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Visual Perspective Illusions as Aviation Mishap Causal Factors

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In the past, aviation spatial disorientation (SD) has been considered predominantly an isolated vestibular problem, associated with lack of outside visual cues. Recent research has challenged the prevailing position by suggesting pilot SD is more commonly caused by problems with cognitive processing of visual spatial strategies. Among the confounding visual stimuli known to occur in-flight, several visual perspective illusions have been identified as reoccurring mishap causal factors. These illusions occur in part because humans exhibit a strong instinctive tendency toward considering themselves level with distant horizontal references, regardless of their true altitude. Also contributing to perspective illusion occurrence is the fact that objects viewed slightly above the perceived horizon will appear magnified in size and exaggerated in elevation above actual aircraft altitudes. Although perspective illusions have been recognized and studied for centuries, the impact of these sensory misperceptions on aviation safety has only recently been subjected to close scientific scrutiny.

Aviation spatial disorientation (SD) is best described as a pilot’s inability to correctly interpret aircraft attitude, altitude, or airspeed in relation to the earth or other points of reference. If not recognized immediately, this sensory misperception can lead to controlled flight into the ground, midair collision, or inappropriate control inputs resulting in aircraft stall (Patterson et al., 1997). The ubiquity of this problem has been well documented by mishap reports and surveys that indicate virtually all pilots’ experience some form of SD during their careers. On an annual basis, accident statistics suggest each year SD results in the destruction of at least 20 DoD aircraft, the deaths of 25 flight crew, and asset losses of over 400 million dollars (Patterson, 2006).

Despite a lack of empirical accident investigation data, previous research has mainly emphasized anomalies within the vestibular system as the principal source of SD in flight. Consequently, most of the existing work on aviation SD has focused on nuances of the vestibular system under a variety of carefully controlled laboratory settings. Although, these efforts have generated direct applications toward treating clinical pathologies such as Meneire’s disease or intravestibular trauma, directly linking these results to cockpit environments requires a considerable leap of faith. As an example, research evaluating the theoretical aviation vestibular illusion referred to as pilot “inversion” illusion revealed that producing this sensory misperception in the laboratory with a subject’s eyes closed and head restricted, was relatively easy; however, in realistic cockpit environments with eyes open and head unrestricted, recreating this speculative SD problem was difficult if not impossible to accomplish (McCarthy 1994). Current accident statistics cast doubt on past efforts to mitigate SD through training and design efforts, since the SD mishap rate (25% -30%) has remained unchanged for decades and current trends suggest a possible increase in SD events (Patterson, 2012).

Although past explanations for spatial disorientation have concentrated on isolated vestibular illusions as primary causal factors, analysis of aircraft accidents and flight crew surveys suggest the most common forms of aviation SD are generated from conflicting visual cues that confound cognitive processing of pilot spatial strategies. This revised interpretation of causal factors has helped identify and classify common SD events, which has further led to specific SD categorization into interactive functional areas identified as vestibular, cognitive, and visual components (Figure 1).
Since current research suggests well defined pilot spatial strategies are essential for both prevention of SD and enhancement of cockpit designs, it is important to define this concept within the context of aviation nomenclature (Patterson et al., 1997). In general terms the word strategy refers to having a plan of action aimed at achieving a particular goal. When applied to spatial problems: a spatial strategy may be defined as a cognitive process that allows one to sense spatial patterns for the purpose of predicting and manipulating future spatial positions.

When describing in-flight spatial relationships, the term “sight picture” is often used to explain how visual cues interact within a pilot’s field of view. To better characterize this descriptive technique, effective pilot “sight pictures” have been described as having specific retinal images defined as primary and secondary spatial cues. Patterson et al. (1997) have previously classified primary spatial cues as stabilized retinal images that remain centered on or near the pilot’s central (foveal) field of view, while secondary spatial cues are defined as unstabilized peripheral images that will often appear in motion relative to the primary cue. During solo flight with visual meteorological conditions (VMC), distant steer points situated within the outside horizon view will typically serve as the pilot’s primary spatial cue. Since perception of aircraft position, relative to this primary cue, is crucial for maintaining spatial orientation, peripheral views of the aircraft structures such as glare-shield, canopy bows, or wings play a vital role as secondary spatial cues that allow pilots to gauge aircraft attitude relative to the horizon.

Often times pilots will consciously, and sometime unconsciously, determine aircraft orientation by comparing retinal distances or angles between primary and secondary cue images (Figure 2A). The reasons why dynamics of these sight picture cues are critical toward formulation of an effective spatial strategy are: they provide immediate visual feedback indicating aircraft response to pilot control inputs. As an example, if a VMC solo pilot is using a real horizon as a primary spatial cue with the aircraft glare-shield serving as a secondary spatial reference, a sight picture depicting increasing separation between these two cues would suggest the aircraft nose is dropping in response to forward control stick movements. Conversely, a decrease in separation between primary and secondary cues would provide a pilot with visual feedback indicating the aircraft’s negative pitch angle was decreasing as the control stick was pulled backward. An important aspect of this spatial strategy is the concept that visual feedback from secondary spatial cues will move in the same direction as the stick control movements. This characteristic has been identified as a critical aspect of any human controlled system and is often referred to as the “principle of the moving part” (Roscoe, 1968).
In contrast to conventional SD training and design doctrines, recent research has shown that sensory spatial reflexes routinely impact perception of spatial cues within a pilot’s sight picture. Reflexes such as the opto-kinetic cervical reflex (OKCR) and opto-kinetic nystagmus torsion (OKN-T) have been shown to cause pilot head and eye rotation toward the horizon when looking “outside” the aircraft during VMC roll or pitch maneuvers (Patterson et al., 1997; Moore, 2008) (Figure 2B). Presumably, these intuitive sensory spatial reflexes improve spatial awareness by maintaining the horizon image as a retinally stabilized primary spatial cue, against which peripherally viewed cockpit images (secondary spatial cues) will appear to move in synchrony with the control inputs.

In-flight Perspective Illusions

Perspective illusions occur in part because humans have a strong instinctive tendency to consider themselves level with distant horizontal references, regardless of their true altitude (Bresson, 2003). Also contributing to perspective illusions is the fact that anything we view as being slightly above our perceived horizon will appear as being magnified in size and exaggerated in its elevation. The strength of this illusion can be verified by viewing the common “moon illusion” (also known as the “Ebbinghaus illusion”) which is a type of perspective illusion first identified in 350 BC (Roberts, 2005). This well-known spatial misperception occurs when a full moon located slightly above the horizon is perceived as being much larger than a full moon positioned directly overhead. In reality, the retinal images in both situations are the same; however, the human sensory-cognitive system has evolved in a manner that makes this illusion very convincing and difficult to overcome (Figure 3A). Although perspective illusions have been recognized and studied for centuries, the impact of these sensory misperceptions on aviation safety has only recently received close scientific scrutiny.

![Figure 3](http://www.moillusions.com/2008/09/ponzo-illusion-collection.html)

Among the confounding visual stimuli that can occur in flight, several visual perspective illusions have been identified as reoccurring mishap causal factors. Currently, these types of visual problems are defined as: “wings level”, “masked terrain”, “high wire”, and “black hole” illusions. The etiology of cockpit perspective illusions revolves around the premise that pilots will on occasion, inadvertently apply a real horizon spatial strategy to situations where only fixed horizons or stationary ground references are available. Within low level flight environments, perspective illusions can readily occur when rising terrain or deteriorating visual conditions obscure the real horizon and, subsequently, force pilots to rely upon whatever fixed horizontal references become available within their forward fields of view. In these situations, distant shore or ridgelines are often used as horizontal references; even though fixed ground images of this type have spatial dynamics considerably different from those generated by real horizon images. The major cognitive-spatial differences between real and fixed horizons are: with level flight, the curvature of the Earth causes real horizon cues to move backward in space at a rate constant with the aircraft’s forward movement. Because of this visual phenomenon, retinal image separation between the glareshield and horizon images will remain constant within a pilot’s sight picture, as long as the aircraft attitude also remains constant. However, if aircraft attitude deviates in the roll or pitch axis, there will be a corresponding change in retinal distance between the glare shield and horizon images. With a real horizon, changes in the sight picture between the horizon primary and glareshield secondary cues provide a pilot with immediate visual feedback that indicates both the direction and the extent of pitch or roll variations. In contrast, when distant ground references are viewed from the cockpit, initial visual angles between the object and cockpit are usually quite small and somewhat similar to the visual angle of the real horizon. However, unlike a real horizon that keeps moving backward when an aircraft in level flight goes forward, distant ground references that are fixed in space will slowly descend within a
pilot’s sight picture as the distance between the aircraft and object decreases. The reason for this shift in visual perspective is: rather than remaining stable, the visual angle of ground objects changes at an increasing rate as the distance between the aircraft and object are reduced. When pilots have a real horizon available to serve as their primary spatial cue, changing visual angles of ground objects seldom create any spatial misinterpretations; however, when flying in conditions where outside visual references are degraded by weather or darkness, loss of a real horizon reference can create situations where pilots rely on fixed ground points as their primary spatial cue. Unfortunately, mishap statistics verify the following perspective illusions listed below continue to pose a significant threat to aviators during both good visibility day conditions and low visibility night landing approaches:

**Wings Level Illusion** – Accident investigators have reported that during low-level flights, *wings level illusion* can readily occur when rising terrain blocks the real horizon, thereby causing pilots to rely on whatever distant horizontal references are available within their forward fields of view (Patterson, 2007; Macknik, 2012). In this situation, distant shore or ridgelines will often appear as reliable horizon cues even though they are fixed or false horizons with azimuths that are usually several degrees below the true horizon. Since fixed horizon cues do not move backward in space as an aircraft in level flight transits forward, these types of horizontal references will gradually drop lower within the pilots visual field; subsequently generating a gradual visual angle decrease that will cause the primary cue (fixed horizon) and secondary cue (glareshield) retinal separation to contract within the pilot’s sight picture. The spatial problem often encountered with this situation is: the gradually decreasing vertical distance between the fixed horizon cue and the glareshield will create the illusion that a level aircraft is nosing up and gaining altitude. In most cases, pilots flying through low level environments will compensate for this problem by frequently selecting new, more-distant fixed horizon references as they continue forward on the flight path; however, if an aviator in this situation attempts to use a fixed or false horizon as if it were a real horizon, the contracting sight picture may cause the pilot to react by slightly lowering the nose to keep the retinal distance between primary and secondary cues constant. This type of response will stabilize the sight picture (primary and secondary cue retinal distance) and generate the illusion that aircraft attitude is constant, even though the pilot may be unknowingly making slight increases in downward pitch to compensate for the changing visual angle between the glareshield and fixed ground reference. This *wings level illusion* is just one of several types of common perspective illusions encountered by pilots when they are forced to use a fixed, rather than real horizon.

**Masked Terrain Illusion** – When flying in low-level environments an additional form of the perspective illusion, referred to as *masked terrain illusion*, can readily occur when pilots are forced to rely upon fixed horizontal spatial cues instead of a real horizon. Similar to the *wings level illusion*, distant ridgelines often appear as reliable horizontal cues even though they are fixed or false horizons with azimuths that typically fall several degrees above the true horizon. Unfortunately, if there is a slightly lower ridgeline in front of a distant ridgeline being used as a horizontal reference, the front ridgeline will typically blend in visually (ie; become masked) with the more distant reference and may not become visually discernible until the aircraft reaches a point very close to the forward terrain. In the event a pilot is already experiencing *wings level illusion* while approaching a masked terrain area, ground impact may occur if a pilot fails to detect the forward obstruction within a recoverable reaction time. The terrain images in *Figure 4* replicate the primary cue perspective as it would have been viewed by a pilot involved in a recent *masked terrain illusion* aircraft accident. *Figure 5* illustrates the pilot’s trajectory deviation attributed to keeping the sight picture constant while experiencing a *wings level illusion*.

*Figure 4*: Left picture illustrates a front ridgeline visually blended with a more distant ridgeline. The right picture is the same image with a dotted white line added to indicate the location of the front (masked terrain) ridgeline.
Figure 5: The solid white line represents the initial climb-out trajectory started by a pilot involved with a masked terrain illusion accident and the dotted line represents the mishap pilot’s gradually reduced climb attributed to a combination of masked terrain and wings level illusions.

**High Wire Illusion** – Suspended wires are among the most significant threats faced by both military and civilian pilots (Patterson, 2010). Data from the National Transportation Safety Board indicates during a recent five year period (2005-2009) wire-strikes involving U.S. civilian pilots, damaged or destroyed 79 aircraft and caused 62 fatalities (Patterson, 2009). Within the U.S. Department of Defense, suspended wires also pose a major risk for military aviators that are often required to fly low altitude flights over unfamiliar terrain; U.S. Army reports indicate helicopter wire strikes average 3 to 4 per year and fixed wing aircraft within the Navy, Marine Corps, and US Air Force report wire strike averages of 2 to 3 per year (Nagaraj, 2008). Wire strikes can occur for reasons that range from inadequate planning to poor outside visibility; however, a specific perspective illusion identified as the high wire illusion has been attributed to several wire strike accidents involving both fixed wing and rotary wing aircraft. In several of these incidents, pilots gave similar description of this illusion by stating, “...the wires came out of nowhere, and looked like they were above us and rising. I only had a second to react by bunting the nose down to try to avoid them...”. Characteristic of this illusion are reports that when wires are first spotted, mishap crews usually have very limited time to react (4-6 seconds) and in each documented case of high wire illusion the pilots believed they were at or below the wire altitude, when in actuality they were typically 100 ft. above the obstruction when it first came into view. If a suspended wire is positioned near or slightly below an aircraft’s level flight path, its visual angle (as seen by the pilot) will be very small or near zero; subsequently the image of the suspended object will remain fixed or stable within the pilot’s sight picture. In contrast, if the pilot is in a situation where it is necessary to use a fixed, rather than real horizon, the visual angle of the more distant and physically lower fixed horizontal reference will first slowly and then rapidly increase as the aircraft approaches (similar to wings level illusion describe previously). At a point dependent upon the aircraft’s altitude and relative distances from the fixed horizon and suspended object, the suspended object (which will be centered on the fovea and therefore remain relatively stable in the sight picture) will appear to rise out of the visual ground clutter as the fixed horizon cue moves lower within the visual field. At this point, there is a high probability that a pilot will misperceive the suspended object as being above his aircraft and rising, even though the object is stationary, and may still be well below the aircraft’s flight path. Unfortunately, in the limited amount of time available, pilots in this situation often instinctively react to this misperception by diving down to avoid what they perceive to be a high wire slightly above their flight path. Although, the high wire illusion is primarily generated from misperceptions of spatial cue movement within a pilot’s sight picture, perspective lines such as those created by the sides of river banks or valley walls have been shown to further reinforce the high wire illusion via the Ponzo perspective illusion; which is known to amplify spatial misperceptions of object height and distance (Ganel, 2008 / Figure 3B).

**Black Hole Illusion** – Aviation spatial disorientation summaries often reference the visual phenomenon known as the black-hole illusion. The following excerpt provides what has become the conventional description of this common visual problem: “A black-hole approach is one that is made on a dark night over water or unlighted terrain to a runway beyond which the horizon is indiscernible, the worst case being when only the runway lights are visible. Without peripheral visual cues to help him or her orient relative to the earth, the pilot tends to feel that the aircraft is stable and situated appropriately but that the runway itself moves about or remains malpositioned (is down sloping, for example). Such illusions make the black-hole approach difficult and dangerous and often results in a landing far short of the runway.” (Dehart, 1996). Recent pilot surveys and mishap statistics indicate excessively low black-hole landing approaches occur frequently among military pilots. Navy and Marine Corps flight crews report black-hole as the second most commonly encountered visual problem, surpassed only by misinterpretation of fixed horizon cues (Gallimore, 2003). Air Force surveys reinforce the severity of this cognitive threat by citing black-hole illusion as the leading visual problem for flight crews of multi-engine aircraft; and among all types of USAF pilots, the third most cited form of spatial disorientation (Matthews, 2002). On a dark night, with no visible “real” horizon present, pilots may unconsciously attempt to use their day/VMC spatial strategy by
substituting the fixed ground cue of the runway as their primary horizontal reference. The problem with employing this spatial strategy at night is: unlike a real horizon which moves backward in space as the plane progresses forward, the viewing angle of the fixed runway image will slowly progress downward as the distance between the aircraft and the airfield continues to decrease (in a manner similar to the wings level illusion). Under these circumstances, the only way a pilot can maintain a constant “sight picture” is to slightly increase the aircraft’s downward pitch angle (Patterson, 2011). Since this action is assumed to be an undetected reflexive response (rather than a well thought out process), it provides a credible hypothesis as to why pilots frequently enter into unintentional low and fast approaches during dark night landings.

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