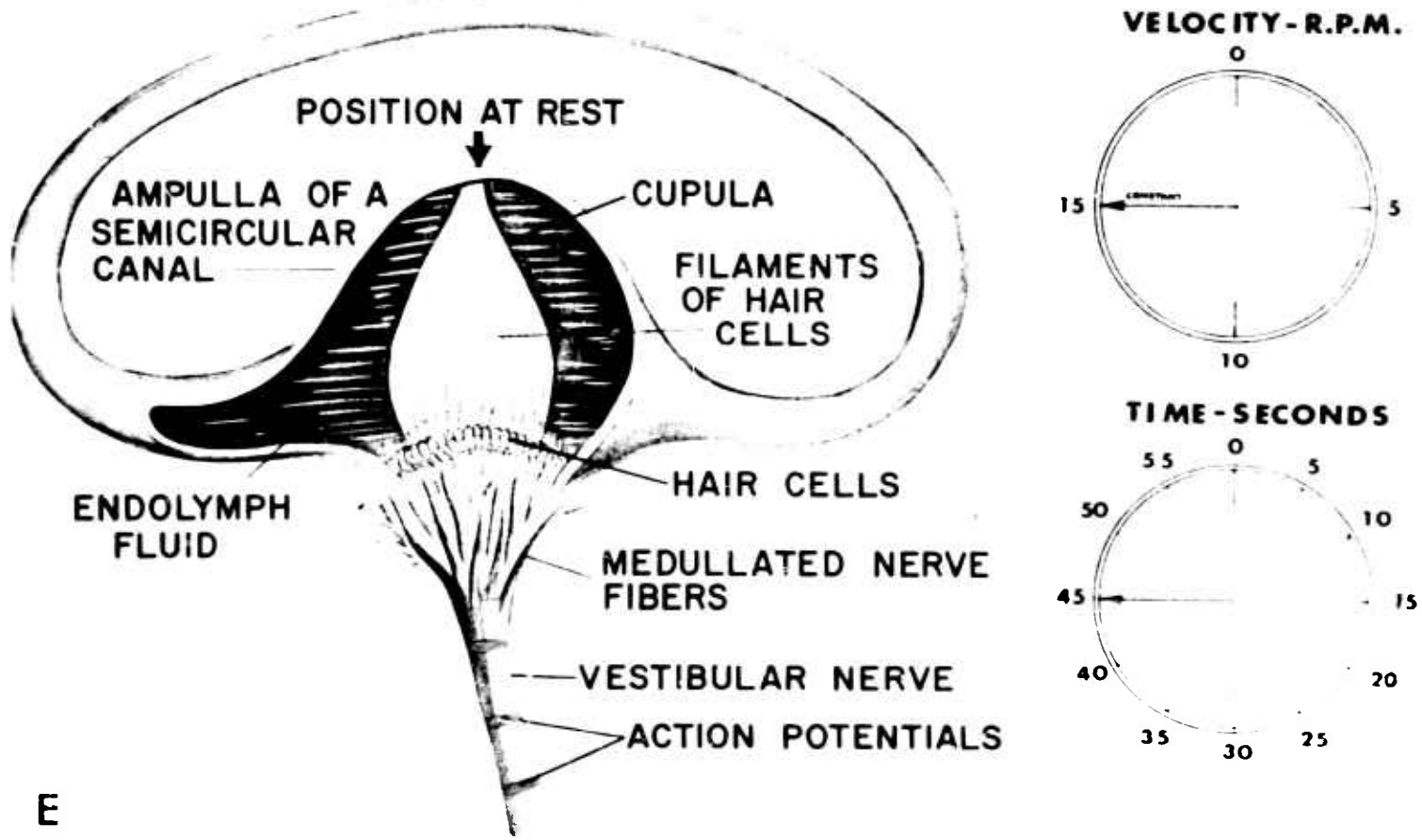
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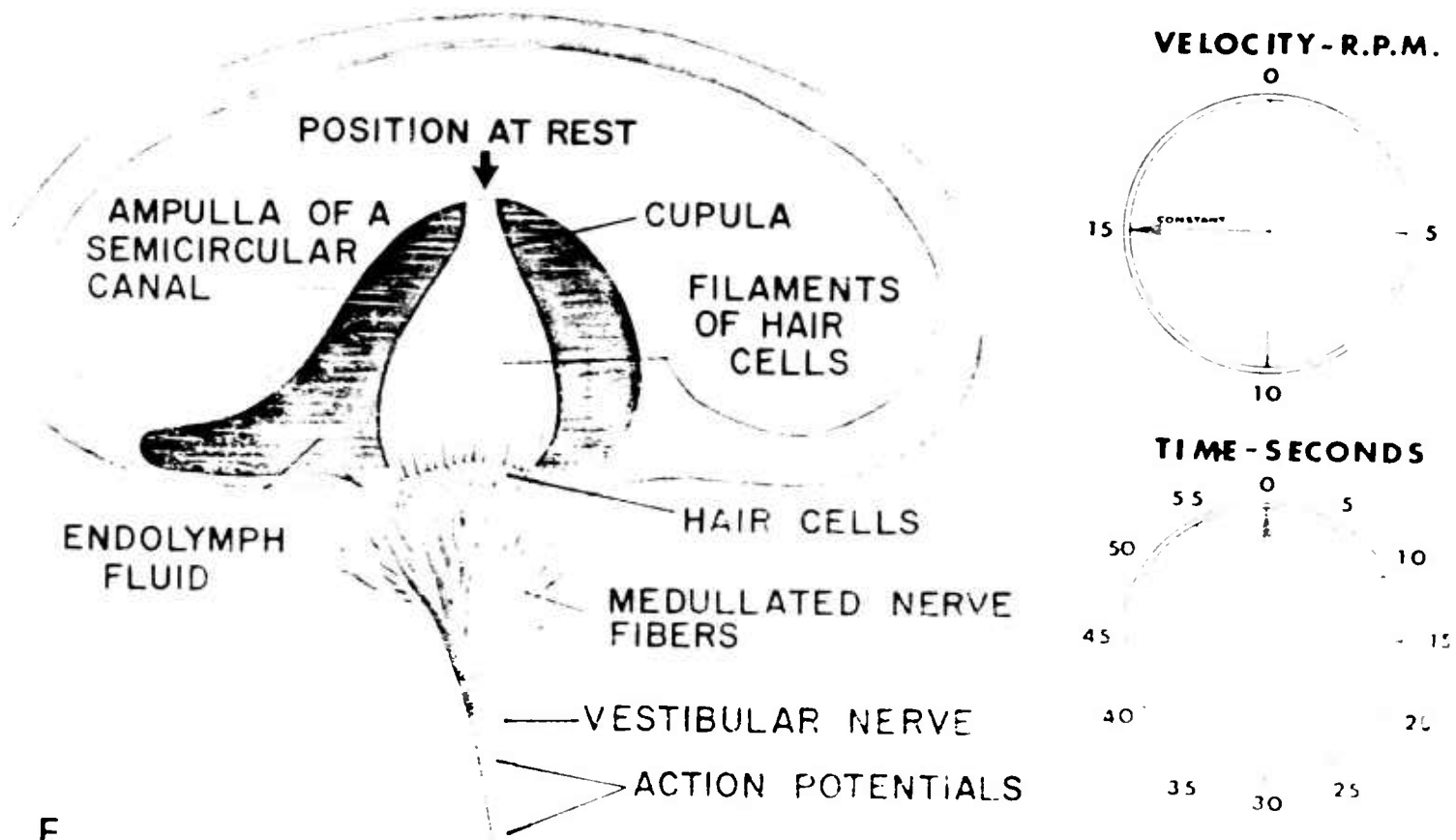
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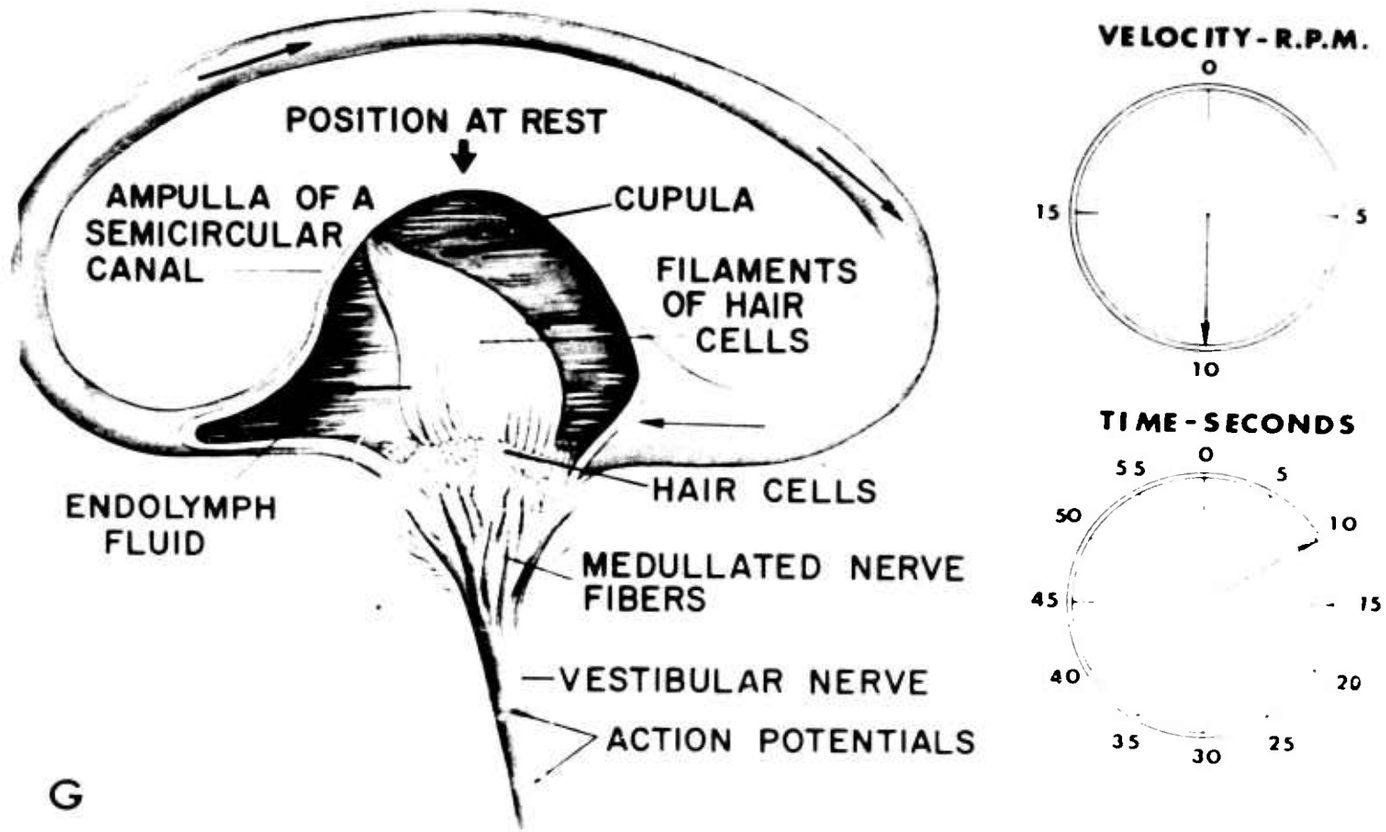
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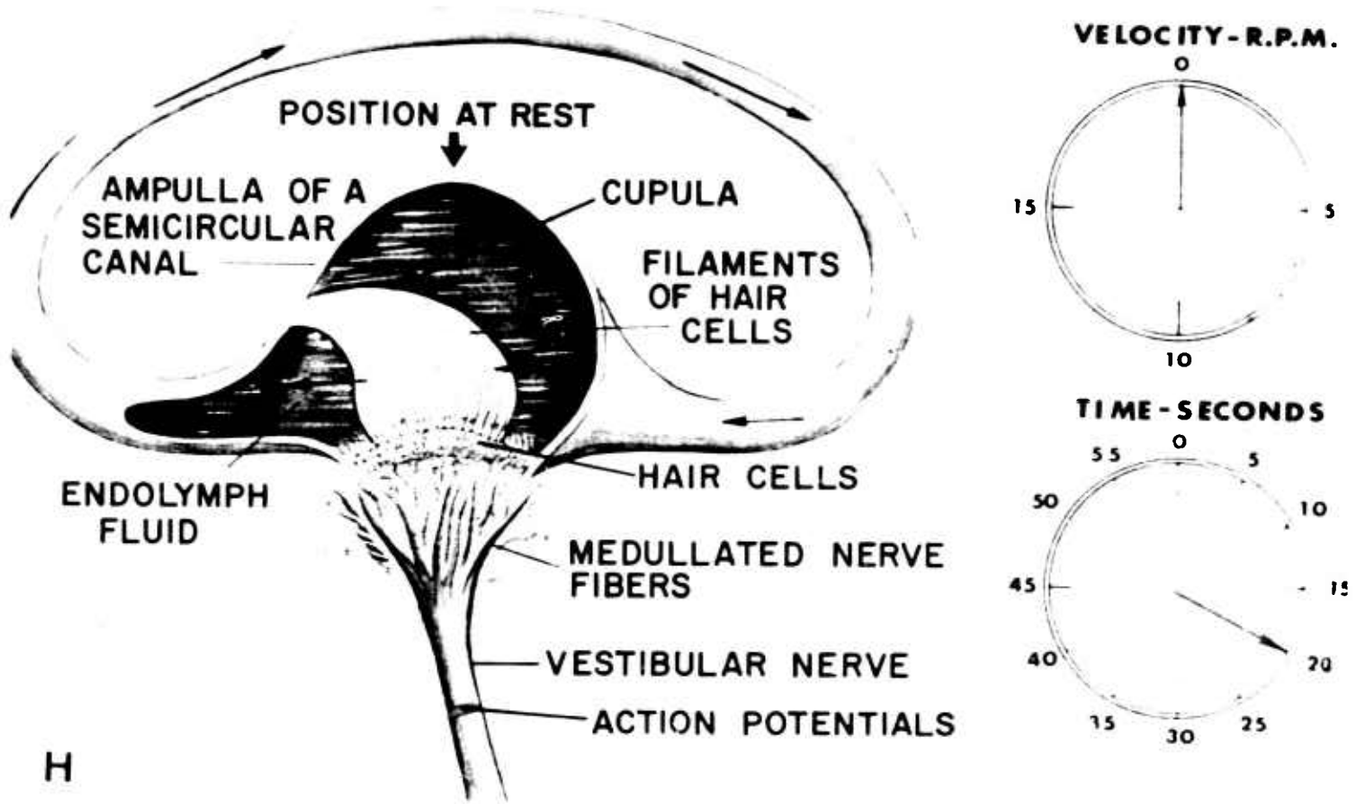
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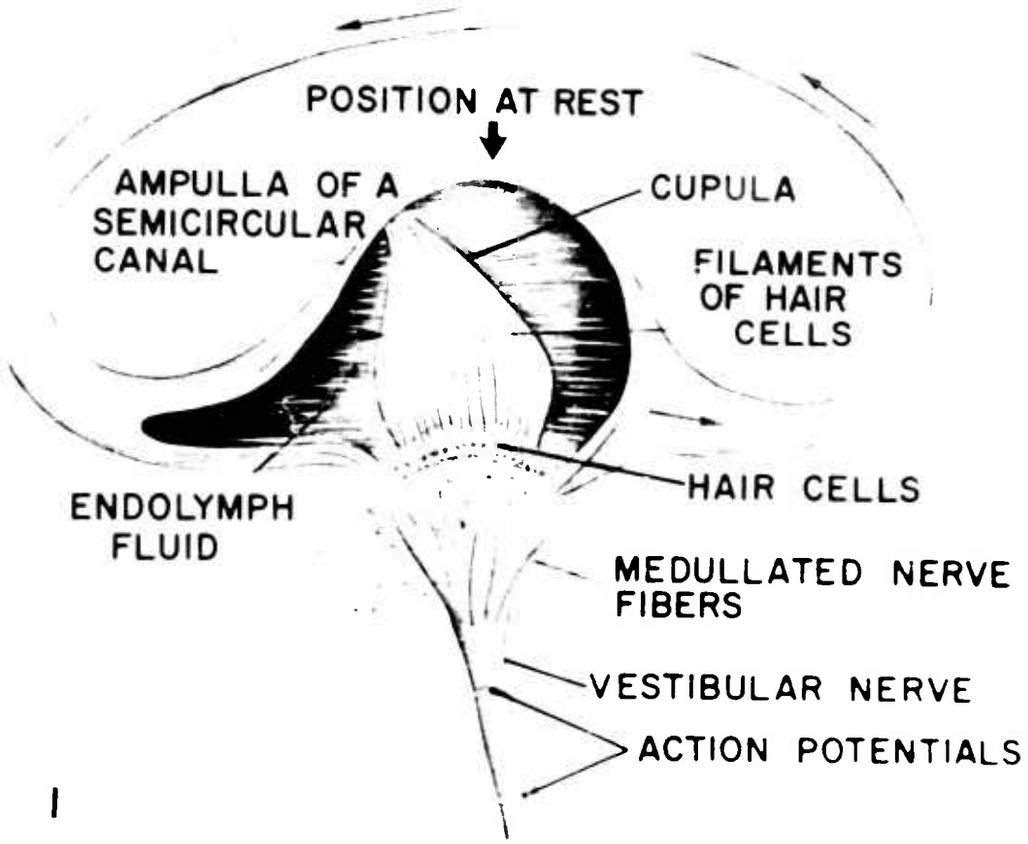
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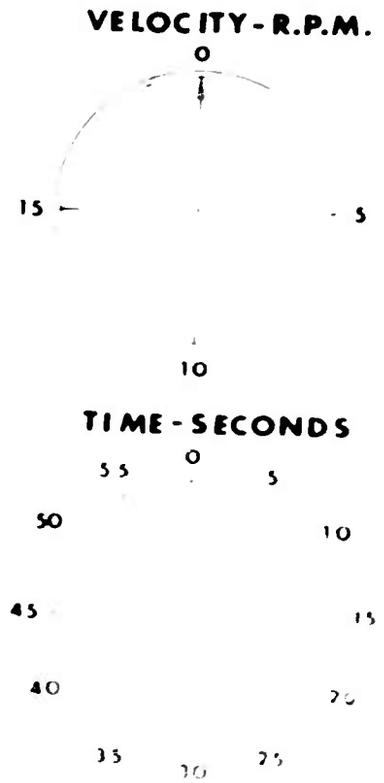
VESTIBULAR NERVE
ACTION POTENTIALS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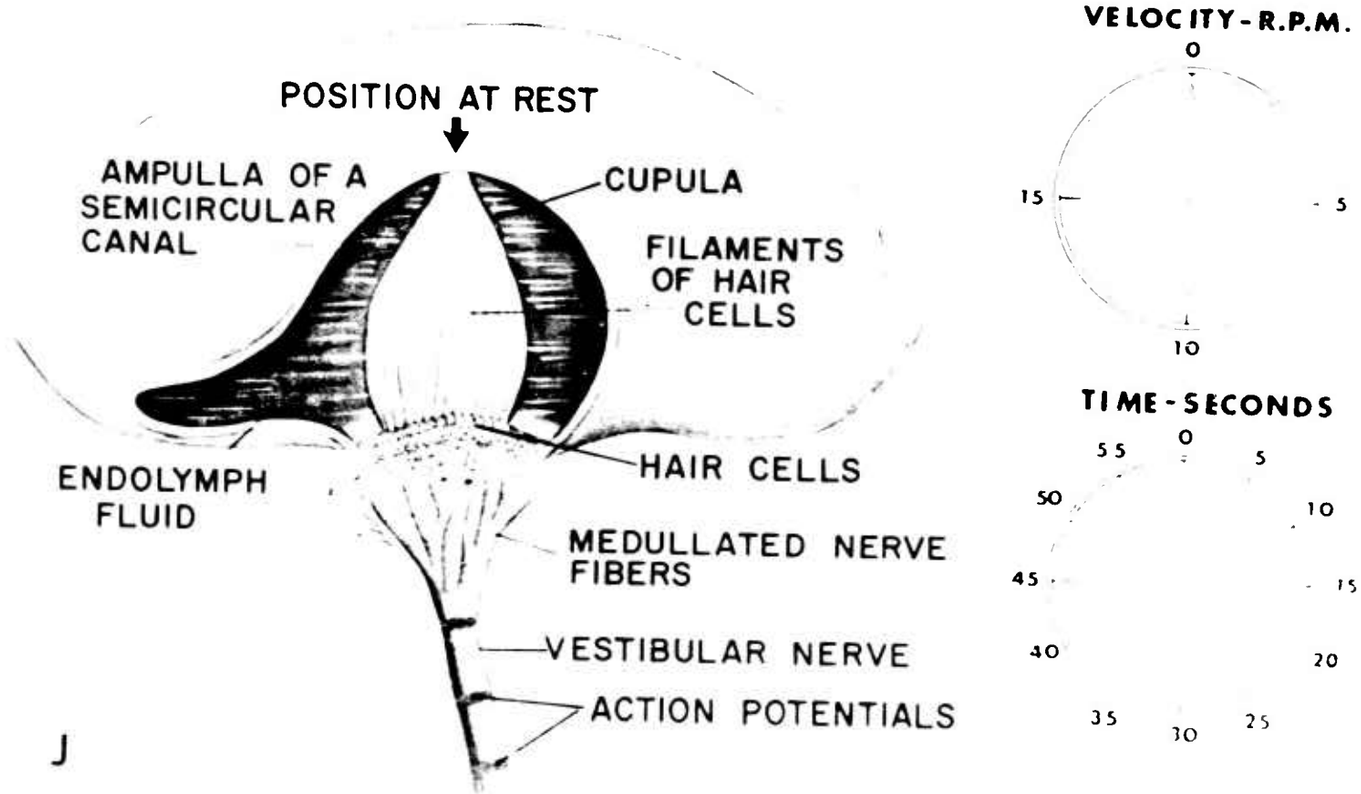
POSITION AT REST
AMPULLA OF A SEMICIRCULAR CANAL
CUPULA
FILAMENTS OF HAIR CELLS
ENDOLYMPH FLUID
HAIR CELLS
MEDULLATED NERVE FIBERS
VESTIBULAR NERVE
ACTION POTENTIALS
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under which Mulder's data were obtained). In real-life situations the threshold may vary considerably, depending upon the state of arousal or upon the motivations of the individual.

A specific type of angular acceleration that bears mentioning is vestibular Coriolis acceleration. The vestibular Coriolis effect results when one set of semicircular canals has equilibrated to a constant angular velocity (i.e., the endolymph has "come up to speed" with the canal walls), and a head motion is made in a plane other than the plane of the constant angular velocity. When a second set of canals (out of the plane of rotation, and unstimulated) is rotated into the plane of constant angular velocity, an angular acceleration is imposed upon the second set of canals. Simultaneously, an angular deceleration is imposed upon the first set of canals, as the first set is rotated out of the plane of constant angular velocity. Despite the fact that the sensation of motion generated by the canals is appropriate to the stimuli received by the canals, the stimuli that the canals receive during Coriolis accelerations are not truly representative of the angular motions undergone by the canals. By virtue of the fact that the endolymph has to absorb or dissipate angular momentum when moving into or out of a plane of rotation, which processes do not take place in the actual plane of motion because of the constraint placed upon the endolymph by the membranous canal walls, the plane of stimulation of the canals is different from either the plane of constant angular velocity or the plane of the inducing stimulus rotation (head motion). This results in a perception of motion occurring in a plane in which no read motion exists. If, for example, one is yawing (rotating about his vertical axis) in the clockwise direction at a constant angular velocity, and he pitches his head forward and downward so that his chin touches his chest, he will perceive (in addition to his pitching movement) that he is rolling (rotating about an anteroposterior horizontal axis) in the clockwise direction. Similarly, if one were to be pitching at a constant velocity, and he were to roll his head onto his left shoulder, he would get a sensation of yaw; the perception is in a plane other than the plane of motion of either the constant angular velocity or the inducing stimulus velocity. Three factors are important in the development of the vestibular Coriolis effect: (1) ω_1, the angular velocity of the constantly rotating system; (2) ω_2, the angular velocity of the

movement into the plane of the rotating system; and (3) t, the time over which ω_2 acts.

$$\text{Coriolis effect} \sim \omega_1 \omega_2 t$$

states the relationship between the intensity of the vestibular Coriolis effect and the parameters responsible for its development. ω_1 can be as low as 0.1 revolution per minute (0.6 degree per second) for perception of the vestibular Coriolis effect. At high values of ω_1 (e.g., 40 r.p.m.) the slight head motions concomitant with breathing can result in a Coriolis effect.

You have probably heard the term *nystagmus* used in other discussions of vestibular function. Nystagmus is a sweeping motion of the eyes in the direction opposite the direction of an imposed angular acceleration, followed by a quick return of the eyes to the center position, with oscillatory repetition of the sweep and return, resulting in an apparent jerking of the eyes in the direction of angular motion (fig. 12). The amount of nystagmus developed is directly related to the amount of deflection of the cupulae in the semicircular canals in the plane of rotation: nystagmus is, therefore, caused by angular acceleration. Postrotatory nystagmus can easily be seen when a subject is placed in a rotating chair, and then after having been spun at a constant angular velocity for 20 or 30 seconds, he is brought suddenly to a stop. In this example, as always, the slow component of the nystagmus will be in a direction opposite the angular acceleration (in the same direction as the deceleration) and the quick component will be in the same direction as the acceleration. Nystagmus is an exaggeration of the physiologic compensatory eye movements (concomitant with angular accelerations) that serve to help keep an area of fixation upon the retina while the head is being subjected to angular motion. As might be expected, nystagmus can be horizont ' vertical, or rotary, depending upon the plane in which the angul acceleration acts. In general, the nystagmus is in the same p e as the plane of angular motion; nystagmus secondary to vestibular Coriolis stimulation, however, is not in the plane of either of the stimulating motions but is instead in the plane of the created sensation of angular motion.

There are compensatory eye movements generated by stimulation of the otolith organs, as well. When the head is tilted to the left, for example, the eyes rotate slightly counterclockwise

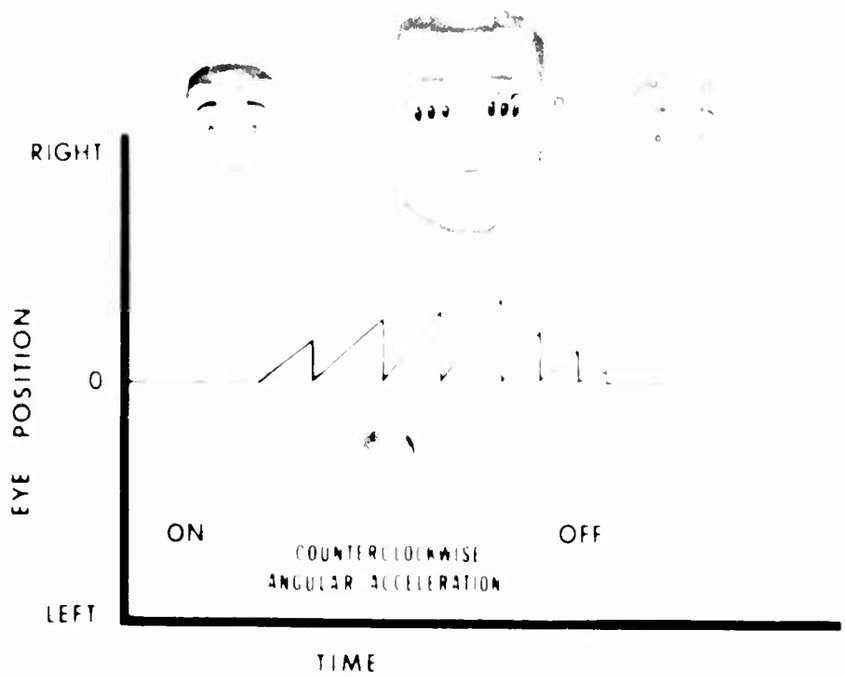

FIGURE 12

Vestibular nystagmus. During and immediately after the application of an angular acceleration the eyes will oscillate in approximately the pattern shown. Nystagmus is an exaggeration of the compensatory vestibulo-ocular reflex that serves to stabilize an image on the retina during angular motion.

(from an observer's viewpoint) and remain there as long as the head is in its new position. This compensatory motion of the eyes about their visual (anteroposterior) axes secondary to a change in the relative direction of the gravity vector is known as ocular counterrolling (fig. 13). Counterrolling is to the otolith organs what nystagmus is to the semicircular canals; i.e., each of these reflexes can be measured objectively as an indication of the state of function of the responsible end-organ system. The otolith organs also cause compensatory downward, upward, and probably sideward deviations of the eyes when the head is subjected to increased vertical g loading, decreased or negative vertical g loading, and lateral linear accelerations, respectively. This unnamed vestibulo-ocular reflex serves to keep the retinal image stabilized while the head is undergoing movement, just as do nystagmus and counterrolling.

We have discussed the physiology of the vestibular system as though it were a very simple electrical circuit in which any stimulus of a certain direction and magnitude always requires a certain characteristic response. Such is not the case, for the vestibular system as a whole is really quite subject to modifying influences. It is true that the physical characteristics of the semicircular canals and otolith organs do not change, and that there is a constant mathematical relationship between stimulus strength and the physical events in the end-organs (between amount of angular acceleration and cupular deviation; between linear acceleration and otolithic membrane position); nevertheless, a given stimulus

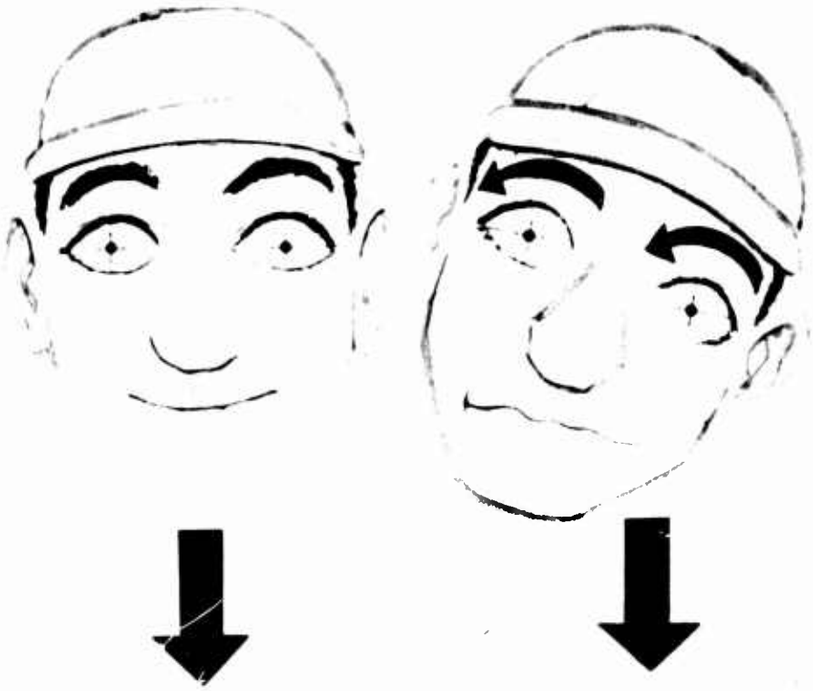

FIGURE 13

Ocular counterrolling. As the head is tilted (as the direction of the gravity vector changes with respect to the head), the eyes tend to rotate about the visual axes as shown. This and other vestibulo-ocular reflexes of otolith-organ origin serve to preserve visual acuity by stabilizing the retinal image during changes in direction and magnitude of linear accelerations applied to the head.

strength does not always result in the same perception of motion or the same vestibulo-ocular reflex. With repeated exposure to vestibular stimulation of various types, one can develop a relative insensitivity to the stimuli, as manifested by decreased or absent subjective and objective effects. Some figure skaters, for instance, can decelerate from a spin of 7 revolutions per second to a full stop in about 1 second (over 2000 sec.$^{-2}$), and have no dizziness or nystagmus. Fighter pilots show similar response decrements so long as they fly frequently and thus maintain "flying trim." Despite the apparent hypofunction of the vestibular system in such people, they are nevertheless perfectly able to pass vestibular tests requiring very sensitive monitoring by the end-organs and nervous system. All this suggests that the vestibular system, like the auditory and other sensory systems, is capable of a certain amount of autoregulation. This autoregulation allows the central nervous system to perceive what is deemed important to the organism, while refusing admittance to sensory information which is repetitive, irrelevant, or inconsequential. The vestibular efferent system, mentioned earlier, has been suggested as being important in the autoregulation process, and there are undoubtedly many other mechanisms which come into play to result in the vestibular response-shaping phenomenon known as vestibular "habituation" or "suppression."

REVIEW OF PROPRIOCEPTIVE FUNCTION

Anatomy and physiology

Proprioception is the sensory process which enables one to determine his body position and movement in space. It includes, strictly speaking, the vestibular, subcutaneous, and kinesthetic sensors. Vestibular function has already been discussed at length: this section, therefore, deals only with subcutaneous and kinesthetic sensation.

The subcutaneous receptors which are of major importance in proprioceptive function are the Pacinian corpuscles (fig. 14A). These tiny laminated ovoids are buried deep in many body structures, including the dermis, joints, and mesentery. They respond to pressure applied over their surfaces, but the exact method by which they transduce this pressure into neural impulses is unknown. The sensations they elicit when stimulated are the feelings of pressing one experiences on his seat when he sits, on his feet

when he stands, on his hands when he lifts something heavy, or on his head when he wears a tight hat. This is the so-called "seat-of-the-pants" sense referred to in flying, so named because a pilot can determine from the Pacinian corpuscles in the subcutaneous tissue of his buttocks and other body areas the direction and intensity of the resultant linear acceleration vector acting upon his body.

The kinesthetic sense, or "muscle sense of position" as it is sometimes inadequately labeled, is supplied by four different sensory end-organ types: the neuromuscular spindle, the Golgi tendon organ, and the joint receptors (2 types).

The neuromuscular spindles are rather complex structures, 1 to 3 millimeters long, which are distributed throughout the

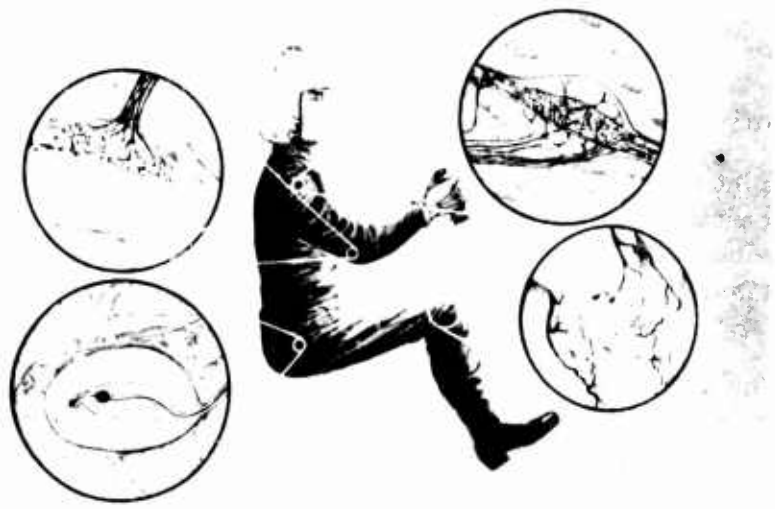

FIGURE 14

Subcutaneous and kinesthetic sensors.

A. *Pacinian corpuscle.*
B. *Neuromuscular spindle.*
C. *Golgi tendon organ.*
D. *Joint receptors.*

muscles of the body and serve to inform the central nervous system about the state of stretch of muscle masses (fig. 14B). When a muscle contracts, the included neuromuscular spindles relax, and the nerve impulses originating from those spindles decrease in frequency; simultaneously, the antagonist muscle and its spindles are being stretched, with the result that an increase in neural impulses comes from the stretched antagonist spindles. This is not the whole story of the neuromuscular spindles, however. The ends of each spindle apparatus are comprised of small muscle fibers which, when contracted, stretch the central (sensory) portion of the spindle and cause the spindle to generate sensory nerve impulses. These small muscle fibers are supplied by efferent nerve fibers which, some authors believe, are activated by vestibular stimulation, and are thus extremely important in the generation of postural reflexes.

The Golgi tendon organs are small nerve-ending complexes found in tendons near their attachments to the muscle fibers (fig. 14C). They, too, are responsive to stretch (tension); but, unlike the neuromuscular spindles, they generate more rather than fewer neural impulses when their associated muscle mass contracts.

Joint receptors are of two types: the "spray" type, a branching network arising from a single axon; and the lamellated type, which resembles a small, elongated Pacinian corpuscle. They are both abundantly situated in the fibrous layer of the joint capsule, and appear to indicate position and movement of the joint (fig. 14D).

The kinesthetic sense does not generally serve to orient one to his surroundings: its main purpose is to inform him of the relative motion and relative position of his body parts. The subcutaneous sense, on the other hand, is capable of informing one of his position in relation to the earth, if he is in contact with some earth-bound object. For this reason "proprioception" (meaning the subcutaneous and kinesthetic sensory systems) is usually included with vision and vestibular sense as a primary spatial orientation modality.

SPATIAL DISORIENTATION

One who does not correctly perceive his position, attitude, and motion relative to the earth is said to be spatially disoriented.

Obviously, a pilot is not expected to perceive firsthand his geographic position, attitude, heading, altitude, airspeed, rate of turn, and vertical velocity; but he does have instruments in the aircraft which will give him complete spatial orientation information, upon which he may accurately base his own percepts. The aircraft instruments are, after all, extensions of the pilot's own senses, and as long as he correctly interprets and uses his instruments when deprived of external visual references, he will remain spatially oriented. If, however, the pilot is unable to see, believe, interpret, and process the instrument information presented to him, he is then likely to develop spatial disorientation when conducive conditions prevail.

We will first discuss the fundamentals of instrument and formation flying; then we will categorize and analyze the types of sensory illusions that can compromise flying ability.

Instrument flying

There are three modes of flying: (1) by visual flight rules (VFR); (2) by instrument flight rules (IFR); and (3) in formation flight. When flying VFR, a pilot is required to prevent in-flight contact with other aircraft by continually being on the lookout for them and avoiding them. Bad weather, with concomitant poor visibility and low ceilings, often prevents the pilot from observing the visual flight rules. If he is qualified to fly in IFR weather conditions, he may file an IFR flight plan, and let the various air traffic control facilities on the ground direct his route of flight in such a way as to assure him of the fact that he will not occupy a given airspace simultaneously with another aircraft. In order to fly IFR, however, the pilot must be proficient in maintaining his exact orientation at all times, and must be able to control the aircraft very precisely so as to keep his altitude, heading, and velocity within very narrow limits. The basic processes employed in instrument flying are described in the following pages taken from AFM 51-37, "Instrument Flying."

CHAPTER 7

Attitude Instrument Flying

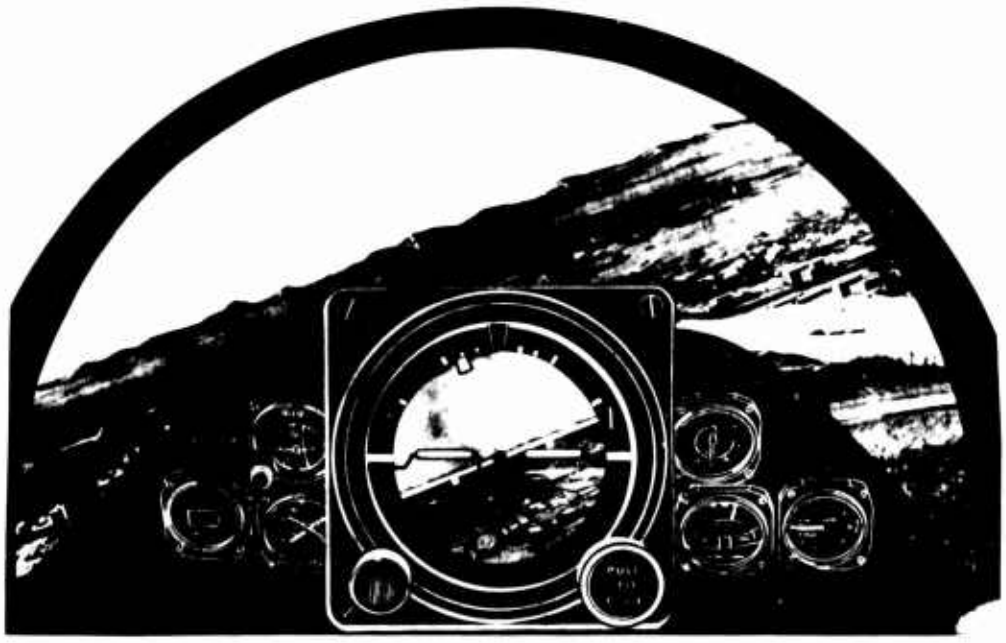

Figure 7-1. Attitude Instrument Flying

Aircraft performance is achieved by controlling the aircraft attitude and the thrust/drag relationship. Aircraft attitude is the relationship of the longitudinal and lateral axes to the earth's horizon. To determine this relationship during instrument flight, the pilot substitutes the horizon bar on the attitude indicator for the earth's horizon. Therefore, the attitude indicator is used to *control* aircraft attitude (pitch and bank).

In this manual the term *power* is used in place of the more technically correct term thrust/drag relationship. Power is controlled by reference to power indicators, e.g., manifold pressure, exhaust total pressure, exhaust pressure ratio gage(s), or tachometer(s). A proper combination of power control and attitude control will achieve the desired aircraft performance. Therefore, power and attitude indicators are termed *control instruments*. These instruments directly measure power and attitude and are calibrated to permit adjustments by definite amounts.

The performance of the aircraft is determined by reference to the altimeter, vertical velocity indicator, heading indicator, airspeed mach indicator, and the turn and slip indicator. This group of instruments is termed *performance instruments*. These instruments indicate the aircraft's performance regardless of whether the pilot is referring to the earth's horizon, the attitude indicator, or both, to control the aircraft's attitude.

Aircraft position is determined by a third group of instruments termed *navigational instruments*. This group of instruments includes various types of course indicators, range indicators, glide slope indicators, and bearing pointers. Since this chapter is concerned with basic aircraft control and not with the aircraft's position over the ground, *navigational instruments* are discussed in later chapters.

This chapter discusses the techniques and procedures for controlling aircraft attitude and power by reference to the control instruments. The techniques and procedures for accomplishing specific maneuvers are discussed in Chapter 8, Instrument Flight Maneuvers.

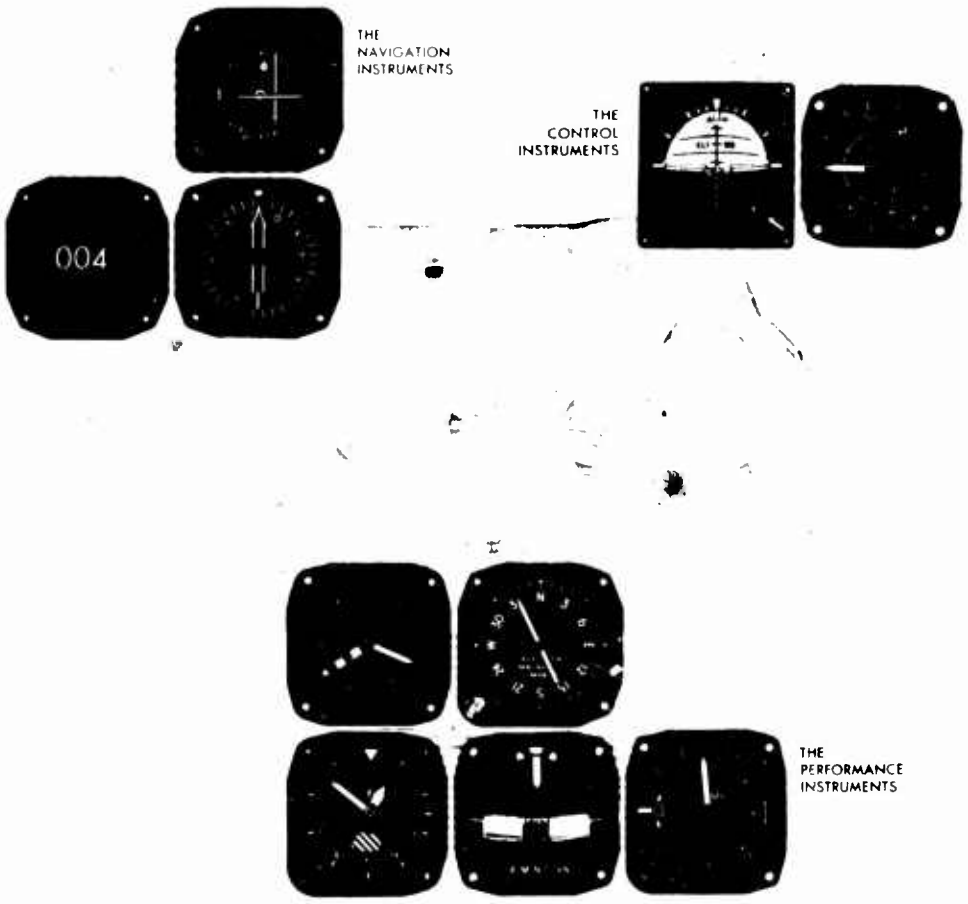

Figure 7-2. The Concept of Attitude Instrument Flying: Control-Performance-Navigation

Figure 7-3.
Pitch Attitude Indications

ATTITUDE CONTROL

Proper control of aircraft attitude is the result of maintaining a constant attitude, smoothly changing the attitude a definite amount, and knowing when and how much to change the attitude. Aircraft attitude control is accomplished by proper use of the attitude indicator. The attitude indicator provides an immediate, direct, and corresponding indication of any change in aircraft pitch or bank attitude. In addition, by means of the attitude indicator small pitch or bank changes are easily seen and changes of any magnitude can be readily accomplished.

Pitch Control

Pitch changes are accomplished by changing the "pitch attitude" of the miniature aircraft or fuselage dot definite amounts in relation to the horizon bar. These changes are referred to as bar widths, or fractions thereof, and/or degrees depending upon the type of attitude indicator.

Bank Control

Bank changes are accomplished by changing the "bank attitude" or bank pointer(s) definite amounts in relation to the bank scale. The bank scale is graduated at 0, 10, 20, 30, 60, and 90 degrees. This scale is located at the bottom of some attitude director indicators.

Figure 7-4.
Bank Attitude Indications

POWER CONTROL

Proper power control results from the ability to smoothly establish or maintain desired airspeeds in coordination with attitude control changes. Power changes are accomplished by throttle(s) adjustment and reference to the power indicators. Power indications are not affected by such factors as turbulence, improper trim, or inadvertent control pressures. Therefore, little attention is required to insure that the power indication remains constant, once it is established.

A pilot knows, from experience in an aircraft, approximately how far to move the throttle(s) to change the power a given amount for precise airspeed control. Therefore, he can make power changes primarily by throttle movement, giving a minimum of attention to the power instruments.

CROSS-CHECKING THE INSTRUMENTS

The basic concept of aircraft control requires the pilot to adjust the aircraft attitude and power to achieve the desired aircraft performance. Therefore, the pilot must be able to recognize *when* a change in attitude and/or power is required. By *cross-checking* the instruments properly, the pilot will know *when* to change the attitude and/or power.

Cross-checking is the proper division of attention and interpretation of the flight instruments. Attention must be efficiently divided between the control and performance instruments in a sequence that insures comprehensive coverage of the flight instruments. Looking at each of the instruments at the right time is of no value unless the pilot understands and evaluates what he sees. Therefore, *proper division of attention* and *interpretation* are the two essential parts of a cross-check.

Cross-check techniques or the sequence for checking the instruments vary among pilots and throughout various phases of flight. The pilot should become familiar with the factors to be considered in dividing his attention properly. He should also know the symptoms which enable him to recognize correct and incorrect cross-check technique.

Factors Influencing Cross-Check Technique

A factor influencing cross-check technique is the *characteristic manner in which instruments respond* to changes of attitude and/or power. The control instruments provide direct and immediate indications of attitude and/or power changes. Changes in the indications on the performance instruments will lag slightly behind changes of attitude and/or power. This lag is due to inertia of the aircraft and the operating principles and mechanisms of the performance instruments. Therefore, some lag must be accepted as an inherent factor. This factor will not appreciably affect the

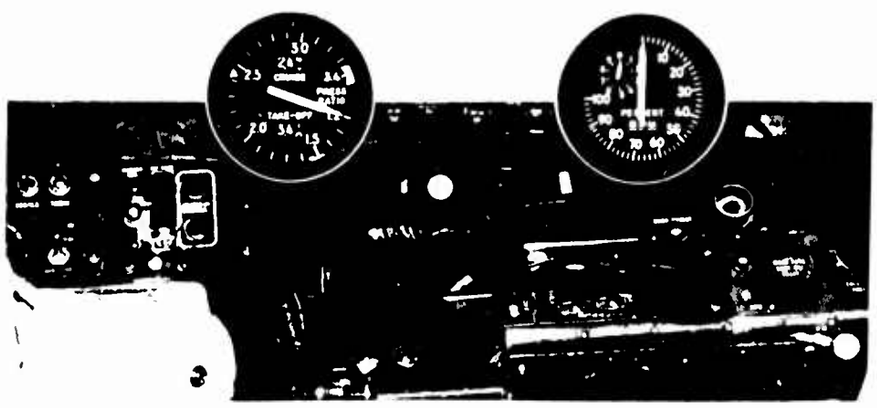

Figure 7-5. Power Changes can be Made Primarily by Throttle Movement

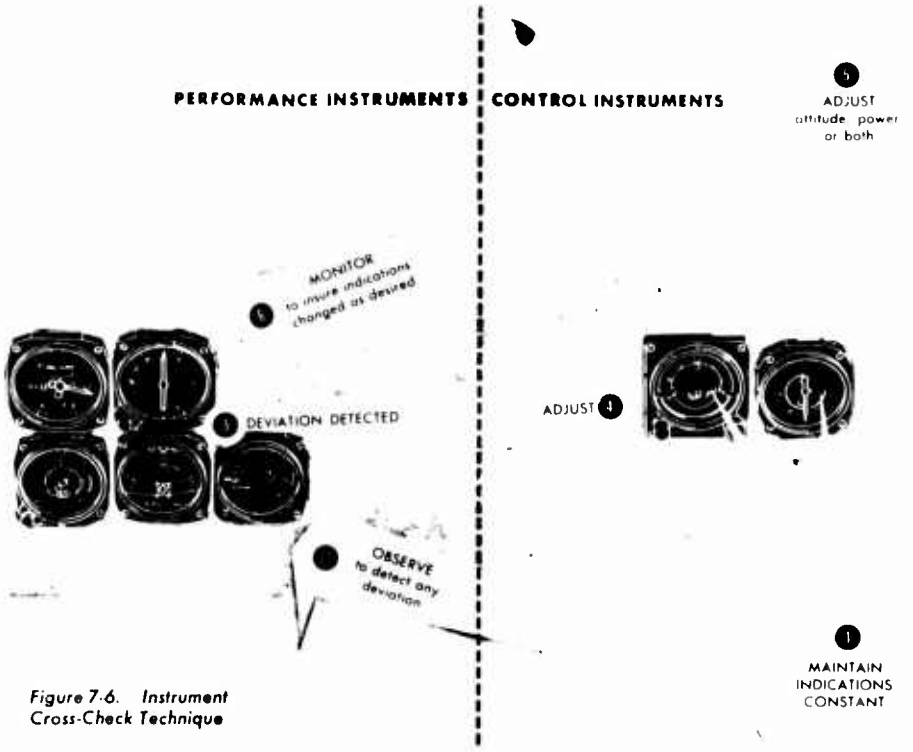

Figure 7-6. Instrument Cross-Check Technique

tolerances within which the pilot controls the aircraft; however, at times a slight unavoidable delay in knowing the results of attitude and/or power changes will occur.

Lag in the performance instruments should not interfere with maintaining or smoothly changing the attitude and/or power indications. When the attitude and power are properly controlled, the lag factor is negligible and the indications on the performance instruments will stabilize or change smoothly. The pilot must not be lured into making a flight control movement in direct response to the lag in the indications on the performance instruments without first referring to the control instruments. If permitted, such action invariably leads to erratic aircraft control and will cause additional fluctuations and lag in the performance instruments. Sufficient reference to the control instruments will minimize the effect of lag on the performance instruments, nullify the tendency to "chase" performance instrument indications, and result in smooth aircraft control.

Another factor influencing cross-check technique is the *location of the flight instruments*. In some aircraft the flight instruments are scattered over a wide area of the instrument panel. The pilot is unable to bring several instruments into his cross-check at the same time. He must rapidly scan each instrument individually back and forth across the instrument panel. More advanced instrument systems such as the flight director and integrated flight instrument systems have reduced the division of attention to a small area. The pilot can see more of the flight instruments with one look. The task of cross-checking the instruments is much easier because the pilot can simultaneously observe the attitude indicator and the proper performance instruments.

An important factor influencing cross-check technique is the *ability of the pilot*. All pilots do not interpret instrument presentations with the same speed. Some pilots are faster than others in understanding and evaluating what they see. One reason for this is that the natural ability of pilots

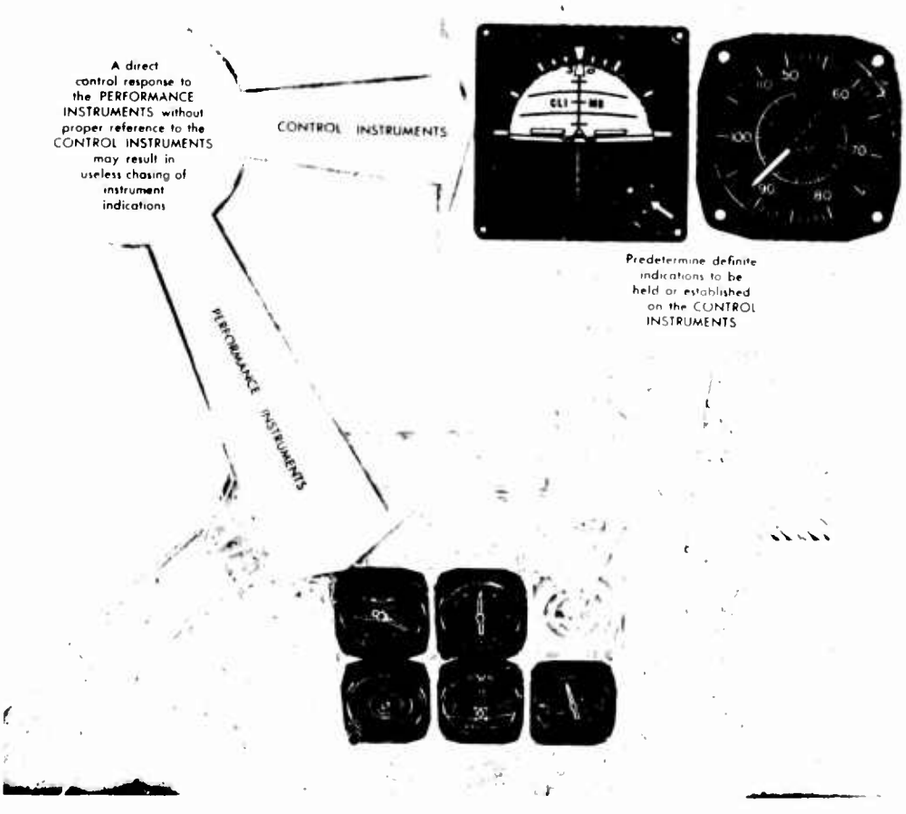

Figure 7-7. Factors Determining Cross-Check Technique

varies. Another reason is that the experience level of pilots differs. The pilot who is experienced and flies regularly will probably interpret his instruments more quickly than the inexperienced pilot who flies only occasionally. The pilot who interprets his instruments quickly and correctly does not have to refer back to them for information as often as the pilot who is slow to interpret. Also, he is able to bring several instruments into his cross-check with one glance, interpreting them simultaneously. Therefore, the speed in which he divides his attention does not have to be as rapid as the pilot with less ability, who must scan the instruments rapidly to stay ahead of the aircraft.

The attitude indicator is the only instrument which the pilot should observe continuously for any appreciable length of time. Approximately 10 seconds may be needed to accomplish an attitude change required for a normal turn. During this 10-second period, the pilot may need to devote his attention almost exclusively to the attitude indicator to insure good attitude control. The attitude indicator is also the instrument that he should observe the greatest number of times. This is shown by the following description of a normal cross-check. A pilot glances from the attitude indicator to a performance instrument, back to the attitude indicator, then a glance at another per-

formance instrument; back to the attitude indicator and so forth. This cross-check technique can be compared to a wagon wheel. The hub represents the attitude indicator and the spokes represent the performance instruments.

This example of a normal cross-check does not mean that it is the only method of cross-checking. Often a pilot must compare the indications of one performance instrument against another before knowing *when* or *how much* to change the attitude and/or power. An effective cross-check technique may require that attention to the attitude indicator be inserted between glances at the performance instruments being compared. Preponderance of attention to the attitude indicator is normal and desirable to keep the fluctuations and lag indications of the performance instruments to a minimum. This technique permits the pilot to read any one performance instrument during a split-second glance and results in smooth and precise aircraft control.

A proper and relative amount of attention must be given to each performance instrument. Pilots seldom fail to observe the one performance instrument whose indication is most important. The reverse is a common error. Pilots often devote so much attention to one performance instrument that the others are omitted from the cross-check. Also, they often fail to cross-check the attitude indicator for proper aircraft control.

Recognizing a Correct and Incorrect Cross-Check

A correct or incorrect cross-check can be recognized by analyzing certain symptoms of aircraft control. Symptoms of insufficient reference to the control instruments are readily recognizable. If the pilot does not have some definite attitude and power indications in mind that should be maintained or established and the other instruments fluctuate erratically through the desired indications, then the pilot is not referring sufficiently to the control instruments. This is usually accompanied by a lack of precise aircraft control ("chasing" the indications) and a feeling of ineffectiveness and insecurity by the pilot.

Sufficient reference to the attitude indicator can be easily determined. If the pilot has in mind definite pitch and bank attitudes that are to be held constant or changed, he is referring to the attitude indicator sufficiently.

Except for fixation on the power indicators, the problem of too much attention being devoted to the control instruments is rarely encountered. This is normally caused by the pilot's desire to maintain the performance indications within close tolerances. Too much attention to the control instruments can be recognized by the following symptoms. If the pilot has a smooth, positive, and continuous control over the indications of the control instruments but large deviations are observed to occur slowly on the performance instruments, a closer cross-check of the performance instruments is required.

An incorrect cross-check can result in the omission of or insufficient reference to one or more instruments during the scanning process. Pilots are inclined to omit some performance instrument(s) from the cross-check, although other performance instruments and the control instruments are being properly observed. For example, during a climb or descent, a pilot may become so engrossed with pitch attitude control that he fails to observe an error in aircraft heading.

The indications on some instruments are not as "eye-catching" as those on other instruments. For example, a 4-degree heading change is not as "eye-catching" as a 300 to 400 feet-per-minute change on the vertical velocity indicator. Through deliberate effort and proper habit, the pilot must insure that *all* the instruments are included in his cross-check. If this is accomplished, he should observe deviations on the performance instruments in their early stages.

Analysis of the cross-check technique will assist the pilot in recognizing a correct or incorrect cross-check. A correct cross-check results in the continuous interpretation of the flight instruments which enables the pilot to maintain proper aircraft control at all times. Remember, rapidly looking from one instrument to another without interpretation is of no value. Instrument systems and the location of the flight instruments vary. Pilot ability also varies. Therefore, each pilot should develop his own rate and technique of checking the instruments which will insure a continuous and correct interpretation of the flight instruments.

CHANGING ATTITUDE AND POWER INDICATIONS

As previously stated, the basic concept of aircraft control requires the adjustment of aircraft attitude and power to achieve desired performance. By cross-checking the performance instru-

ments properly, the pilot knows when to change the attitude and/or power. A change of aircraft attitude and/or power is required when any indication other than that desired is observed on the performance instruments. However, it is equally important for the pilot to know *what* and *how much* pitch, bank, or power change is required.

What to Change

The pilot knows *what to change* by understanding which control instrument to adjust to achieve the desired indications on the performance instruments. Pitch attitude control is used primarily to maintain an altitude or to control the rate of climb or descent. Pitch attitude control may be used to maintain airspeed during maneuvers requiring a fixed power setting. Bank attitude control is used to maintain a heading or a desired angle of bank during turns. Power control is used for maintaining or changing the airspeed except for maneuvers using a fixed power setting; for example, full power for a prolonged climb.

How Much to Change

How much to change the attitude and/or power is, initially, an estimate based on familiarity with the aircraft and the amount the pilot desires to change the indications on the performance instruments. After making a change of attitude and/or power, he should observe the performance instruments to see if the desired change occurred. If not, further adjustment of attitude and/or power is required. Therefore, instrument flight is a continuous process of cross-checking the performance instruments and adjusting the control instruments.

TRIM TECHNIQUE

The aircraft is correctly trimmed when it is maintaining a desired attitude with all control pressures neutralized. Proper trim technique is essential for smooth and precise aircraft control during all phases of flight. By relieving all control pressures, the pilot will find that it is much easier

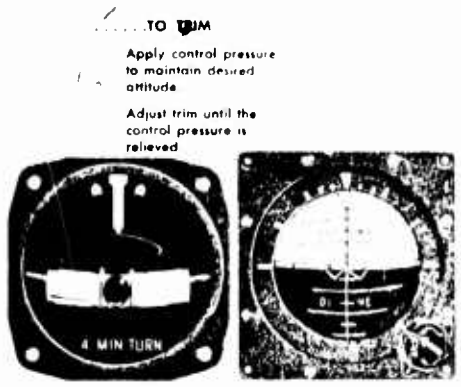

Figure 7-8. Trim Technique

to hold a given attitude constant. Also, more attention can be devoted to the navigation instruments and additional cockpit duties.

An aircraft is placed in trim by applying control pressure(s) to establish a desired attitude and then adjusting the trim so that the aircraft will maintain that attitude when the flight controls are released. The aircraft should be trimmed for coordinated flight by centering the ball of the turn and slip indicator. This is accomplished by using rudder trim in the direction the ball is displaced from center. Differential power control on multi-engine aircraft is an additional factor affecting coordinated flight. Balanced power/thrust should be used, when possible, to aid in maintaining coordinated flight.

Changes in attitude, power, or configuration may require a trim adjustment. Independent use of trim to establish a change in aircraft attitude invariably leads to erratic aircraft control. Smooth and precise attitude changes are best attained by a combination of control pressures and trim adjustments. The trim controls, correctly used, are aids to smooth aircraft control.

Formation flying

Formation flight, as far as a wingman is concerned, is neither VFR nor IFR, but involves the use of a special skill in following the lead aircraft. While in formation, the wingman must allow the lead aircraft (or tanker, as the case may be) to be his sole attitude reference source; his only job is to trust and follow the leader, which he does by watching the leader and making appropriate control movements as necessary to maintain the proper position with respect to the lead aircraft.

It is obvious that formation flying in weather or at night can completely deprive a pilot of any visual reference to the earth, because the lead aircraft does not function as an indicator of the horizon during turns, climbs, and dives, nor does the pilot have much time to be looking at his own instruments during formation flight.

Causes of spatial disorientation

There are vestibular and nonvestibular causes of spatial disorientation. We shall deal with the vestibular causes first.

The vestibular system is well-suited for "routine ground operations" like turning the head, walking, running, jumping, falling, etc.; but for flying it is inadequate. This is because the frequency response of the semicircular canals is inappropriate under the conditions of angular acceleration prevalent in flight, and because the otolith organs cannot distinguish between the force of gravity and other linear accelerations acting upon the flyer. The vestibular system thus makes errors, and these errors can result in spatial disorientation.

(The terms *vertigo* and *pilot vertigo* are, in flying parlance, essentially synonymous with spatial disorientation. Although medical usage of the word vertigo usually connotes sensations of actual spinning, most pilots do not require that vertigo mean anything other than confusion regarding one's spatial orientation, even though spinning sensations often occur during episodes of spatial disorientation.)

The trouble with the semicircular canals is that, in flight, they allow certain angular motions to remain unperceived; yet they cause the perception of other angular motions which do not exist.

The most common form of spatial disorientation, the *leans*, results from the fact that some angular motions escape perception. If, for example, an aircraft is given an acceleration on the roll axis of 2.5°/sec.^{2} for $\frac{1}{2}$ second, a constant angular velocity roll of $1\frac{1}{4}$°/sec. results. According to Mulder's law, however, the angular motion will not be perceived, because the product of the angular acceleration and the duration of application of the acceleration did not exceed Mulder's constant of 2.5°/sec. If the plane continues its roll at the same rate for 30 seconds, the aircraft would be in a $37\frac{1}{2}$° bank at the end of this time without the pilot's being aware of it, provided he keeps the airplane in coordinated flight by applying rudder pressure. Once the bank error is observed on the attitude instrument, the pilot will apply control pressure to correct the attitude. If in his correction the pilot accelerates the airplane in the opposite direction at 25°/sec.^{2} for 1 second, the product of the acceleration and the time of application of acceleration is considerably greater than that required for threshold perception of angular motion, and, therefore, the pilot will perceive the roll correcting back to the vertical. Because of the fact that the original roll was not perceived, and the return roll was perceived, the pilot is forced to assume that he has rolled into a bank in the direction opposite that of the original bank, despite the fact that he is straight and level. If the pilot thinks he is in a bank in one direction, but the attitude indicator shows he is straight and level, he will do either of two things. Either he will roll the plane in the direction of the original roll until he thinks he is straight and level, or he will remain straight and level according to the attitude indicator, thus retaining his false perception of bank. If he does the latter—as is more desirable, of course—he will still feel compelled to align his body with the perceived vertical; and in doing so, the pilot actually leans in the direction of the original subthreshold roll (fig. 15).

The leans can be generated in the opposite way as well. If an aircraft is rolled in one direction by turbulence in a suprathreshold way, and the pilot corrects the change of attitude very slowly and smoothly, he may be in a situation where a subthreshold correction has followed a suprathreshold perturbation, and the pilot's semicircular canals have "recorded" angular motion in one direction only. In this case the pilot will perceive the vertical to be in a direction opposite the direction of the original perturbation; and

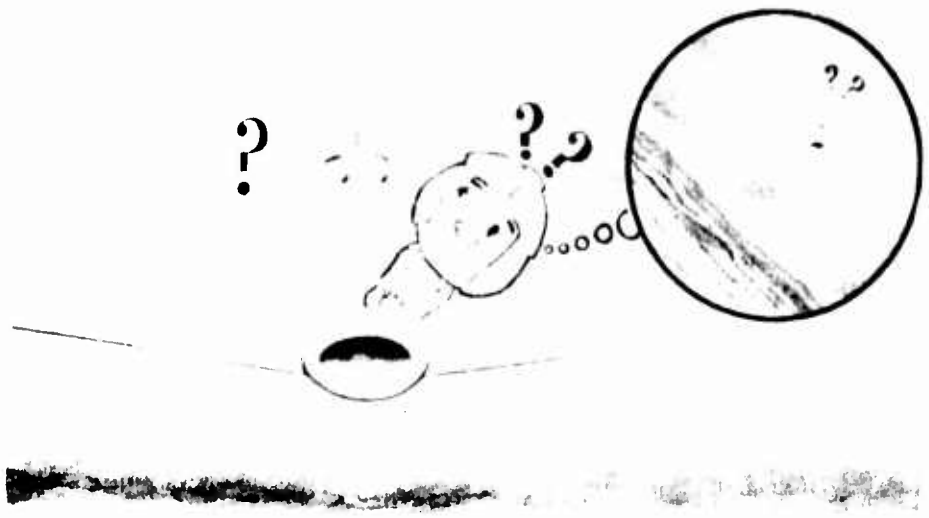

FIGURE 15

The leans. In this case the pilot is able to control the aircraft attitude by reference to instruments, even though his perception of the horizontal is false. He is leaning in an attempt to align himself with the perceived vertical.

after completing his correction, he will still be anxious to roll the plane to align with his perceived upright, despite the fact that the attitude indicator indicates straight and level. Under these circumstances the pilot will be inclined to lean in the direction opposite the original roll.

We have spoken about Mulder's constant as though it were the magic number which must be exceeded for perception of angular motion (in this case, perception of roll) to occur: this does not appear to be the exact truth of the matter. We know that the threshold of perception of angular accelerations is raised considerably by such things as vibrations, noise, inattention, etc.; and it is highly probable that angular accelerations of much greater

magnitude than that used in our illustration of the leans go unperceived under actual flight conditions. It is also probable that the threshold for a given individual fluctuates according to the individual's need to receive vestibular information. If, for example, a pilot is jarred into a state of anxiety about his attitude by unusual turbulence, he will probably reflexly lower his vestibular threshold in an attempt to monitor orientation information more critically. In doing so during a series of turns, he would be likely to generate false impressions about his attitude by virtue of his monitoring like stimuli in unlike ways.

Two other illusions which result from the inability of the semicircular canals to perceive all angular motions all the time are the *graveyard spin* and the *graveyard spiral.*

As stated previously, the semicircular canals monitor angular accelerations to give angular velocity information. They do not perceive angular velocity per se. When a pilot gets into a spin, he undergoes an initial angular acceleration, and perceives the angular motion of the spin for a short while following the cessation of angular acceleration. After this short while (usually about 20 seconds), the fluid in the pilot's semicircular canals in the plane of rotation "comes up to speed" with the surrounding canal walls; and the cupula returns to its resting position, despite the continuation of the angular motion. In other words, the semicircular canals have equilibrated to the rotating motion, and no motion is perceived. If the pilot then makes the proper control maneuver to stop the spin, he will undergo an angular deceleration which will be monitored by his semicircular canals; and his central nervous system will interpret his sensations as representing a spin in the opposite direction. Even though his instruments are telling him that he is not spinning, he nevertheless has the sensation of spinning; and, if deprived of external visual reference, he will be tempted to make a control correction so that he spins in the direction of the original angular motion. This eventuality is known as the graveyard spin (fig. 16).

The graveyard spiral is similar to the graveyard spin in that the semicircular canals equilibrate to a constant angular velocity and, therefore, persisting rotary motion goes unperceived. In the graveyard spiral, however, the angular velocity is in the form of

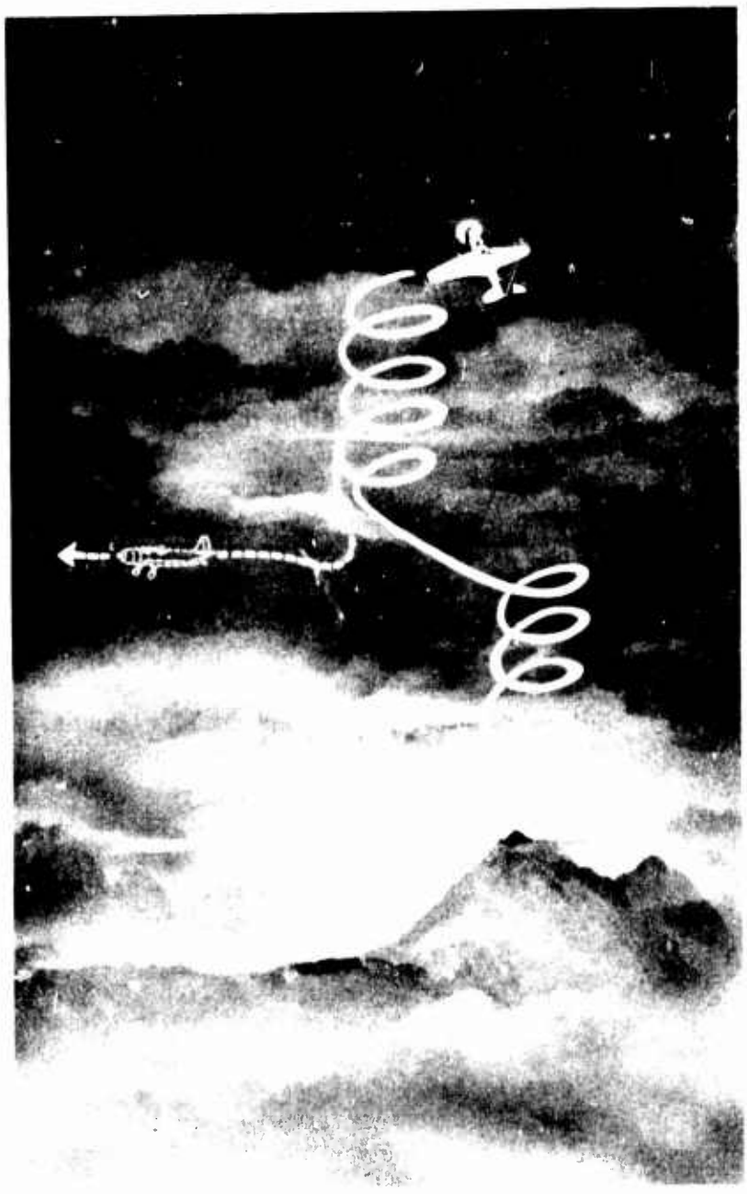

FIGURE 16

The graveyard spin. In recovering from a prolonged spin, this pilot perceives the start of a spin the opposite direction. (The dotted line indicates perceived motion; the solid line shows actual motion.) Correcting for this impression, he goes into another spin in the original direction.

a coordinated banked turn, rather than a spin. If an inexperienced pilot remains in a constant-rate coordinated turn for a period of time (long enough for his semicircular canals to equilibrate), he will then lose the sensation of turning. The novice, noting the decrease in altitude (caused by the decrease in lift resulting from the banking of the aircraft), may pull back on the stick and perhaps add power in an attempt to gain back the lost altitude. This maneuver only serves to tighten the spiral, unless he has the presence of mind to correct first the banked attitude of the aircraft. Once the spiral has started, the pilot will suffer an illusion of turning in the opposite direction if he tries to stop the turning motion of the aircraft. Under these circumstances he would not be likely to make the appropriate corrective action, and would probably continue tightening his spiral until he managed either to get a good outside visual reference or to make contact with the ground.

Another illusion that can occur when the semicircular canals equilibrate to a constant angular velocity is the *Coriolis illusion.* A discussion of the mechanics of the vestibular Coriolis effect was presented earlier, and it can easily be seen how such an effect could be generated in an aircraft. If a pilot is maneuvering his aircraft in a constant-rate turn (as in a penetration turn or holding pattern), he is, of course, undergoing a constant angular velocity. If he were to move his head up and down, side to side, or move it in any other plane of motion not in the plane of the turn of the aircraft, he would then experience the Coriolis illusion (fig. 17). The illusory motion is in a plane of rotation in which there is no actual angular motion, and a pilot trying to correct for an illusory motion of that nature is very likely to lose control of his aircraft. The Coriolis illusion is probably the most dangerous and devastating of the vestibular illusions, partly because of its overwhelming quality and partly because of the fact that it usually occurs in maneuvers which are close to the ground. A particularly bad situation is the one in which a pilot is making a penetration turn and is requested to make a radio frequency change, which action requires him to rotate his head to look for the frequency selector switch. This head movement often results in the generation of a sensation of roll, which, when corrected for at low altitude in a high-performance aircraft, is often fatal.

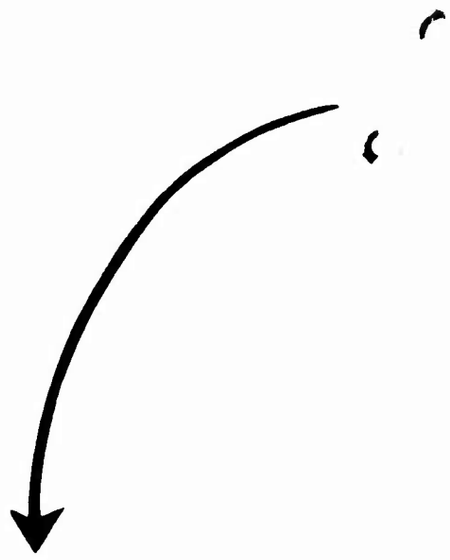

FIGURE 17

The Coriolis illusion. Depending upon how the pilot moves his head while in a prolonged turn, the vestibular Coriolis effect can cause several very surprising and overwhelming illusions of change in aircraft attitude. Attempting to "correct" his attitude while under the influence of a Coriolis illusion can lead a pilot to disaster.

The term *oculogyral illusion* (OGY) has been used to describe the apparent relative motion of an object in front of a person when the person and the object are together subjected to angular acceleration. Oculogyral illusions can be observed in the cockpit during Coriolis stimulation, spins, and the like. A similar phenomenon, the *audiogyral illusion*, occurs when a person and a sound source are together subjected to angular acceleration: the event observed in this case is the apparent motion of the sound source relative to the subject. The oculogyral and audiogyral illusions are, of course, caused by semicircular canal stimulation, but the exact mechanism of the development of the illusions is unknown.

The body is not equipped with sensors capable of informing the brain of all the different linear accelerations acting upon it. We have instead the utricle and saccule, which tell us the direction and magnitude of the resultant g vector. The false sensations that we get, because the otolith organs are unable to distinguish between the earth's gravity and other, superimposed, linear accelerations, are called *oculogravic illusions* (OGIs). On the ground, we expect the vertical direction (that is, "upward") to be in the direction opposite the direction of the 1-g gravity vector. In the air, however, the resultant g vector does not always point in the same direction as the gravity vector. For example: if a pilot accelerates a plane in the forward direction at the rate of 32 ft./sec.^{2} (980 cm./sec.^{2}), there would be a 1-g inertial vector pulling his otolithic membranes posteriorly; the 1-g gravity vector would combine with the 1-g inertial "force" vector to result in a 1.414-g resultant "gravity" vector pointing posteriorly and down, halfway between the vector representing the "pull" of gravity and the vector representing the inertial force resulting from the linear acceleration. The pilot, imagining "up" to be in the direction opposite that of the resultant vector, would then perceive the horizontal plane to be 45° down from the nose of the aircraft. If he were to correct for the apparent nose-up attitude of the aircraft, he would push the plane into the ground at an angle of 45°. The oculogravic illusion does not occur if adequate outside visual reference is available; but if the pilot is flying in weather or on a dark night, he is considerably more susceptible to the illusion. It is suspected that a number of pilots have been lost because of their experiencing the oculogravic illusion shortly after takeoff at night over unlighted terrain or water (fig. 18).

It is entirely probable that the illusion of a nose-down attitude occurs during decelerations caused by extending speed brakes or otherwise reducing forward velocity; if so, the illusion has not yet been reported as causing an operational hazard.

Another variation of the oculogravic illusion occurs during the pushover from a climb into level flight. Under these circumstances the centripetal and tangential accelerations acting upon the aircraft yield an inertial vector which combines with the 1-g gravity vector to form a resultant vector that rotates backward and upward relative to the pilot (fig. 19). This gives the pilot

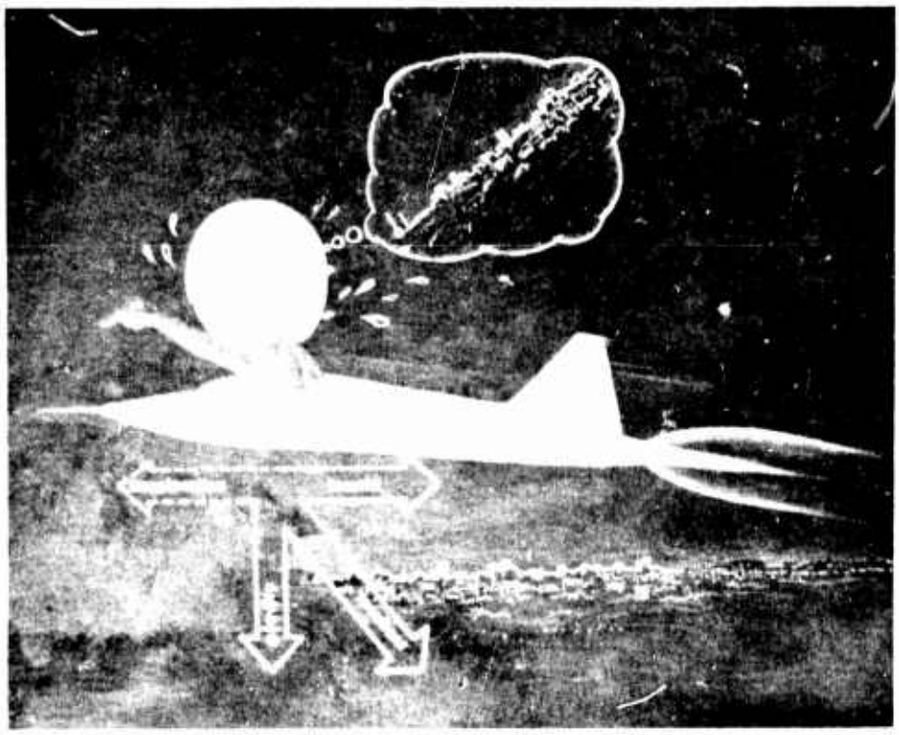

FIGURE 18

The oculogravic illusion. When a high-performance aircraft takes off, the acceleration can be such as to appreciably change the direction of the resultant "gravity" vector, with the effect that the visually deprived pilot perceives a false vertical. If he tries to fly his aircraft according to the perceived horizon, he will fly into the ground.

the sensation that he is tilting over backward until he is inverted, whereupon he is likely to try to correct for this illusory attitude by pushing the nose of the aircraft abruptly downward, thus intensifying the illusion. It has been suggested that this particular form of the oculogravic illusion is especially dangerous, because of the fact that aerodynamic characteristics of some aircraft would prevent safe recovery once the nose-down, negative-angle-of-attack attitude is entered.

Two other illusions caused by linear accelerations deserve mention. As we know, the otolith organs can monitor changes in the length of the gravity vector as well as changes in the direction of

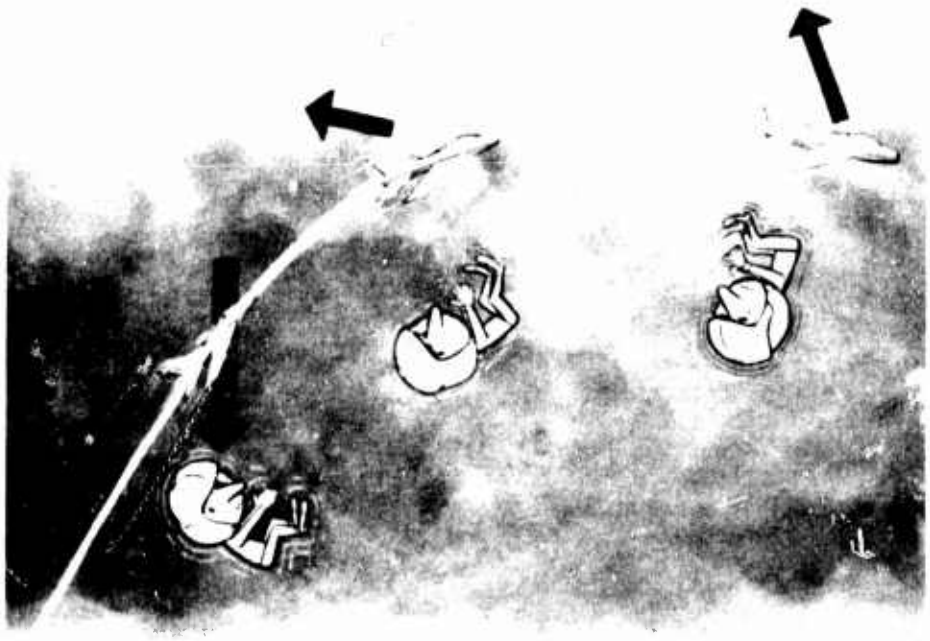

FIGURE 19

Another form of oculogravic illusion. As the resultant g vector rotates to the rear and top of the aircraft during level-off, the pilot perceives himself pitching backward until he feels inverted. To correct for this sensation the pilot may pitch the plane downward, thus aggravating the situation by intensifying the illusion.

it, and the *elevator* and *oculoagravic* illusions result when the utricle and saccule respond to changes in the length of the gravity vector. An increase in length of the applied gravity vector (as during an acceleration in the upward direction) results in a compensatory downward "tracking" eye movement, as the body tries through this vestibulo-ocular reflex to maintain visual fixation upon the environment during the upward acceleration. If an instrument panel, situated directly in front of a pilot, does not move relative to him while his eyes are making the reflex compensatory downward shift of gaze caused by upward linear acceleration, the pilot will observe the instrument panel, and hence the nose of the aircraft, to rise. This illusory upward motion of the immediate surroundings is called the elevator illusion (fig. 20).

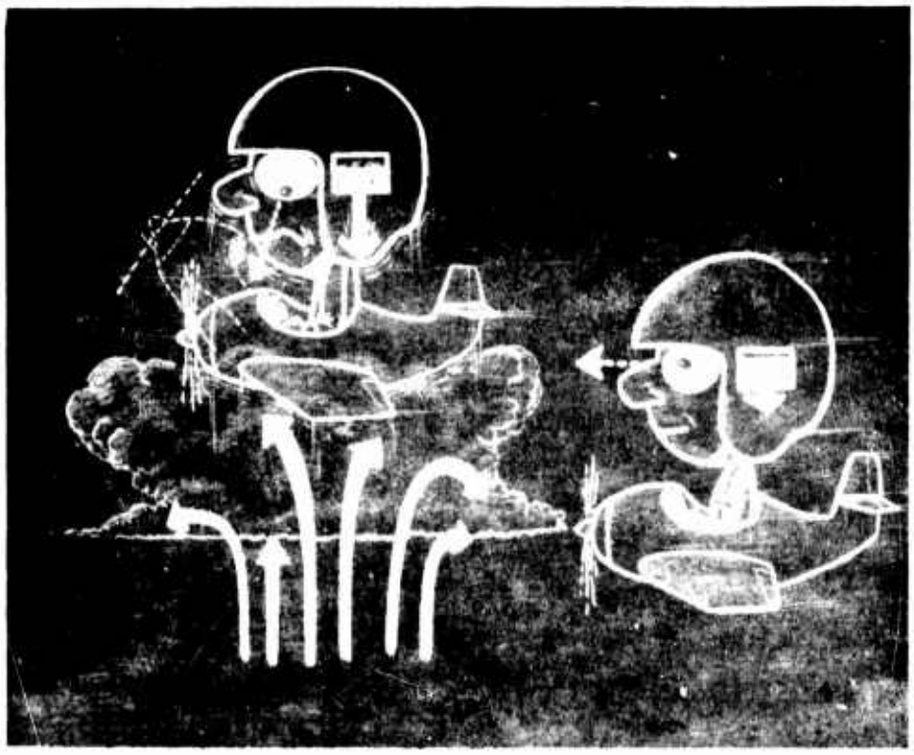

FIGURE 20

The elevator illusion. This pilot's otolith organs have been stimulated by an increase in the length of the g vector acting upon his head. The compensatory vestibulo-ocular reflex driving his eyes downward has caused him to observe (falsely) the instrument panel and nose of the aircraft to rise.

The oculoagravic illusion is the exact opposite of the elevator illusion. As the applied gravity vector is decreased and approaches zero g (as during a sudden downdraft), the eyes will reflexly attempt to compensate for the downward acceleration and an upward shift of gaze will occur. This results in an apparent downward shift of any object immediately in front of the pilot, who may interpret this downward shift of the instrument panel as an actual change in the aircraft attitude. Both the elevator and oculoagravic illusions are suppressed by good outside visual reference, but certainly can compromise pilot performance in bad weather.

There are a number of diseases of the vestibular system which can cause true, "medical" vertigo, such as vestibular neuronitis and Meniere's disease; but these pathologic vestibular conditions are not to be confused with spatial disorientation. A relatively common form of "pathologic" vertigo is seen in some aircrew when they fly with upper-respiratory infections. These individuals complain of spinning sensations and motion sickness during ascent, descent, or while accomplishing a Valsalva maneuver. It is suspected that this "alternobaric vertigo," as it has been called, results when a blocked eustachian tube suddenly opens, allowing the slowly developed pressure differential across the round window to dissipate rapidly, thus causing a mechanical stimulation of the organs of the inner ear.

The following are some nonvestibular factors which subtract from a pilot's proficiency in maintaining his orientation, and are classically included in discussions of spatial disorientation.

Autokinesis is the illusory phenomenon of movement which a static light exhibits when stared at for a long enough time in the darkness (fig. 21). This phenomenon can readily be observed by taking a lighted cigarette into a completely dark room and waiting for it to appear to move: the apparent movement will begin after approximately 8 or 10 seconds. The cause of the autokinetic phenomenon is not known at this time. As can well be imagined, it is disturbing to pilots who are flying at night and are visually fixated upon the light of another aircraft or of a star. It has been found that the autokinetic phenomenon becomes less apparent as the visual framework is expanded. For this reason it is desirable for an aircraft to have several staggered formation lights upon it rather than a single light source, if it is to be followed by another aircraft.

A common problem associated with night flying is the *confusion of ground lights with stars* (fig. 22). Many incidents are recorded in which pilots have put their aircraft into very unusual attitudes in order to keep some ground lights above them, having mistaken them for stars. Actual feelings of complete inversion are not infrequent under these circumstances. How often have we heard of the pilot who mistakenly "joined up on a star" because he thought a star or a planet was an aircraft with which he was

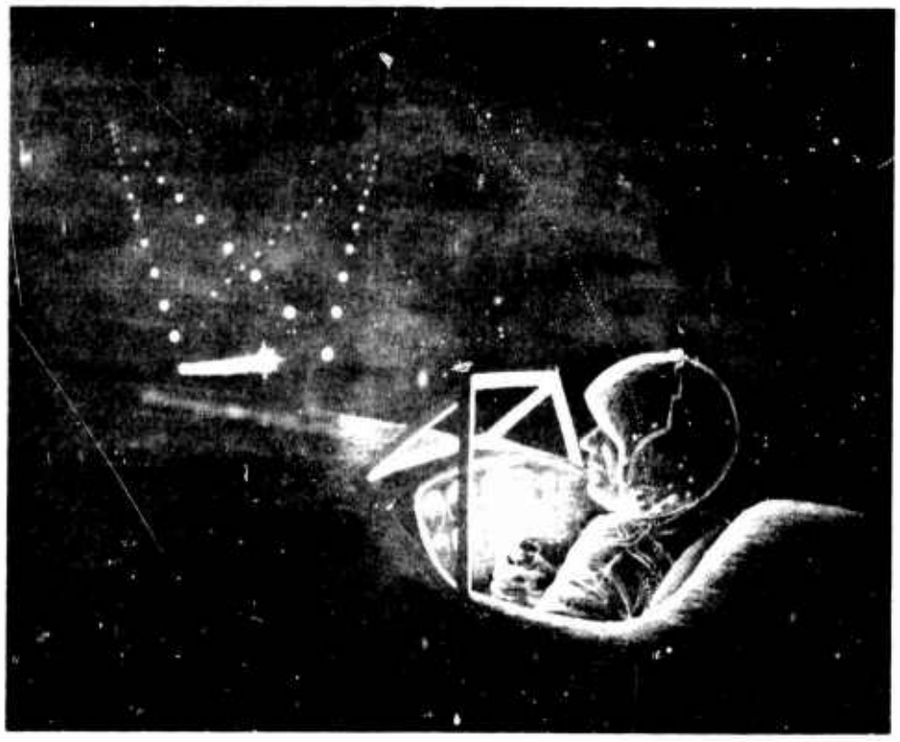

FIGURE 21

inesis. A static light, stared at for several seconds in the dark, wil ear to move.

sup osed to rendezvous? Less frequent but just as dangerous are the illusions caused by certain patterns of ground lights which are imagined to represent things which they are not. Some pilots, for example, have misinterpreted the lights along a seashore as the horizon, and have maneuvered their aircraft dangerously close to the sea while under the impression that they were flying straight and level. There are stories of pilots who have confused certain geometric patterns of ground lights (such as moving trains, etc.) with runway and approach lights, and have been badly shaken up by the near misses. Pilots who suffer from these illusions but are not lucky enough to recover in time do not report these incidents, of course; so that little can be gleaned from the accident investigation statistics about the actual role of falsely interpreted visual cues in aircraft accidents. Here, as always, the principle holds:

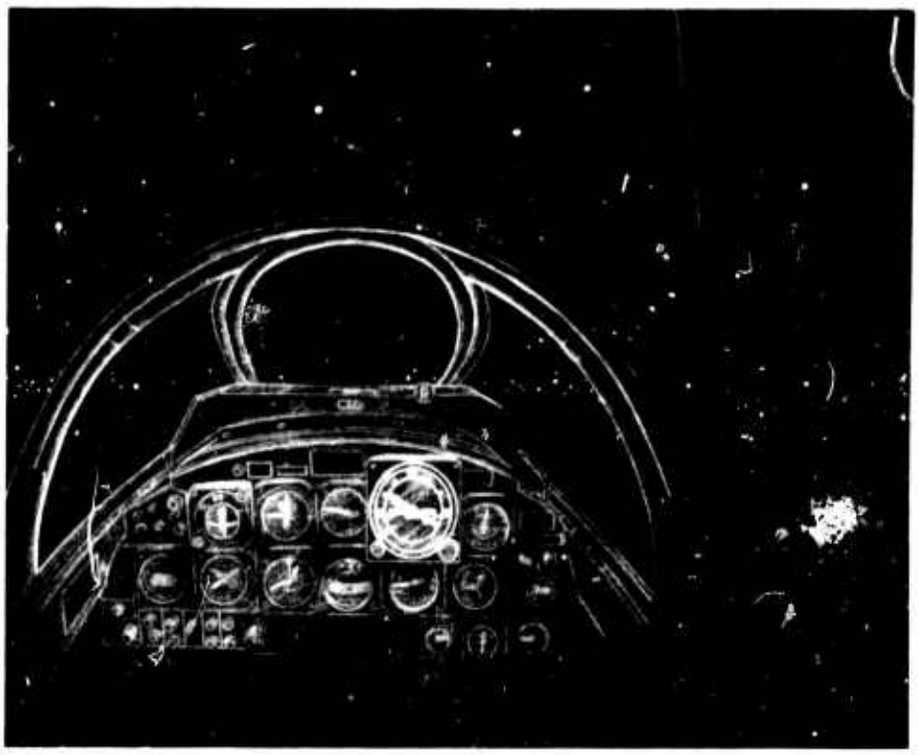

FIGURE 22

Confusion of ground lights with stars.

when sensorily deprived and adequately stressed, one will perceive what he needs to perceive in order to perform, even though it may mean supplying an illusory perception.

Nonhorizontal ground layers often cause consternation in pilots flying VFR "on top." A cloud deck which slopes creates an illusion of horizontality of the cloud layer and, therefore, nonhorizontality of the aircraft wings, when the wings are actually straight and level (fig. 23). If the pilot aligns the wings of the aircraft with the cloud deck, he will enter either a turn or a slip, and will be ripe for a good case of pilot vertigo. His only recourse is to observe and trust his attitude indicator and other instruments, and control the aircraft with strict reference to them. A similar situation occurs in regions where the aurora borealis is present. Conflicting

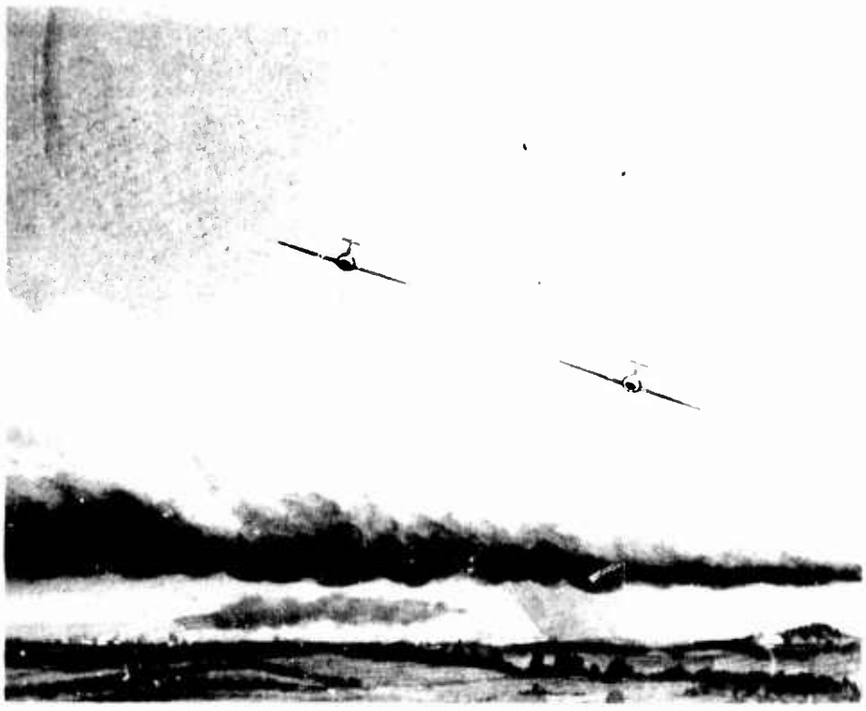

FIGURE 23

Flying on top of a sloping cloud deck. These pilots have succumbed to the temptation to align the wings of the aircraft with the apparent horizon.

cues of horizontality and verticality generated by the aurora borealis have caused many incidents of spatial disorientation, especially during night formation flying in northern regions.

Another compromising psychologic phenomenon which is often mentioned in discussions of spatial disorientation accidents is *fascination.* Fascination is said to occur when a pilot, for one reason or another, ignores orientation cues while his attention is focused on some other object or goal. "Target hypnosis" is a type of fascination which happens all too commonly, and is characterized by the incidents that occur when pilots become so intent upon hitting their targets during gunnery practice that they neglect to pull up in time to prevent their crashing into the targets. A second type of fascination is known as the "mental block" type, in

which a pilot's sensory information processing appears to shut down for brief periods while he gazes about him at the clouds, stars, etc., and he misses instrument fixes or radio calls. A pilot can be said to have had fascination only if he has demonstrated poor performance under conditions when all the sensory cues needed for correct performance were present in generally adequate amounts. The factors contributing to fascination are not well understood; and the contributions of hypoxia, fatigue, drugs, and basic personality structure might be of considerable import in fascination incidents and accidents.

Included only for convenience in the category of spatial disorientation is *geographic disorientation*, or just plain being "lost." It is easy for one to be mistaken about his direction of travel under an overcast sky when such things as section lines and roads deviate from a straight north-south or east-west course, or when mistakes have been made in interpreting air navigation charts over barren country. In IFR flying, such confusion may result from lack of instrument proficiency, misreading maps, or electronic failure; but the dangers of being lost are not of the same order of magnitude as are the dangers associated with one's being deceived as to his attitude and motion by illusory cues from deceived organs of equilibrium.

The interesting thing about spatial disorientation is that a particular set of linear and/or angular accelerations or misleading visual cues will not always produce illusory phenomena. When adequate external visual references are available, spatial disorientation does not happen, despite the presence of the same linear or angular accelerations that can produce spatial disorientation when outside visual reference is excluded. In addition, even if outside visual reference is excluded, and the same erroneous vestibular cues are presented to a pilot on several different occasions, he will not always perceive illusory phenomena. When the pilot is extremely busy with cockpit chores, when he is anxious, when he is fatigued, when he is less proficient at instrument or formation flying, apparently when he is mentally stressed for any reason, he is then more likely to become spatially disoriented in a given set of acceleratory conditions. In other words, the pilot's ability to resist spatial disorientation is enhanced greatly by adequate visual reference, and diminished by mental stress.

Normally, the instrument cross-check is little trouble to accomplish for an experienced pilot. When the pilot is making a transition from the external visual reference to the instruments, however, or when the pilot is very busy with other cockpit procedures, or is generally stressed by any of a multitude of things, his instrument cross-check is necessarily hurried and quite often neglected. It is believed that the pilot, at these critical times, places more reliance upon the continuous, natural vestibular cues which are readily available than upon the coded, intermittently sampled, panel information. If this is allowed to happen, sensory conflict—between the visual and vestibular systems—appears. At this point emerges the difference between "the quick and the dead": now the pilot must decide about which sensory information to act upon in order to control the aircraft. This decision is not always easy, because acting upon vestibular information is almost reflex, but acting upon the information presented by the instrument panel in the face of conflicting vestibular cues requires a very deliberate, concentrated effort. Sometimes, in fact, the sensory conflict is not even recognized: pilots have been known to transmit radio messages during episodes of vertigo, claiming that "the aircraft control is goofed up," or "the attitude indicator isn't working," and asking "what's wrong?" Occasionally a pilot is completely oblivious to the fact that he is disoriented and proceeds to fly into the ground without even realizing his error. It is easy to see that any factor which will adversely affect the judgment and will power of the pilot at this point will necessarily decrease his chances of survival in a disorientation situation. Hypoxia, various medicines (particularly amphetamines and barbiturates), g stresses, temperature stresses, and emotional problems could conceivably tip the scales in favor of death during the critical moments in the fight to regain aircraft control.

The fact that the normal instrument cross-check is stress-sensitive leads to an interesting speculation upon what might happen to a pilot once he has become disoriented. If the disorientation is in itself a stress-provoking condition, then, in an underconfident or apprehensive pilot who has become disoriented, even more reliance might be placed upon vestibular information than the visual (instrument) information, and additional erroneous sensory cues would be received by the pilot. As these additional false orientation cues are supplied, even more mental stress and anxiety

would be generated by the false orientation and sensory conflict, and further reliance would be placed upon the "natural" vestibular information. Thus, we would have a condition representing "positive feedback," from which it would be extremely difficult to extricate the true orientation perception and the equanimity with which a pilot should operate. Conceivably, under these conditions a true "panic state" would result; and another good pilot would return to the dust from which he came, because he was designed to walk, run, and swing in trees, but not to fly.

Statistics

How common is spatial disorientation? In 1955 Ruffel Smith credited disorientation as being probably the most common cause of fatal accidents in the RAF not caused primarily by mechanical failure. In 1956 Nuttall and Sanford studied spatial disorientation in one of the USAF overseas commands, and found that it was the cause of 4% of all flying accidents in that command and 14% of all fatal accidents in the command. They also found that virtually 100% of pilots in the command had experienced spatial disorientation at least once, and some had up to 20 experiences with vertigo. A review of all major aircraft accidents in the Air Force (1958) revealed that disorientation of the pilot was involved in more than 25% of cases in which physical, physiologic and pathologic factors were implicated. These are the classic statistical figures on spatial disorientation accidents and incidents, and there is no reason to suspect that now, 10 years later, the figures are drastically different.

What conditions are most conducive to spatial disorientation accidents and incidents? It has been reported that pilots of jet aircraft suffer from spatial disorientation five times as often as pilots of propeller-driven aircraft. It is further estimated that, as might be expected, pilots with relatively little actual instrument time are more susceptible to spatial disorientation than pilots with a lot of actual instrument practice under their belts. Particularly hazardous are the weather in-flight refueling situations and other types of formation flying in weather. A large number of spatial disorientation accidents and incidents have been reported during the penetration turn and final approach to an airfield; it is then that Coriolis illusions are most likely and most devastating. Another critical time is during the first minute or so after take-off,

during which time oculogravic and possible Coriolis effects come into play. Generally speaking, a low proficiency, stressed pilot flying a high-performance aircraft on an IFR or formation flight in weather or at night would probably be so likely to get spatial disorientation that even Lloyd's of London would not insure him.

Preventive measures

Indoctrination of pilots is the first important step to take in the fight against spatial disorientation accidents. Lectures, demonstrations, and movies discussing sensory functions and the conditions under which they become inadequate should be given periodically for pilots by physiologic training officers and flight surgeons. Updating and improvement of training aids should be accomplished periodically to insure the adequate dissemination of pertinent knowledge to the pilot population. After all, "forewarned is forearmed."

Some changes in the art and science of flying have resulted directly from studies of spatial disorientation accident trends. For example, maunfacturers are now aware of the problem associated with placing radio-frequency selector knobs in positions where the pilot has to turn his head to change frequencies, and modern aircraft have such knobs placed so that no extreme head movements are required to operate them. Attitude indicators have undergone substantial improvement with regard to their verisimilitude. Several potentially dangerous flying practices (for example, instrument takeoffs and night formation rejoins) have been officially discouraged in some commands. Other safety measures taken in attempts to reduce the incidence of spatial disorientation events exist, but are not myriad.

Several areas of research and development are being explored in the search for more reliable and effective pilot performance in disorienting situations. Basic research in vestibular physiology is constantly being undertaken, with special emphasis being placed on the problem of how the brain processes sensory information under different conditions of flight. The problem of obtaining reliable epidemiologic data on spatial disorientation is one of major importance and requires continuous attention by flight surgeons, PTOs, and others concerned with the when, where, and why of

spatial disorientation. Finally, new training devices are being developed which, it is hoped, will become effective factors in the eventual elimination of spatial disorientation accidents.

MOTION SICKNESS

Roughly half of those of you reading this material have been motion sick at one time or another. *Motion sickness* is apathy, headache, stomach awareness, pallor, perspiration, nausea, vomiting, and prostration, usually in that sequence, and usually concomitant with motion. Included in the general term "motion sickness" are airsickness, seasickness, train sickness, car sickness, amusement-park-ride sickness, and camel sickness. Some people have been known to become motion sick while looking at motion pictures of heaving and pitching ocean vessels, or while looking through a microscope and moving the slide back and forth under the objective in search of particular structures.

Importance

The importance of motion sickness is principally military. The following quotation from Armstrong provides the statistics associated with the World War II military effort:

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

Motion sickness took a particularly high toll among amphibious assault troops in World War II: a "very high" percentage of these troops were motion sick upon arrival at the beach landing area unless they were allowed to look over the edge of the vehicle as it approached the beach.

Current estimates as to the number of pilot trainees that get motion sickness place the figure at approximately 18%, with the probability being that a substantially greater percentage get

motion sickness of one form or another during training. Approximately 40% of all aircrew trainees become motion sick during some phase of their training. It has also been estimated that between 0.5% and 1.5% of aircrew trainees have refractory motion sickness and are unable to complete the training program because of it.

Motion sickness is probably the most important vestibular problem to be anticipated in our space effort. Some of the cosmonauts have been plagued during their flights with "vegetative reactions," which must be interpreted as motion sickness. In the space efforts of the United States, astronauts have been relatively free of motion-sickness symptoms, although some of them have experienced seasickness shortly after splashdown. It is anticipated by some scientists that severe, although not insurmountable, problems with motion sickness will be encountered if a manned satellite is rotated to provide artificial gravity. Extremely nauseating Coriolis effects are incumbent in such a system, and the evidence indicates that careful selection and training of spacecrew on the ground may be necessary to prevent critical performance decrements due to "space sickness" generated by the rotating environment.

Etiology

In isolating the factors contributory to the development of motion sickness, we find that motion—i.e., vestibular stimulation—is certainly a prime suspect. Abnormal stimulation of the semicircular canals, as in a rotating chair or rotating room, especially during Coriolis stimulation, can certainly cause motion sickness. Likewise, stimulation of the utricle and saccule alone, as in a 4-pole swing, a bouncing elevator, or a heaving ship deck, can also induce motion sickness. In such devices as centrifuges, aircraft in aerobatics, life rafts bobbing on the ocean, and ordinary swings, there is a combined stimulation of both the semicircular canals and otolith organs; and, of course, motion sickness does occur following such stimulation. Of particular interest is the fact that destruction of the vestibular end-organs results in complete immunity to motion sickness in the individual suffering the deprivation, thus indicating that the vestibular system is of primary importance in the pathogenesis of motion sickness (fig. 24).

FIGURE 24

It usually requires motion (i.e., vestibular stimulation) to generate motion sickness.

There are several ways in which the visual system, as well, can be important in the development of motion sickness. It has long been known that, when outside visual reference is denied to a person undergoing motion, he is more likely to become motion sick than he would be if he had an outside visual reference available to him. Cases in point: the navigator who becomes motion sick in turbulent conditions while the rest of the aircrew do not; the pilot who becomes sick when he rides as a passenger even though he would not have become sick if he had been piloting; and the sailor who becomes motion sick while below deck, and comes up to view the horizon in an attempt to forestall development of motion-sickness symptoms. Visual stimulation can also be important in the absence of any real motion. The examples given in which people become sick while watching movies of ships on rough seas and while studying microscope slides are good examples of the phenomenon of a moving visual environment causing motion sickness without direct vestibular stimulation. There are reports of a high incidence of motion sickness in instructors teaching in

the Navy 2-FH-2 helicopter simulator, which had no actual motion of its own, but portrayed appropriate motion by the movement of a projected visual reference. In fact, one's visual reference does not even have to be moving in order for him to develop motion sickness in the absence of true motion: "anti-gravity" houses in amusement parks (constructed on a slant so that the earth's gravity vector is not perpendicular to the floor) have reportedly caused motion sickness in some people who enter those "illusogenic" structures.

Motion sickness can result in the absence of unusual vestibular *or* visual stimulation. Susceptible people can be made motion sick while sitting in a chair in a room where a revolving sound source is presented to them. As the sound revolves about the person, he gradually develops nystagmus and motion sickness—a condition termed "auditory vertigo."

Some studies have revealed that proprioceptive (subcutaneous and kinesthetic) stimulation may contribute to the development of motion sickness. Actual mechanical irritation of the viscera, however, does not cause motion sickness.

It has often been said that the olfactory system is responsible for the development of motion sickness, and that the odor of aircraft compartments, of stale (or fresh) emesis, or of other offensive materials is contributory to the motion-sickness syndrome. It is not reasonable to suspect that these odors are any more responsible for motion sickness than they are for the emesis they can produce without the aid of motion.

Certain psychiatric factors appear to be of importance in the development of motion sickness. The state of fear or insecurity has long been suspected of potentiating actual motion to produce airsickness and seasickness. Some studies have indicated that the personality characteristics of emotional lability and excessive rigidity are positively correlated with motion-sickness susceptibility.

It is possible to condition a person, like one of Pavlov's dogs, to develop motion sickness at the presentation of a conditioning stimulus. A pilot trainee or other aircrew member who has become motion sick on previous maneuvers in an aircraft, may become

conditioned to develop symptoms of motion sickness at the mere sight of an aircraft (fig. 25). It is advantageous, of course, to prevent the development of conditioned motion sickness through the use of appropriate prophylactic medications early in flight training.

As is evident, there are a number of factors which are or may be important in the production of motion sickness. *The most important common factor, however, in the production of motion sickness is lack of sensory congruity as determined by previous experience.* How sensory incongruity is related to the development of motion sickness can reasonably be surmised. The following paragraphs are extracted from a recent aeromedical review in which arguments are presented that the vestibular efferent component (discussed in the section on vestibular function) is seen as an integral part of the mechanism of motion-sickness development and suppression.

> The most tenable explanation regarding the causation of motion sickness is one incorporating the concept of sensory incongruity. Steele in his work discusses this concept very adeptly and develops the idea that motion sickness is likely to occur in a susceptible individual whenever the information coming from different sensory modalities is conflictual. Furthermore, what is considered conflictual sensory information is a function of past experience. Thus, when visual information (e.g., an aircraft bulkhead in reference to which a passenger observes himself to be stable) is at odds with vestibular information (telling the passenger that he is actually being accelerated), then motion sickness is likely to ensue. The situation produced in the helicopter simulator is easily seen to be more conflictual for the instructors than the students. The instructors, who had considerable prior experience in helicopters and therefore much occasion to associate movement in the visual field with feelings of acceleration from the vestibular sense and "the seat of the pants," experienced sensory incongruity when no vestibular correlate of the changing visual field was available. The students, on the other hand, having little if any prior time in helicopters, did not generally recognize the sensory incongruity, and were therefore much less likely to develop motion sickness. Another case in point is the man who becomes motion sick while viewing microscope slides: the lack of vestibular stimulation under conditions when his visual reference (the field of view) is darting back and forth and up and down must certainly be conflictual for him. The incongruity may not necessarily even primarily involve the vestibular sense: motion sickness can result when an auditory reference is rotating and the visual reference is stable (although it can be argued that the primary conflict may be between the rotating auditory reference and the stable vestibular reference).

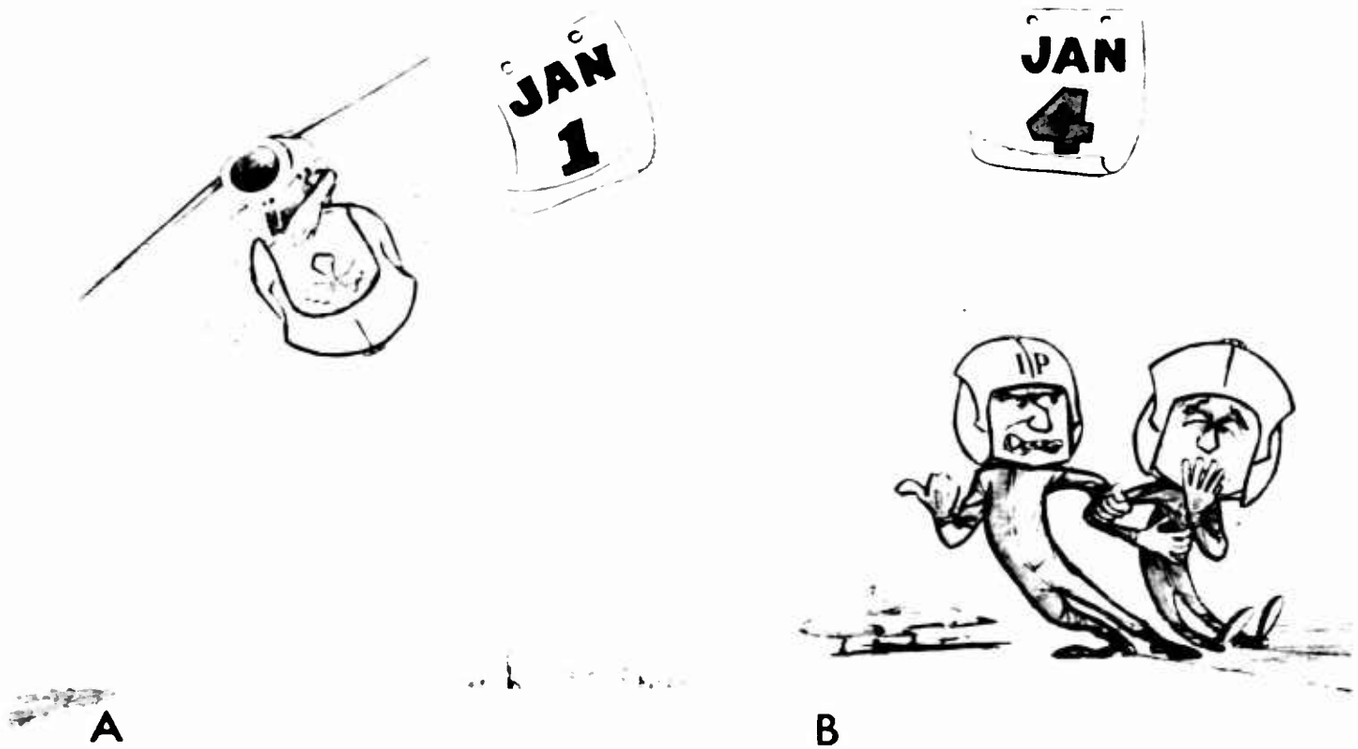

FIGURE 25

Conditioned motion sickness. (A) Having become airsick on a number of training flights, ths student pilot (B) now gets airsick just looking at an airplane.

If we accept the fact that a functioning vestibular end-organ is a *sine qua non* in the production of motion sickness, and the fact that sensory incongruity, regardless of the level of vestibular stimulation, is primarily responsible for the production of motion sickness, how can we reconcile these facts? Let us call on the vestibular efferents for the answer.

When a sensory incongruity exists and the incongruity is relevant to the orientation of the organism, we can expect central processes to occur that are directed toward resolving the sensory conflict and computing a satisfactory orientation perception. In any orientation problem the vestibular end-organs will of course be consulted, because their primary purpose is to inform the central nervous system about factors (accelerations) influencing body position. When, according to our interpretation of the efferent sensory control theory, there is need for additional vestibular information, the central nervous system then activates or sensitizes the vestibular end-organ by releasing normal suppressive activity mediated by the vestibular efferent nerves. Consequent to this the neural activity of the afferent vestibular components increases, perhaps manifold, over the normal (suppressed) state, as vestibular information flows in abundance into the central nervous system. Even when no accelerations have acted upon the body and a vestibular steady-state exists, the neural activity indicative of the steady-state is amplified, perhaps to an amplitude much greater than would result after a violent linear or angular acceleration when the end-organ is suppressed. Thus, we can see how any sensory incongruity resulting in confused orientation may obligate increased flow of vestibular information. So why does this cause motion sickness?

It has long been suspected that the autonomic outflow characterizing motion sickness somehow results from the proximity of the vestibular nuclei (especially the medical vestibular nucleus) and the dorsal nucleus of the vagus. These nuclei are juxtaposed, and the degree of fraternization that occurs between the cells of the nuclei is probably considerable. If, now, there is an increased neural activity in the vestibular nuclei for any reason, we should expect that "spillover" of neural activity into the dorsal nucleus of the vagus will occur, and that, with adequate intensity and duration of excitation by the vestibular nuclear activity, vagal outflow will be triggered and motion sickness will be the result. To recapitulate: the sensory incongruity, when relevant to orientation, obligates increased vestibular information, which is provided when the efferent system is utilized to sensitize the vestibular end-organs; thereupon, more information is transmitted through the (afferent) vestibular nerves to the vestibular nuclei, which, by virtue of their proximity to the dorsal nucleus of the vagus, then cause leakage of neural activity into the autonomic outflow tracts, and this causes motion sickness.

Since it has been shown that animals are much less susceptible to motion sickness when portions (especially, the flocculonodular lobe) of the cerebellum are ablated, a comment on this observation is in order.

The role of the cerebellum as an integrator of, among other things, orientation information is attested to by the extremely rich innervation of this structure by vestibular, visual, proprioceptive, and other afferent sensory tracts. When the cerebellum is ablated, the orientation-computing function of this structure is also ablated, and sensory incongruity becomes irrelevant. Therefore no need for additional vestibular information is recognized, and no call for same is generated. Under that condition no change in efferent control of vestibular receptivity is likely to occur, and motion sickness thus could not develop . . . .

The proposed hypothesis of the mechanism of motion sickness explains a number of phenomena observed regarding the malady. The role of either semicircular canal or otolith organ stimulation in the production of motion sickness is easily seen. Why intact vestibular end-organs are necessary is also seen. The possibility of one's becoming motion sick without exposure to real motion is reconciled. The importance of past experience on whether or not motion sickness occurs in an individual can be reasoned out; e.g., the habituation to motion-sickness-producing Coriolis accelerations in the Slow Rotation Room can be explained by arguing that the cerebellar "orientation computer" resets itself to accept formerly incongruous information as congruous. The common observation that fear and insecurity predispose one to motion sickness is seen to be reasonable, because a state of fear or insecurity necessitates additional sensory monitoring. Even the work correlating motion sickness susceptibility to emotional lability and to rigid personality characteristics could be supported by this hypothesis, as we might expect sensory incongruity to be all the more unacceptable to emotionally labile or to rigid, compulsive persons than to others. Anatomic variations can be invoked to explain the marked differences in innate susceptibility to motion sickness and the possible hereditary pattern of its occurrence.

It must be emphasized that the above ideas are merely speculations at this point. There are no other theories, however, that will explain all of the factors and facets of motion sickness as a function of one or two simple mechanisms.

Management

If you are called upon to help manage a case of motion sickness, ascertain that it is motion sickness you are dealing with: be sure it is not a more serious medical disorder like shock, increased intracranial pressure, poisoning, intestinal obstruction, or some other critical medical emergency.

Once motion-sickness symptoms have developed, treatment generally tends to be very ineffective and unrewarding. The first step to be taken, obviously, is to stop the motion of the body, or at

least to keep the patient's head still. On an aircraft or a ship, where it is impractical to alter the motion of the vehicle, it is best to have the patient lie down and remain in a supine position during the perturbations. Even so, the patient may still vomit for up to 2 hours after the cessation of motion if the stimulation was overwhelming. Another helpful procedure is to give the patient a familiar orientation structure with which to relate, as is done when a sailor is encouraged to go topside and watch the horizon to counter his impending gastrointestinal doom.

Another procedure which has proved useful in practice, although it cannot be justified from experimental evidence, is to cool off the patient with a blast of wind. Such a maneuver has undoubtedly saved many aviation cadets the embarrassment of having to clean up the cockpit.

After symptoms have appeared, it is useless to attempt to stop their progression by giving oral medications. If it is absolutely necessary to stop motion-sickness symptoms at all costs, the patient should be treated as though he has an acute attack of Meniere's disease; and, if possible, a physician should choose and administer an appropriate subcutaneous or intravenous medication.

Much more rewarding than the "after-the-fact" treatment of motion sickness is prophylaxis. The most effective anti-motion-sickness drug is scopolamine, and the dosage is 0.5 to 1.0 mg. orally more than ½ hour before exposure to motion. The side effects of this drug are dry mouth, photophobia, blurred vision, headache, and even hallucinations (the symptoms of atropine poisoning); and being such, preclude the use of scopolamine in aircrew. Less effective but much more acceptable are meclizine and cyclizine (both antihistamines), the dosage of each being 50 mg. to be taken more than ½ hour before exposure. The side effects of these drugs are considerably less than those of scopolamine; nevertheless, drowsiness, mild dry mouth, and occasional blurring of vision may occur in most individuals (fig. 26).

The main use for these drugs is in the treatment of student pilots and other aircrew during early training flights, during which time they must be allowed to habituate to the motion-sickness-producing stimuli before they develop conditioned motion sickness.

FIGURE 26

The side effects of even the best anti-motion-sickness drugs are drowsiness, dry mouth, and blurring of vision.

These drugs should be used *only* when the trainee is flying with an instructor, or is not in primary control of the aircraft. It may be advisable to use these medications on paratroops and airlifted troops if anticipated casualties from motion sickness will be fewer than anticipated casualties from side effects of the drugs.

Although tests (questionnaires and clinical tests) have been developed which will indicate with high reliability the probability that a certain person will develop motion sickness during training, there is as yet no justification for preventing a person from undertaking aircrew training solely on the basis of a history of susceptibility to motion sickness or on the basis of results of vestibular testing. The reason for this is that most people habituate to motion-sickness-producing stimuli to the point where they can effectively carry out required military tasks. There is evidence to indicate that even those who have unusually refractory motion sickness can be trained to have a markedly lesser degree of susceptibility, if they are properly motivated.

Motion sickness, then, like spatial disorientation, is a costly aeromedical disease. It will continue to be a potential hazard as long as man persists in leaving his evolutionary milieu of motion and takes to the sea, air, and space on military, commercial, and scientific ventures. We must understand more thoroughly the fundamentals of motion sickness if we are to make further advances in its management; and such advances will be required as we expand our environs at an ever-increasing rate.

ACKNOWLEDGMENTS

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ADDENDUM

Page 11, paragraph 3: Some current studies suggest that the semicircular canal system under certain circumstances can be stimulated by linear acceleration. [Cf. Benson, A. J., and M. A. Bodin. Interaction of linear and angular accelerations on vestibular receptors in man. Aerospace Med. 37:144-154 (1966)]

Page 57, paragraph 1: Strictly speaking, the term *oculogravic illusion* refers to apparent movement and displacement of objects in one's visual field when he is exposed to an environment of compounded linear accelerations. Beause of the lack of a more suitable existing term, we shall adopt *oculogravic illusion* to mean not only the visual phenomena but also the perception of change of body position consequent to the compounding of gravitational and inertial forces acting on the body.

Page 77, paragraph 4: Recent studies have shown that a combination of scopolamine and amphetamine provides more protection against motion sickness with fewer side effects than scopolamine alone. [Cf. Wood, C. D., A. Graybiel, and R. S. Kennedy: Comparison of effectiveness of some antimotion sickness drugs using recommended and larger than recommended doses as tested in the Slow Rotation Room. Aerospace Med. 37:259-262 (1966)]