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The Human Balance System: A Refresher for Pilots

Understanding how the body's position-sensing systems function is critical to safe instrument and noninstrument flight.

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Pilots need to thoroughly understand how body-orientation sensors function, and how those sensors can convey misleading information in some situations, to fly safely in both instrument and noninstrument conditions.

The sensors that send information to the human brain so that body position and imposed accelerations can be interpreted, are the semicircular canals, the otolithic (inner ear) organ, the eyes, pressure sensors in the skin, muscles and tendons, and pressure sensors in other body organs.

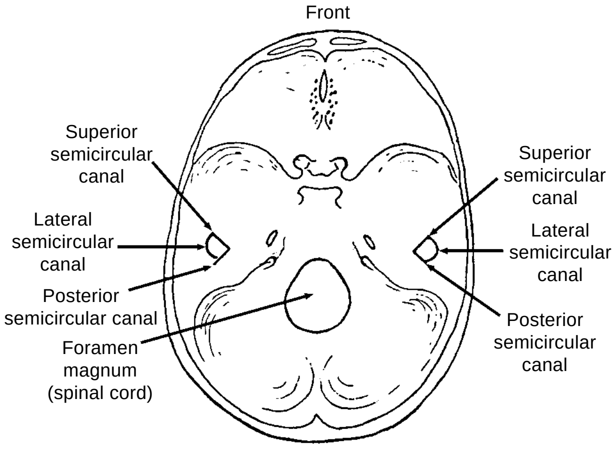
Because of these sensory detectors, individuals are able to perform broken-field running, multiple jumps, high-wire acts, figure skating and aerobatics. Those who are blind can walk and not fall over, so long as the supporting surface environment is stable and does not require corrective actions that would be guided by visual inputs. In the microgravity associated with space flight, humans rapidly learn to move about in this "weightless" condition (they still have mass), demonstrating the nervous system's ability to adapt to new conditions. With respect to flight activities, a major problem arises when outside visual references to the horizon disappear and there is no instrumentation to compensate, and when acceleration in turns simulates the earth's gravity field.

Understanding the orientation sensors will help pilots avoid misinterpreting the information these sensors transmit to the brain.

Semicircular Canals. The semicircular canals are sensors of positive and negative accelerations that fall within a certain rate of onset or offset.[1,2] The canals sense roll, pitch and yaw acceleration motions of the head (Figure 1, page 2). They do not detect either linear acceleration or constant angular velocity, a type of "angular velocity" acceleration toward (around) a central point.

Sudden rotation of the head moves the bony framework structure of the semicircular canals in the skull, causing a lag in the fluid within the semicircular canals. The small sensory hairs in the semicircular canals bend backward with this lagging fluid, and send nerve signals to the brain that the head has initiated a turn. If the turn continues (for example, sitting on a turning piano stool of constant velocity), within about 40 seconds the fluid in the semicircular canals catches up by friction with the moving bony structure of the canal and no more angular acceleration nerve signals are sent. At this point, the turning of the environment gives visual clues to the continuing turn. If the piano stool is slowed down, the momentum of the fluid in the semicircular canal advances the fluid ahead, and as the fluid decelerates by friction, signals are sent to the brain saying that a deceleration is taking place. It takes 15 to 20 seconds following a slower angular velocity or a full stop for the fluid in the ear to be moving so slowly as to cease sending signals.

The reason a person feels dizzy after closing the eyes, spinning on the feet several times and then abruptly stopping is



Location of the Semicircular Canals (Skull, Top View)

Source: Stanley R. Mohler, M.D.

Figure 1

that it takes 15 to 20 seconds for the fluid to come to rest after stopping. The brain, without visual input, still receives semicircular canal signals from the slowing-down fluid that the body is decelerating.

It takes about one degree per second per second of acceleration to stimulate the semicircular canal sensory organ. In other words, in order to keep stimulating these canals with turning, one has to increase the acceleration to two degrees per second by the end of the second second and three degrees per second by the end of the third second and so on.

If the angular acceleration ceases, and a constant rate of turn occurs, the semicircular canals will cease to detect the constant angular velocity. This is why pilots without instrument training do not recognize that the aircraft is turning when outside visual references are lost. This emphasizes the need to rely on the gyroscopic flight instruments (assuming they are functioning correctly). An autopilot will help decrease pilot workload in prolonged instrument flight.

A standard rate turn is three degrees per second and with a smooth roll-in when outside visual reference is lost the pilot should not feel any inner ear sense of turning.

The Otolithic Organ. The otolithic organ consists of the utricle and saccule. This sensory organ detects linear (straight line) accelerations that exceed a certain rate of linear acceleration onset or offset (Figure 2, page 3).[1]

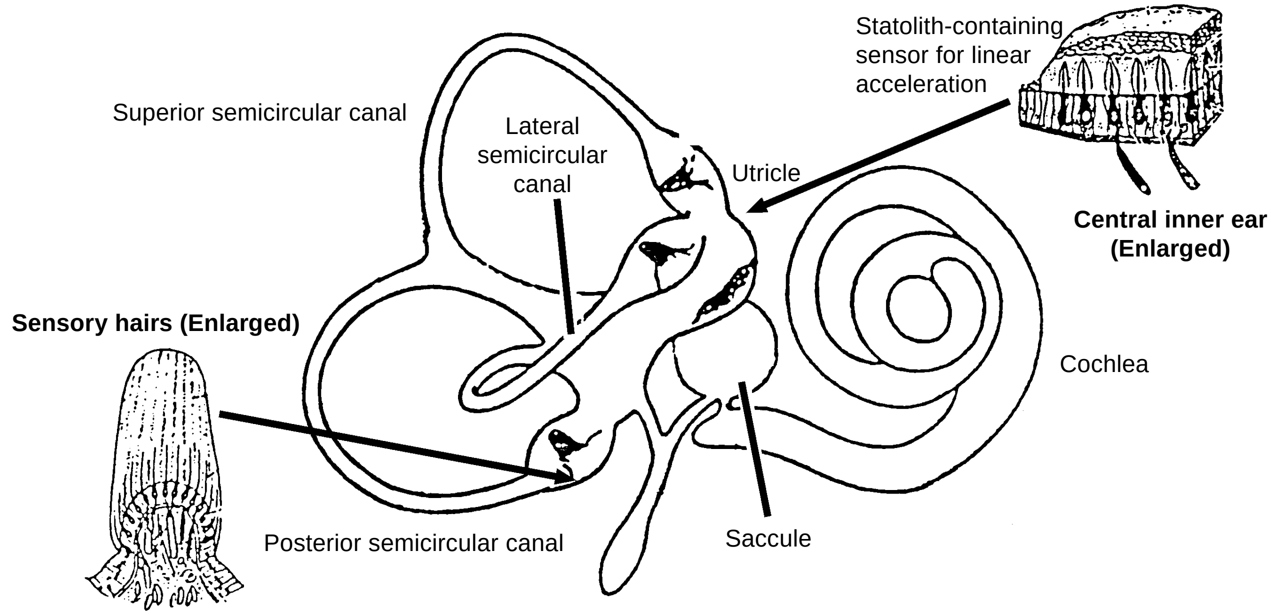
A forward acceleration of the body causes the statoconia (little crystals of calcium salts on sensory filaments) in the otolithic organ to lag with the acceleration. Nerve signals are then sent to the brain stating that the body is accelerating forward in a linear mode. The opposite occurs with deceleration. The utricle and saccule contain these statoconia, also known as statoliths ("stationary stones").

There are statoliths for vertical acceleration, that is, jumping while standing upright, and statoliths for forward acceleration, that is, jumping ahead. In fact, when one starts running, the statoliths lag backwards and the signals to the brain indicate a falling backward, which causes the brain to send signals to the body muscles to lean somewhat forward. This reflex is good because leaning forward causes the body's center of gravity to shift slightly ahead, stabilizing the forward-moving body and maintaining balance. When one slows down, the opposite occurs. This reflex works in the dark to provide stability when running.

This reflex can cause a problem when taking off under instrument meteorological conditions (IMC) with no outside visual references. Sudden acceleration (for example, as occurs with high-thrust propulsion) can cause the pilot to sense that the airplane is pitching up more than it really is. Some pilots have pushed their aircraft back toward the ground as a result. In addition, some gyroscopic attitude indicators will precess (a complex motion executed by a rotating body subjected to a torque, tending to change its axis of rotation), indicating that the plane is pitching up more than it actually is. Under these circumstances a pilot may pitch the aircraft down more than is desirable. Awareness of this phenomenon, a characteristic of human otoliths and also of certain gyroscopic attitude indicators, is especially important.

The Eyes. Visual inputs balance the body through the brain's comparison of visual images transmitted from the retina to the brain with the brain's in-place model (continuously updated) of the outside world. Visual input is unnecessary for orientation on a stable platform, as indicated by a blind person walking around inside his or her house without falling over. Of course, these persons can learn to use hearing to a certain extent in place of vision — for example, to walk through downtown areas by listening to echoes from their cane taps to judge the distance to walls and other large objects. They also use the sense of touch from pressures derived through the cane to the hands as a further sensory input to help picture the immediate environment. It has been found that bats and porpoises learn about their immediate environment through the nature of the echoes returning from their emitted sounds. Humans with intact vision have a tremendous advantage because of the rapidity with which light travels, the great distances over which light is effective (for example, starlight) and the rapidity of a signal from the retina of the eye to the brain processing centers.

The human eyes are moved left, right, up and down, and through many in-between combinations of motion, by six muscles on each eyeball. The individual can turn the eyes at will, and because the whole head and the body can also be turned, a 360-degree spherical visual field is possible. The eyes are also servoed to the neck muscle so that if one turns one's head without visual fixation on an object, for example, to the left,



Structure of the Inner Ear (Side View)

Source: Stanley R. Mohler, M.D.

Figure 2

the eyes will swing to the left automatically. This can readily be demonstrated: try turning your head to the left and shifting the gaze to the right at the same time — you have to fight the reflex. Nevertheless, one can fixate the gaze on an object and override the above reflex automatically, as demonstrated by looking at an object and moving the head back and forth.[1] This override is a benefit because it stabilizes the visual environment while the body changes position as in walking, running, low-level flying or performing aerobatic maneuvers.

Pressure Sensors in Skin, Muscles, Tendons and Body Organs. In the 1 G static environment, the pressure exerted by the gravity field pushes the supporting surface against a standing, seated or lying body, toward the center of the earth. This is a major orientation sensory input. This sense tells which way is down, and is used in the dark. It is especially important for those who are blind.

The pressure sensors in the tendons, muscles, skin, organs and organ attachments indicate the direction toward which gravity is pulling the body, irrespective of whether one is standing on one's head or feet, sitting, lying on a side, or on one's front or back.[3] This sensory awareness rapidly diminishes after a few seconds compared with its initial burst of signals when, for example, you first sit down. Thus, after a few seconds, your conscious awareness from this sense of sitting pressure is markedly reduced. In fact, you have to consciously think about sitting for a degree of sensory awareness to reach once again your conscious mind. This sense cannot distinguish gravitational acceleration from in-flight accelerative forces (or any other accelerative forces). Thus, when outside visual references are lost and a flying aircraft not equipped with orientation instruments enters a steep banking turn pulling Gs, the pilot cannot tell whether the plane is pulling out of a dive or is receiving the Gs from the high-G turn. In both instances, the pressure sensations are the same.

The sensory systems that orient humans during daily terrestrial flight, and flight under visual meteorological conditions (VMC), are interconnected centrally in the nervous system and are continuously cross-checked by the individual during various activities. Confusion comes when one or another of these sensors is triggered by an unusual environmental circumstance that gives conflicting information. If you sit on a piano stool with your eyes closed and spin several times, then stand up suddenly without opening your eyes, the information from the semicircular canals will be conflicting. The fluid in the canals will still be indicating a turn, and the linear standing acceleration will send uninterpretable, and therefore confusing, signals to the brain. An overwhelming dizziness (vertigo) will occur.

Cross-coupling of fluid movements in differently oriented semicircular canals (the "Coriolis" effect) may occur if a sudden head movement is made down or up or to the side while turning, creating inputs that "conflict" within the interpretive centers of the brain. Learning to disregard these conflicts while flying by reference to gyroscopic instruments, and learning how to avoid confusion from sensory conflicts, is a key aspect of instrument flight training.

Individual susceptibility to conflicts in sensory inputs covers a range from almost no effect to extreme dizziness, sweating, nausea and vomiting. Some adaptation may occur in individuals with repeated exposure to various accelerations. Certain medications are available to help susceptible student pilots get through these reactions during instrument training.

Understanding the general principles upon which the human balance system operates is critical for pilots who operate in IMC. Loss of outside visual contact with the horizon causes the human balance system to send conflicting information, resulting in disorientation and, not uncommonly, vertigo. All pilots should experience these sensations while wearing view-limiting devices in flight with an instructor, or through Bárány Chair (a chair that revolves to test a person's susceptibility to vertigo) demonstrations given by U.S. Federal Aviation Administration (FAA) aviation safety counselors or by "flights" in the FAA Vertigon (another device to induce vertigo).

The main lesson for pilots is to maintain orientation of the aircraft by reference to the attitude and flight instruments. Conflicting physiological sensations are to be disregarded, even though these sensations are uncomfortable. Nothing can be done immediately to make these vertigo sensations go away if they are experienced in flight. But with increasing experience, pilots learn to disregard these incoming sensations and to fly the aircraft by reference to instruments.

For some, vertigo may become a normal occurrence with instrument flight, to be expected and disregarded. For others, an increased threshold for the onset of these sensations may develop, and these pilots, during all but the most unusual instrument flight conditions, will not even be aware that conflicting signals are being sent to their higher brain centers. Remember: fly the airplane in accordance with the flight instruments, regardless of physiological sensations when under IMC. This discussion assumes that the flight instruments are functioning normally. If any of the gyroscopic instruments fails, the pilot must recognize this and revert to "partial panel," once again disregarding misleading physiological sensations.

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