The Search for the Opto-Kinetic Cervical Reflex and Reduced Roll Reversals in Pilots Viewing a 3-D Perspective Display

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THE SEARCH FOR THE OPTO-KINETIC CERVICAL REFLEX AND REDUCED ROLL REVERSALS IN PILOTS VIEWING A 3-D PERSPECTIVE DISPLAY

By

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B.A., The College of New Jersey, 2000

A Thesis Proposal Submitted to the Department of Human Factors & Systems in Partial Fulfillment of the Requirements for the Degree of Master of Science in Human Factors & Systems

Embry-Riddle Aeronautical University Daytona Beach, Florida
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Since John Carl embarked on that thesis
He’s never known truly what peace is.
But once it’s defended
The drudgery’s ended,
And most of his suffering ceases.

(Malcolm and Helen Stern)
THE SEARCH FOR THE OPTO-KINETIC CERVICAL REFLEX AND REDUCED ROLL REVERSALS IN PILOTS VIEWING A 3-D PERSPECTIVE DISPLAY

By

John Carl Faust

This thesis research proposal was prepared under the direction of the candidate's thesis committee chair, Shawn Doherty, Ph.D., Department of Human Factors & Systems, and has been approved by the members of the thesis committee. It will be submitted to the Department of Human Factors & Systems in partial fulfillment of the requirements for the degree of Master of Science in Human Factors & Systems.

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Abstract

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Title: The Search for the Opto-kinetic Cervical Reflex and reduced roll reversals in pilots viewing a 3-D perspective display.
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Pilots using conventional instrumentation can suffer spatial disorientation (SD) when unexpectedly forced to transition from visual flight to instrument flight during roll maneuvers. This simulator study was conducted to see if a 3-D perspective display could prevent this form of spatial disorientation by eliciting the opto-kinetic cervical reflex (OKCR), an instinctive postural response that humans use to maintain awareness of their spatial orientation. The current research found evidence of the OKCR in pilots viewing both a 3-D perspective display and an electronic attitude indicator. Pilots viewing a standard moving-horizon attitude indicator produced little or no OKCR response. However, pilots still showed some indication of SD during transitions from visual flight to instrument flight while using the 3-D perspective display.
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Introduction

Humans have evolved in a three-dimensional world that consists of “….visible objects and surfaces which usually maintain a constant relation to gravity and provide a visible frame of reference.” (Howard and Templeton, 1966, p.176 as cited by Liggett, 2000; Previc, 1998). Humans have adapted to this environment by using these visual cues and a subconscious awareness of gravity to orient themselves. When powered flight first began pilots could still use this orientation strategy because aircraft were flown only during good weather when the horizon was clearly visible. However, for aircraft to be truly practical pilots needed to fly in poor weather and at night. This requirement forced the development of instruments that would allow flight in low visibility conditions. These instruments provide orientation cues to the pilot when real-world visual cues are not visible (Liggett, 2000). The instruments used in modern aircraft are based, in large part, on these early instrument designs.

Researchers have found that pilots can have trouble maintaining orientation during instrument flight. This difficulty seems to be caused by a number of factors including a lack of real-world visual orientation cues, a pilot’s inability to differentiate between acceleration forces created by the aircraft and the force of gravity, and with problems in the design of the instruments pilots use for orientation (Gillingham and Previc, 1993). When pilots cannot correctly orient themselves they experience spatial disorientation.
Statement of the Problem

Gillingham and Previc (1993, p. 77) define Spatial Disorientation (SD) as “an erroneous sense of one’s position and motion relative to the plane of the earth’s surface.” If this condition is not recognized it can lead to a loss of aircraft control and ultimately to loss of life (Patterson, Cacioppo, Gallimore, Hinman, and Nalepka, 1997).

Spatial disorientation is pervasive. There is an aviation saying that asserts, “there are two kinds of pilots, those who have experienced SD and those who don’t know they’ve experienced SD” (Baker, 1998, p8). Accident reports indicate that the “typical” pilot involved in a SD related accident has ten years of experience and over 1500 hours in the cockpit (Patterson et al., 1997). Therefore spatial disorientation is a danger to all aviators regardless of their skill or training.

Year after year SD exacts a substantial cost in terms of property damaged or destroyed and in lives lost. Recent reviews of military accident reports show that between 1980 and 1989 the Navy and Air Force suffered a combined total of 382 major aircraft accidents where spatial disorientation was thought to be a factor (Patterson et al., 1997). A similar review of General Aviation (GA) accidents shows that between 1976 and 1992 there were 1022 fatal GA accidents in which spatial disorientation was at least partially involved (Jaslow, 1998).

Military pilots are provided with excellent training, advanced aircraft, and the latest instrumentation. Yet they are not immune to SD. Gallimore, Patterson, Brannon, and Nalepka (2000) found that, during an average year, pilot error due to “sensory or cognitive misperceptions” costs the military a total of 60 aircraft worth over $300 million dollars. Fifty crewmembers are lost as well.
Even with improvements in aircraft and instrument design the SD problem persists. Ercoleine, DeVilbiss, and Lyons (1994) conducted a review of SD-related military aircraft accidents that occurred between 1958 and 1992. They found that the SD accident rate has remained relatively constant through this 34-year period.

Review of the Literature

Humans maintain spatial orientation through the interrelated action of three different sensory systems. These senses include the somatosensory system, vestibular system, and vision (Gillingham and Previc, 1993; Leibowitz and Dichgans, 1980).

The Somatosensory and Vestibular Systems

The somatosensory system receives signals from receptors located in the skin, muscles, and joints. The somatosensory system allows humans to sense the location and movement of their body and limbs. The somatosensory system is also involved in balance and posture control. The somatosensory system is highly integrated with the vestibular system.

Figure 1. Axes of aircraft motion. Gillingham and Wolfe (1985).
The vestibular system is composed of two sets of sensing organs located deep in each ear. These organs are the semicircular canals that discriminate rotational acceleration in three different axes of movement (roll, pitch, and yaw- see figure one) and the otolith organs that recognize linear acceleration and tilt.

The forces that act on the human body while in flight are more complex and varied than the forces humans have adapted to on the surface of the earth (Gillingham and Previc, 1993). The vestibular system often misinterprets this complex and atypical information and this perceptual confusion leads to SD. The vestibular system is designed to sense comparatively abrupt movements with a short duration. Consequently the vestibular system has difficulty sensing gradual movements. That is why, if a pilot does not have a visible indication of the aircraft’s orientation, they may not notice a gradual change in pitch or roll until the aircraft has deviated substantially from its intended attitude.

The human vestibular system has evolved in a terrestrial environment where there is a ubiquitous linear force, gravity, which consistently acts in a downward direction (Baker, 1998). The vestibular system senses the effect of gravity and humans automatically rely on their sense of gravity to help determine their spatial orientation (Friederici and Levelt, 1987). During flight maneuvers the vestibular system may be misled by the acceleration forces caused by a turn, climb, or decent. These acceleration forces can skew a pilot’s judgment of which way is down. This happens because the vestibular system is not able to differentiate between the force of gravity and other accelerative forces. The vestibular system tends to “combine” the gravity force with acceleration forces of a turn or altitude change and this combination results in an
incorrect sense of the true gravity vector (Jaslow, 1998). For these reasons the vestibular system cannot be relied on for accurate orientation information during flight.

Vision

Goldstein (2002) describes the two types of receptors found in the human visual system as centrally located cone-shaped structures that provide high-acuity color vision and peripherally located rod-shaped structures that provide low-acuity black and white vision.

Vision plays a primary role in human spatial orientation (Clapp, 1985; Gillingham and Wolfe, 1985). The dominance of vision in orientation is clearly demonstrated by people who have damage to their vestibular systems. These people, known as labyrinthine defectives, can still orient themselves effectively if they can see their surroundings (Gillingham and Wolfe, 1985). Similarly, when a pilot has a clear view of the horizon that image provides most of the information the pilot requires to maintain the aircraft’s orientation (Gillingham and Previc, 1993). When a pilot flies using this view of the world outside the aircraft for orientation they are said to be flying in Visual Meteorological Conditions (VMC).

Visual Dominance

It is important to understand that whenever a pilot alters the course of an aircraft significantly their vestibular system may misinterpret the resulting accelerative motion cues. These misleading vestibular sensations usually do not affect the pilot’s perception of the aircraft’s attitude when the pilot can see the horizon. This is because the human
orientation system automatically favors visual information over information from the vestibular and somatosensory systems. This important process is called visual dominance (Gillingham and Wolfe, 1985).

Researchers have tested the visual dominance phenomenon by deliberately placing visual stimuli in conflict with stimuli from the vestibular system. Lessard, Stevens, Maidment, and Oakley (2000) conducted one such test to determine if visual information would override a vestibular sensation of either constant rotation or changes in rotational speeds. Lessard et al. found that when visual information conflicted with vestibular information, depending on conditions, up to 69% of subjects experienced visual dominance.

Ercoline, Yauch, and Holoviak (1997) used a moving flight simulator to demonstrate the effects of different SD illusions to pilots. A combination of simulator motion and a lack of visual orientation cues were used to elicit spatial disorientation in the participants. When questions revealed a subject was experiencing SD researchers turned on the out-the-window view. Participants reported that the SD rapidly disappeared when the visual scene was displayed.

The results of these two studies reinforce a key point for the current research. The visual system can automatically override erroneous vestibular cues and provide orientation information that is essential for the prevention of spatial disorientation. Visual research indicates the orientational function of the visual system is separate from other visual processes. This idea is described in the two modes of processing concept.
Two Modes of Processing

In 1967 Schneider conducted a study that investigated the visual abilities of the golden hamster. The results of this study indicated that a hamster's ability to discriminate patterns was apparently separate from their ability to orient themselves in their surroundings (Leibowitz, Post, Brandt, and Dichgans, 1982). This study also indicated that different aspects of a visual scene are processed by different parts of the brain. This idea, labeled the "two visual systems" concept, was later expanded to explain various aspects of visual function in both primates and humans (Held, 1968 as cited by Leibowitz et al., 1982). Held used the term "two modes of processing" to accentuate the functional aspects of this concept when it is applied to human visual function. Held stressed that this convention be used because the human visual cortex is much more complex then the visual cortex found in the hamster (Held, 1970 as cited by Leibowitz et al., 1982).

The two modes of processing concept divides vision into two unique functional subsystems. One system is known as the focal visual mode (Clapp, 1985) and may also be referred to as the focal extrapersonal visual realm (Previc, 1998). The other system is known as the ambient visual mode (Clapp, 1985) and is also referred to as the ambient extrapersonal visual realm (Previc, 1998). Each mode has unique characteristics.

The focal visual mode is used for object recognition and identification. Focal vision accomplishes these tasks by using highly detailed information from the cones. (Gillingham and Previc, 1993) Focal vision is dependent on the clarity of an image reaching the eye; as image sharpness is reduced the ability to identify objects decreases. Focal vision is affected by light intensity; as light levels decline focal vision is less
effective. Focal vision is within conscious control of the observer. Humans choose where they focus their gaze and they are usually aware of what they see. (Leibowitz and Dichgans, 1980) Pilots use the focal visual mode to identify objects in their environment, to make judgments regarding distances and depth, and to distinguish highly detailed images such as the text and symbols found on aircraft instruments (Gillingham and Previc, 1993).

The ambient visual mode is involved in spatial orientation, gaze stability, locomotion, and posture control (Leibowitz and Post, 1982; Sharkey and Hennessy, 2001). There is some disagreement in the literature as to precisely what areas of the retina are involved in ambient vision. Clapp (1985); Leger, Valery, and Bignolles (2000) state that ambient vision is a function of the peripheral retina. Leibowitz and Post (1982); Leibowitz, Shupert, and Post (1984); Previc (1990) Sharkey and Hennessy (2000); and Sharkey and Hennessy (2001) indicate that ambient vision responds to receptors located across the entire retina.

Ambient vision operates on the principle of mass action. The term mass action simply means the ambient visual response to visual stimuli increases in speed and strength as more receptors are activated (Sharkey and Hennessy, 2001). Ambient vision is not dependent on the clarity of an image; it functions effectively even if the image is blurred (Leibowitz and Post, 1982). Ambient vision does not degrade as light levels decrease, instead, ambient vision seems to have an all or nothing response to visual stimuli and it functions down to the absolute threshold of light detection (Clapp, 1985). Ambient vision appears to operate with little or no conscious awareness (Gillingham and Previc, 1993).
Ambient vision reacts to movement of the distant visual field (Previc, 1998), especially those images that are perceived as the background (Previc, 1993). Therefore, visual stimuli that are perceived as close to the observer should not activate the ambient visual mode. Brandt, Wist, and Dichgans (1975) conducted an experiment to determine the effect of location in depth of stationary and moving contrast fields on a subject’s dynamic spatial orientation. For this experiment both stationary and moving contrasts were simultaneously presented at different distances from the subject. Brandt et al. found that visual stimuli presented in the foreground had a weak effect on subject orientation. The same visual stimuli presented as the background had a powerful effect on spatial orientation. Brandt et al. concluded that human spatial orientation relies heavily on visual information found in the retinal periphery and depth periphery.

Previc (1993) also recognized the importance of perceptually distant stimuli in spatial orientation. His study provided subjects with a helmet-mounted display (HMD) of a visual scene in an attempt to prevent a motion-based spatial disorientation illusion. When the visual scene failed to prevent the SD Previc acknowledged that the close perceptual proximity of the head-mounted display to the subject might be the primary reason it was not effective. Previc concluded that, “If the display properties of an HMD do not create the illusion that its attitude symbology is located beyond the aircraft, then that HMD may be ineffective in generating truly ambient orientational percepts…” This idea is central to the current research. A perceptually distant image of the horizon is required to activate the ambient visual mode. A cockpit display of attitude information that lacks depth may not elicit a response from the ambient visual system and its attendant orientational functions.
**Visual-vestibular Interaction**

The ambient vision mode provides spatial orientation through a complex interaction with the vestibular and somatosensory systems (Leibowitz and Post, 1982; Leibowitz et al., 1984). As people move within their environment the flow of visual information across the retina shifts and changes. Humans use this visual information flow to maintain their orientation and adjust their posture. This process is automatic and usually occurs without conscious awareness.

Lee and Aronson (1974) conducted research that illustrates the link between ambient vision and reflexive posture control. During this experiment subjects stood in the center of an uncommonly constructed room. While the floor of this room remained stationary the walls and ceiling were designed to move in, unison, back and forth around the standing person. The movement of the room was designed to replicate the optic flow of the surrounding environment visually experienced by a person who is swaying back and forth. When exposed to this visual stimulus a subject will automatically lean in a direction opposite to the optic flow, in an attempt to “maintain” their balance. Subjects exhibited this compensatory leaning effect with room movements as small as six millimeters. As researchers moved the room back and forth the subjects “swayed like puppets visually hooked to their surrounding…unaware of the real cause of their disturbance” (Lee & Aronson, 1980 as cited by Goldstein, 2002).

The moving room experiments reveal the powerful influence of visual orientation information in human posture control. In fact this visual information is so strong it can completely override balance and posture information provided by the vestibular and somatosensory systems (Lee & Aronson, 1980 as cited by Goldstein, 2002).
The Opto-kinetic Cervical Reflex

In 1973, Hasbrook and Rasmussen observed another postural phenomenon that also seems to be a result of the link between the ambient visual mode and vestibular system. Hasbrook and Rasmussen were studying the in-flight performance of pilots using two different aircraft instruments. During the test flights the safety pilot noticed that pilots seemed to tilt their heads in a direction opposite to the aircraft's bank during turns while flying in Visual Meteorological conditions (VMC) (Hasbrook and Rasmussen, 1973).

In 1995 Patterson conducted a detailed study of this head-tilt phenomenon, which he labeled the Opto-Kinetic Cervical Reflex (OKCR). Patterson theorized that this compensatory head movement allows a pilot to maintain a relatively level image of the horizon on their retina. This stable image of the horizon seems to act as a primary visual cue while concurrent movement of the cockpit structures, visible in the pilot's peripheral field of view, act as secondary spatial cues allowing the pilot to maintain awareness of the aircraft's changing orientation relative to the earth and thus maintain spatial orientation (Gallimore, Brannon, Patterson, and Nalepka, 1999; Patterson et al., 1997).

This arrangement provides an additional benefit in that secondary spatial cues move in the same direction as control movements. This visual-spatial strategy follows...
the principle of compatible motion (Gallimore et al., 1999). Sanders and McCormick (1993) applied the principle of compatible motion to vehicle control and state that vehicle movement should follow control movement. For example, turning a steering wheel to the right to turn the vehicle right. The OKCR provides this compatible motion because the pilot’s head stays relatively normal to the horizon while the aircraft tilts. Therefore, as the pilot moves the yoke to the right the peripherally viewed cockpit moves right as well.

Patterson had pilots fly a series of maneuvers during VMC and Instrument Meteorological Conditions (IMC) flights in a fixed-base flight simulator. These tasks included solo navigation, coordinated turns, and pitch maneuvers. Pilots completed each of these tasks while flying solo and in formation with a simulated lead aircraft. Patterson tracked the OKCR response of the pilots during each of these tasks by using a head-tracking device that senses and records the position and movement of each subject’s head. The head-tracking data was synchronized with aircraft roll data from the simulator to determine pilot head tilt in relation to aircraft roll motion. (Patterson, 1995)

Patterson carefully documented pilot head tilt response in each condition. He found that OKCR response varies throughout aircraft roll. For example, during solo low-level navigation in VMC, pilots showed three different phases of head tilt. First, pilots exhibited negligible head tilt up to ±5° of aircraft bank. Second, from ±5° to ±30° of aircraft bank pilots exhibited a 3:1 head tilt. In other words for every 3° of aircraft bank the pilot’s head tilted 1° in the opposite direction to compensate. Third, once the aircraft passed ±30° of bank the pilot’s head tilt continued to increase at a gradually reducing rate until the aircraft reached its maximum bank angle of 80°. Maximum head tilt was 16° ±7.0 (Patterson, 1995).
**Ambient Vision as Theory for OKCR**

The OKCR research that has followed Patterson's 1995 work has focused mainly on noting the presence of the OKCR in pilots operating under various conditions. These conditions include aircraft type (Braithwaite, Alvarez, Jones, Higdon, Groh, Beal, and Estrada, 1997; Merryman and Cacioppo, 1997; Shimada, 1995); pilot field of view (Gallimore et al., 1999; Gallimore et al., 2000); active verses passive flight tasks (Smith, Cacioppo, and Hinman, 1997); and variations in simulator motion (Gallimore, Liggett, and Patterson, 2001).

To date, there has not been an explicitly stated theoretical explanation for the OKCR phenomenon. The current research proposes that the OKCR may be an expression of the ambient visual mode. There are a number of similarities between the ambient visual mode and the OKCR that suggests a correlation between these two phenomena. The balance of this literature review will attempt to point out a number of parallels between ambient vision and the OKCR.

Leibowitz and Post (1982) indicate that focal vision and ambient vision operate independently and simultaneously. They use an example of a person walking while reading a book to demonstrate this principle. The person uses focal vision to read the words on the page while ambient vision allows them to move through their environment and navigate around large obstacles.

Two of the OKCR studies have shown a similar disassociation between focal vision and the OKCR. Patterson (1995) and Gallimore et al. (2000) conducted simulator studies in which pilots flew in formation with a computer-generated lead aircraft. While the pilots fixated on the lead aircraft with their focal vision the ambient visual system
continue to function as was evidenced by the presence of the OKCR during banked turns. When the visual image of the horizon was removed, leaving only the focal stimulus of the lead aircraft, the OKCR stopped. This indicates that the OKCR was responding only to the horizon stimulus. The focal stimulus of the lead aircraft had no apparent effect on the OKCR thus demonstrating the independent and simultaneous nature of the OKCR relative to foveal vision.

Ambient vision responds to movement of visual images on the retina and uses that information for spatial orientation and posture control. Braithwaite et al. (1997); Patterson (1995); and Smith et al., (1997) suggest the OKCR is also a postural reflex that is driven mainly by the rotation of the horizon image on the fovea and near-peripheral visual field. The visual stimulus of the tilting horizon image seems to elicit the OKCR in a manner similar to the compensatory leaning response exhibited by subjects in the moving room study described in the previous section.

Ambient vision responds to movement of the distant visual field (Previc, 1998). Previc (1993) suggests that stimuli must be perceived as “beyond the reach of the observer” in order to trigger the ambient visual mode. Braithwaite et al. (1997); Gallimore et al. (1999); Gallimore et al. (2000); and Patterson (1995) conducted studies that looked for OKCR responses during VMC flight and IMC flight. The researchers found that pilots exhibited the OKCR while looking at the distant horizon during VMC flight. Conversely, the pilots did not show evidence of the OKCR while watching the attitude indicator in IMC flight. These results suggest the OKCR is responding to the distant visual stimulus provided by the real horizon but not to the close visual stimulus presented by the attitude indicator.
Two studies that looked for pilot OKCR response during VMC flight and IMC flight found different results. Liggett (2000) tested the effect of a helmet-mounted display (HMD) of attitude symbology on the OKCR response. In this study pilots did not show evidence of the OKCR during VMC or IMC flight. Given these results, Liggett theorized that the pilots were selectively focusing on the HMD attitude symbology during both VMC and IMC flight.

Gallimore, Liggett, and Patterson (2001) conducted a series of experiments that looked for the OKCR under various conditions. Two of the HMD experiments showed evidence of the OKCR during VMC flight as would be expected. The third experiment found very limited head tilt in VMC. Again the researchers determined that the pilots were focusing on the attitude symbology on the HMD in order to hold a particular bank angle rather than looking at the out-the-window view of the horizon. These results support the idea that the OKCR is sensitive to far domain movement and not sensitive to near domain movement.

The ambient visual response to visual stimuli decreases as the number of stimulated receptors is reduced due to the property of mass action. When performing visual research scientists often refer to a subject’s field of view (FOV) to describe how much of the retina is exposed to visual stimuli. Logic would suggest that a given number of receptors are exposed to the visual stimuli provided by a given FOV. Therefore, as the FOV is reduced the number of receptors exposed to a visual image is reduced as well.

Two experiments have been conducted that were specifically designed to determine the effect of FOV on the OKCR response. Gallimore et al. (1999) conducted a simulator study in which the pilot’s FOV was restricted to 40, 60, and 100 degrees
circular. The researchers found that the FOV manipulation had no effect on the intensity of the OKCR response. However, Gallimore et al. (2000) conducted an OKCR study that used four levels of FOV. For the first part of the study the pilot’s FOV was 180°. During the second part of the study the pilot’s FOV was restricted to 40, 60, and 100 degrees circular. The 40 to 100 degree FOV manipulation had no effect on the OKCR response. However, Gallimore et al. found that the OKCR response from the 180° FOV condition was significantly stronger then the OKCR response found during the 40 to 100 degree FOV test. This result suggests the OKCR is affected by larger changes in FOV. Consequently the 40 to 100 degree FOV manipulation used by these two studies may have been too small to generate a noticeable change in OKCR response.

A comparison of OKCR responses recorded in seven different studies seems to reveal a relationship between FOV and the strength of the OKCR response. Figure three combines the results of studies using FOV’s ranging from 360°, 180°, (40°, 60°, 100° combined), and 24° for pilots flying fixed-wing aircraft or fixed-wing aircraft simulators. The graph in figure three shows the OKCR response generally decreasing as FOV is reduced. The slope of the OKCR response line graphically indicates the strength of the OKCR response. This graph seems to support the idea that large changes in FOV generate noticeable differences in the strength of the OKCR response. It is important to note that while smaller changes in FOV should affect the OKCR response, the difference in the slopes may not be considered significantly different when using regression analysis and ANOVA techniques.
The ambient visual response does not degrade as illumination levels decrease.

Braithwaite et al. (1997) compared pilot OKCR response during flights in daylight conditions and at night in simulated "half moonlight conditions" while using night vision goggles (NVGs) in a helicopter simulation. It is important to note that during the daytime condition the pilot had a 160° view of the horizon from the out-the-window view. In the nighttime condition the pilot wore NVGs that restricted FOV. Braithwaite et al. did not include the FOV specifications for the ANVIS Mk6 night vision goggles, however, the Night Vision Equipment Company website states that this NVG has a FOV of 40°.

Braithwaite et al. did not describe any attempt to control for FOV during the study so the FOV variables and lighting variables may be confounded. Pilots were exposed to either a 160° FOV daylight view of the horizon or a 40° FOV nighttime NVG view of the
horizon. Braithwaite et al. reported “no strong significant differences in the magnitude of the OKCR between the two conditions.” Of the five tasks conducted in both day and night conditions only one task revealed a significant difference in the OKCR response between day and night conditions. The lack of “strong significant differences” in the OKCR in spite of the extreme differences in the two conditions provides credible evidence that the OKCR response does not degrade as illumination levels decrease.

The aforementioned studies demonstrate many similarities between the ambient visual system and the OKCR. These findings also suggest that the function of these two phenomena may be based on the same underlying mechanisms. However, most of these effects have been shown only under VMC conditions. Pilots often fly at night or in bad weather when visibility outside the aircraft is limited or nonexistent and visual flight is not possible. At this point pilots must use the aircraft instruments to maintain spatial orientation and control the aircraft.

_Aircraft Instruments_

Modern aircraft use six primary flight instruments including the airspeed indicator, attitude indicator, altimeter, turn and slip indicator, compass, and vertical speed indicator. The current research will focus on the attitude indicator (AI) because it is the primary instrument pilots use to maintain spatial orientation during IMC flight. The AI consists of a miniature image of the horizon and a symbol that represents the aircraft relative to that horizon. The pilot uses this instrument
to determine the attitude of the aircraft relative to the earth. Figure four shows a typical attitude indicator.

During instrument flight pilots typically scan all six primary instruments for flight information while concentrating primarily on the attitude indicator. For example, Spady (1978) studied the instrument scanning behavior of airline pilots during instrument approaches. During this study Spady found that pilots spent 75% of their instrument scan time focusing on the attitude indicator. This constant monitoring of the AI is necessary to maintain awareness of the aircraft's orientation and to prevent spatial disorientation. Unfortunately, researchers have found that pilots can have problems with the attitude indicator. Many of these problems can be traced to a concept known as the pilot's frame of reference.

**Pilot Frame of Reference**

The pilots' frame of reference (FOR) refers to how pilots perceive the movement of their aircraft, and themselves, relative to the earth during flight. Researchers have not reached a consensus regarding the pilot's FOR consequently there are two opposing viewpoints.

The "traditional" view holds that the pilot uses an aircraft-based frame of reference. This simply means that while flying the pilot sees the aircraft, and themselves, as stable while the horizon moves and tilts beyond the aircraft's windscreen. Figure five shows an illustration of the aircraft FOR. An attitude indicator designed with an
aircraft FOR is often referred to as a moving-horizon indicator or "inside-out" display (Johnson & Roscoe, 1972). Figure four shows a typical moving-horizon AI. This instrument shows the horizon moving and tilting behind a fixed, abstract, aircraft symbol thereby providing the aircraft FOR.

Most aircraft flown in the United States are equipped with moving-horizon attitude indicators. Small aircraft usually have an electromechanical version of the moving-horizon AI (figure four) while many modern passenger jets and fighter aircraft use its modern equivalent, the Electronic Attitude Indicator (EAI) (Previc and Ercoline, 1999). See figure six.

Poppen, a naval flight surgeon, summed up the rational for the aircraft FOR in 1936 by stating that the attitude indicator should be like a "porthole" through which the pilot viewed an exact analog of what they would see while looking out the cockpit window (Roscoe, Johnson, and Williges, 1980). In fact, both Poppen and Doolittle supported the moving-horizon attitude indicator design based on their belief in the efficacy of the aircraft FOR (Roscoe et al., 1980). A key assumption of the aircraft frame of reference is that pilots keep their head in line with their body and the z-axis of the aircraft as the
aircraft rolls (Gallimore et al., 1999). If this were the case the moving-horizon attitude indicator would provide an image of the horizon that should match the pilot's view out the window as shown in part A of figure seven.

The other orientation strategy is known as a world-based frame of reference. A world-based FOR holds that while flying the pilot sees the aircraft, and themselves, as moving and tilting relative to a stable and motionless horizon. Figure eight shows an illustration of the world-referenced view. Attitude indicators that are designed with a world frame of reference are often called moving aircraft displays or “outside-in” displays because they show an image of a miniature aircraft moving in front of a stable horizon. Figure nine shows a proposed moving aircraft attitude indicator.

It is interesting to note that the moving-horizon attitude indicator has been accepted as the standard attitude indicator in the U.S. aviation community in spite of the fact that pilot performance with this display has been problematic. In fact the aircraft FOR, which the moving-horizon Al is based on, is now largely accepted as a de facto standard in U.S. human factors literature. For example, a human factors text by Sanders and McCormick (1993) supports the use of the aircraft FOR in the following statement against the use of moving aircraft displays:
Such displays are also called outside-in, bird’s eye, or ground-based displays. When the real plane banks to the left, the display indicator (the plane symbol) also rotates to the left. The problem is that the pilot sitting in the cockpit does not see the real horizon as level and his or her plane as tilted. What the pilot sees out the cockpit window is a tilted horizon and an aircraft that from the pilot’s frame of reference is horizontal. (Sanders and McCormick, 1993, p. 153).

The OKCR research provides strong evidence that the above statement is false. The OKCR research shows that in VMC conditions pilots tilt their heads to compensate for aircraft movement and to hold the horizon line relatively level thus using a world-referenced view (Smith et al., 1997). The moving-horizon AI, however, is designed with an aircraft FOR. Therefore, pilots must change their orientation strategy from a world FOR to an aircraft FOR when they transition from VMC flight to IMC flight when using the moving-horizon AI (Patterson, 1995). This frame of reference conflict is illustrated in Part B of Figure seven. The OKCR research confirms that pilots do switch frames of reference during the VMC to IMC transition because pilots exhibit the OKCR during visual flight but not during instrument flight while using the moving-horizon AI (Gallimore et al., 1999; and Gallimore et al., 2000; Patterson, 1995).

This required switch between frames of reference forces the pilot to reverse their orientational percept at the moment of VMC to IMC transition. As stated earlier, the OKCR provides a stable image of the horizon that acts as a primary visual cue while concurrent movement of the cockpit structures, visible in the pilot’s peripheral field of view, act as secondary spatial cues allowing the pilot to maintain awareness of the aircraft’s changing orientation (Gallimore et al., 1999; Patterson et al., 1997). These
secondary spatial cues move in the same direction as control movements thus following the principle of compatible motion.

At the instant of VMC to IMC transition the OKCR stops and the pilot’s peripheral view of the cockpit is suddenly motionless. The cessation of the OKCR causes the pilot to lose motion compatibility between control movements and aircraft movements. At the same time the moving-horizon attitude indicator, which is designed with an aircraft FOR, responds to pilot control movements by moving in a direction opposite to control motion. When the pilot turns the yoke right the AI rotates left (Gallimore et al., 1999). This forced switch between frames of reference and the resulting perceptual changes may confuse and disorient the pilot during the VMC to IMC transition thus leading to spatial disorientation.

Gillingham and Previc (1993); Liggett and Gallimore (2002) state that VMC to IMC transitions are especially likely to produce disorientation. Bellenkes, Bason, and Yacavone (1992) conducted a review of 33 naval aviation incidents that occurred in the 1980’s and found that many of the in-flight SD incidents occurred while pilots were attempting to transition from VMC to IMC flight.

Collins and Harrison (1995) conducted a SD survey of 96 F-15C Desert Storm combat veterans shortly after they returned from the Gulf War. The survey was used to determine the frequency of SD episodes during various combat-related flight tasks. The study also tracked the effect of weather and nighttime verses daytime operations on the SD rate. Collins and Harrison were especially interested in what effect visual transitions from the out-the-window view to instruments (or the reciprocal) would have on the occurrence of SD. Accordingly SD frequency counts were separated into “Visual
Transition (VT) and No Visual Transition” (No VT) categories. Collins and Harrison found that, throughout daytime flights, pilots experienced 1.88 times more SD events during VT conditions then in No VT conditions. The survey also showed that, during flights in poor weather, pilots reported 1.94 times more SD events during VT conditions then in No VT conditions. Interestingly, pilots reported having half as many SD events during VT conditions then in No VT conditions during nighttime flights. Collins and Harrison did not offer a rationalization for this last finding. One possible explanation is that pilots were experiencing SD but were unaware of it. If the nighttime conditions offered few visual cues this could be possible.

Patterson (1995) and Gallimore et al. (1999) suggest that the transition from VMC to IMC conditions is a frequent contributor to spatial disorientation, most likely due to the switch between the two different frames of reference. Spatial disorientation that occurs during the VMC to IMC transition often takes the form of roll reversals.

**Roll Reversals**

During the transition from visual flight to instrument flight pilots may misinterpret the movement of the horizon line on the moving-horizon attitude indicator as indicating movement of the aircraft’s wings instead of movement of the horizon. This error becomes apparent when the pilot attempts to roll the aircraft in one direction and mistakenly rolls it in the opposite direction (Patterson, 1995). The act of rolling the aircraft in the wrong direction is known as a roll reversal.

Researchers have found that pilots are susceptible to roll reversals. Fitts and Jones (1961) conducted a review of pilot errors in reading and interpreting aircraft
instruments. They found that seven percent of experienced pilots reported committing roll reversals with the moving-horizon attitude indicator during typical flight conditions.

Hasbrook and Rasmussen (1973) studied the in-flight performance of pilots using moving-aircraft and moving-horizon attitude indicators. One part of this study focused on roll reversals committed during recovery to level flight during IMC. Certain procedures were followed to insure the test pilot would have no awareness of the aircraft’s initial attitude. When instructed the test pilot would take control of the aircraft, scan the instruments, and attempt to bring the aircraft to a wings level attitude. The subject’s response was scored as a roll reversal if their initial control input increased the bank angle of the aircraft more than two degrees above the bank angle recorded at the start of the trial. Hasbrook and Rasmussen found that, depending on conditions, the more experienced pilots committed roll reversals on up to 9.3% of the trials. Less experienced pilots committed roll reversals on 29.2% of the trials.

Patterson (1995) looked at roll reversal rates during unexpected VMC to IMC transitions as part of his simulator-based work on the OKCR. For this part of the experiment pilots flew in formation with a simulated lead aircraft while in VMC. Pilots were instructed to perform an unusual attitude recovery task known as a lost wingman recovery (an immediate return to straight and level flight) if they lost sight of the lead aircraft. For this test a five-degree increase in bank angle was used as a roll reversal criterion. Patterson found that 64% of the pilots committed roll reversals under these difficult conditions.

Gallimore et al. (1999) looked at the effect of three levels of FOV (40°, 60°, and 100°) on pilot OKCR and roll reversals during an unusual attitude recovery task in a
simulator study. The flight tasks and the roll reversal criterion were the same as those used in Patterson's 1995 study mentioned above. However, the lost wingman recovery was performed in both VMC and IMC conditions. The results showed that pilots committed roll reversals on 30.6% of the trials. The FOV manipulation had no significant effect on the number of roll reversals. Interestingly, pilots committed the same number of roll reversal errors in both VMC and IMC conditions during the recovery task. The researchers had thought the pilots would exhibit fewer roll reversals in VMC due to the extra orientation cues available from the out-the-window view. Gallimore et al. speculated that this result may have been due to a lack of a horizon view or that pilots automatically transition to instruments while performing the recovery task.

Braithwaite et al. (1997) looked at roll reversal rates during a lost wingman recovery transition to instruments in IMC conditions. This work was part of an OKCR study conducted in a full-motion helicopter simulator. Braithwaite et al. found that 25% of the pilots committed roll reversals during the recovery task.

These studies show that pilots using conventional attitude indicators can experience SD and commit roll reversals when transitioning from VMC to IMC conditions most likely due to a switch between the two different frames of reference. Therefore roll reversals may provide a useful objective measure of pilot SD during transitions. The current research will use roll reversals as a measure of SD.

Researchers have been studying a new type of display for aviation use that could improve pilot orientation in flight and may help reduce roll reversals committed during VMC to IMC transitions. This display, called a three-dimensional perspective display,
provides the pilot with a computer-generated image of the terrain and sky ahead of the airplane on a Cathode Ray Tube (CRT) or flat panel display.

*Three-dimensional Perspective Displays*

A 3-D perspective display utilizes depth cues that humans naturally use to interact with, and navigate through, their environment. These perspective cues help give the impression of three dimensions and depth within the displayed image (Wickens, Todd, and Seidler, 1989). Most of the perspective cues used in 3-D perspective displays are the same as those cues found in perspective paintings or photographs. These displays may also use motion-based depth cues such as occlusion (when the movement of a nearby object blocks one's view of a more distant object) and motion parallax (when objects move across one's field of view, objects that are closer to us seem to move more quickly then objects that are in the distance) (Wickens et al., 1989).

Many 3-D perspective displays contain three basic elements that can be seen in the image of the *Goodrich SMARTDECK* shown in figure ten. These elements include a background image of the sky and approaching terrain; a "highway-in-the-sky" (HITS) symbology for flight path guidance and primary flight instrumentation around the periphery of the "highway" display. (Wickens et al., 1989) state two closely related arguments for why 3-D perspective displays may be better suited then conventional 2-D instruments for displaying orientation information to the pilot. The first argument is based on the
concepts of task integration and display integration that stem from the Proximity Compatibility Principle (PCP). The PCP states that integrated tasks, those tasks that require the assimilation of many distinct pieces of information, will benefit from having those separate data sources combined into a single display (Wickens and Hollands, 2000). The integrated display reduces the mental effort required to incorporate the information into a unified whole.

Flight control is primarily an integrated task. The pilot must be aware of the aircraft's current position in three-dimensional space and the rate of change in heading, rate of climb, and airspeed. The pilot must also be aware of the aircraft's orientation in three axes (pitch, yaw, and roll) (Haskell and Wickens, 1993). The PCP indicates that flight control would be best suited by an integrated display.

Conventional instruments do not provide an integrated display of flight data. Each of the six individual primary flight instruments supplies only part of the information about current aircraft state. The pilot must continually combine these separate pieces of information to form a mental picture of what the aircraft is doing. A 3-D perspective display, however, presents the pilot with an integrated display of orientation information. This single display of the approaching terrain and sky ahead of the aircraft provides the pilot with an awareness of the aircraft's current orientation relative to the earth.

Haskell and Wickens (1993) conducted a study that compared pilot performance while using a single, integrated 3-D display or an array of 2-D instruments. These displays were carefully constructed to provide equivalent information in a purely spatial format. The results from this study indicated that pilots using 3-D perspective displays performed better on integrated tasks than pilots using the array of 2-D instruments.
The second argument noted by Wickens et al. (1989) states that 3-D perspective displays provide spatial information to the pilot in a manner that is highly compatible with the pilot's mental model of the natural world. A mental model is a mental construct that contains assumptions and ideas about some process or function (Johnson-Laird, Girotto, and Legrenzi, 1998). As humans use their mental model over time they learn from their mistakes and these lessons are used to refine the model. Therefore, as a mental model is used over time it becomes more accurate.

Humans have years of experience in visually orienting in and navigating through a three-dimensional environment. Consequently the mental model people use for 3-D spatial orientation has become well established and highly refined. The fundamental task facing a pilot is one of spatial orientation and navigation through three-dimensional space. Therefore, the 3-D perspective display's three-dimensional image should provide spatial information in a format that fits well with the mental model a pilot naturally uses for orientation.

Instrument flight with a conventional AI, however, requires the development of a new mental model based on an abstract horizon symbol and the aircraft frame of reference. This new mental model allows the pilot to translate the movement of the AI into an accurate interpretation of the aircraft's attitude. This mental model is relatively new and not very well established. If the pilot experiences extreme stress or fatigue this mental model could break down.

The horizon image generated by a 3-D perspective display may help reduce pilot spatial disorientation by triggering a pilot's ambient visual system and the OKCR. If
pilots do exhibit the OKCR it would offer a number of benefits that, taken together, provide another argument for the use of 3-D perspective displays.

*OKCR in 3-D Perspective Displays*

In visual flight the pilot's head stays relatively normal to the horizon while the aircraft rolls (as seen in Figure 6b). This OKCR response allows the pilot to maintain motion compatibility between control movements and aircraft movements. During conventional instrument flight the pilot does not have motion compatibility because the OKCR does not occur. Without the OKCR the moving-horizon Al may be interpreted as moving in opposition to control movements. This loss of motion compatibility seems to contribute to a form of SD that is often expressed in roll reversals. If a 3-D perspective display elicits the OKCR response as argued in the section above, the pilot would maintain motion compatibility during instrument flight and this should reduce both SD and roll reversals during the VMC to IMC transition.

Conventional instrument flight in IMC requires the integration of information from numerous instruments. This complex cognitive skill is highly susceptible to stress and fatigue. Spatial disorientation often generates high levels of stress. If the pilot becomes aware that their spatial orientation has been compromised their ability to control the aircraft begins to break down. Gillingham and Previc (1993) explain what happens once a pilot becomes disoriented:

"There is the tendency to revert to more primitive behavior, even reflex action, under conditions of severe psychologic stress. The highly developed, relatively newly acquired skill of instrument flying can give
way to primal protective responses during disorientation stress, making appropriate recovery action unlikely.”

The OKCR is not a cognitive skill. Evidence suggests the OKCR is an instinctive, reflexive orientation response. Sharkey and Hennessy (2000) describe the ambient visual system as being more primitive in evolution than the focal visual system used to interpret conventional instruments. There is also evidence that animals display an orientation reflex that looks like the OKCR. For example, figure eleven shows a horse and rider in a turn. The horse’s body is tilted relative to the ground (the visual horizon) but its head is held normal to the visual horizon (Hasbrook and Rasmussen, 1973). The primitive and deeply ingrained nature of the OKCR may make it more resistant to stress or fatigue. Therefore pilots exhibiting the OKCR while viewing a 3-D perspective display may be less likely to lose their orientation during disorientation stress.

When a pilot uses the focal visual mode for orientation during conventional instrument flight they must actively resist inaccurate vestibular orientation information and rely on the artificial orientation cues provided by the moving-horizon AI (Gillingham and Wolfe, 1985). This process of resisting vestibular input is known as vestibular suppression (Gillingham and Previc, 1993). A pilot, while under stress or not paying attention, may unintentionally act on this erroneous vestibular information. In fact, the pilot may trust these vestibular orientation cues more than the orientation cues provided by the instruments (Gillingham and Previc, 1993).
This unwarranted reliance on vestibular orientation cues occurs because the vestibular system is operating naturally and automatically through normal neural channels. In contrast, the orientation information from the AI is being processed unnaturally through the focal visual mode (Gillingham and Wolfe, 1985). The visual dominance effect, which usually prevents unwanted vestibular orientation cues, does not seem operate perhaps because the pilot is not using ambient vision for orientation.

An OKCR response to a 3-D perspective display would allow the natural visual dominance process to suppress erroneous vestibular input through the action of the ambient visual system. This natural inhibition of vestibular signals would lessen the chances of SD and would reduce the pilot’s workload.

Conventional instrument flight in IMC requires the use of focal vision. To use the focal visual mode for orientation pilots must consciously look at the graphics on the attitude indicator, extract orientation information, and mentally integrate this data with additional information gleaned from other instruments to understand what the aircraft is doing. This process requires conscious effort and work. Focal vision has a very narrow field of view so pilots have to apply focal vision to one instrument at a time during the instrument scan. As was mentioned earlier, pilots can spend up to 75% of their instrument scan looking at the attitude indicator (Spady, 1978). Therefore pilots may use as little as 25% of their scan time looking at all the other instruments in the cockpit.

Ambient vision handles orientational information automatically, naturally, and without effort. Ambient vision operates independently from focal vision and both modes function simultaneously (Leibowitz and Post, 1982). If the 3-D perspective display triggers the OKCR then the ambient visual mode could process orientation information
from the 3-D perspective display at the same time the focal visual mode is attending to other information. This parallel process would reduce workload and save time.

Pilots using the conventional moving-horizon Al must switch from a world frame of reference (FOR) to an aircraft FOR when transitioning from visual flight to instrument flight. This forced switch in reference frames can cause a type of SD that is often expressed in the form of roll reversals. If a 3-D perspective display elicits the OKCR response then pilots would be interacting with this display as they do with the out-the-window view. Consequently, pilots would be operating with a world frame of reference during both visual flight and instrument flight. If this is true then a pilot's VMC to IMC transition should be generally free of spatial disorientation and roll reversals.

Display Design Influence on the OKCR

As noted earlier, Braithwaite et al. (1997); Gallimore et al. (1999); Gallimore et al. (2000); and Patterson (1995) found that pilots did not exhibit the OKCR while viewing conventional attitude indicators during IMC flight. This lack of the OKCR response may indicate the ambient visual system is not responding to conventional Al's. Application of what is known about the ambient visual system will be useful here to provide assumptions as to why the OKCR is not triggered by conventional Al and EAI designs but may be elicited by the 3-D perspective display. There are four aspects to ambient vision that can be applied to display design including: clarity of the displayed image, lighting conditions, depth cues provided within the display, and display size.

The first two elements, image clarity and lighting can be discounted as aspects of display design that might affect ambient visual function. The conventional Al and EAI
provide clear, sharp display images. Even if the displayed images were blurred the ambient visual system would still function. Therefore display image clarity does not explain why conventional instruments do not elicit the OKCR response. The AI and the EAI both provide some form of illumination for low light conditions. Even if these lighting systems worked poorly it would not matter because the ambient visual system operates effectively even in very low light conditions. Therefore display lighting does not seem to be limiting the OKCR response to the AI and EAI.

Ambient vision responds to perceptually distant background images so a visual stimulus that is perceived as close to the observer should not activate the ambient visual mode. The conventional AI and the more modern EAI both provide abstract, two-dimensional horizon images that contain no depth information. The lack of depth cues and perspective cues within the horizon images of the AI and EAI may be limiting the ambient visual system response and therefore restricting the OKCR. Three-dimensional perspective displays, however, present depth information through the use of perspective cues. Because of the depth information inherent in the 3-D perspective display its horizon representation should be perceived as a distant background image thus activating the pilot's ambient visual mode and the OKCR.

Ambient vision uses visual information from across large areas of the retina. As more receptors are stimulated the ambient visual response increases. These characteristics indicate that display size may be important in generating a response from the ambient visual system. The AI and the EAI are typically provided on 3 in. square and 4 in. square displays respectively. This small display area may not stimulate enough receptors to activate the ambient visual system. The 3-D perspective image may be
provided on displays that measure up to ten by thirteen inches. This larger display area may stimulate enough visual receptors to elicit the OKCR response.

The Current Study

The current study will look for the OKCR in pilots viewing an AI, EAI, and a 3-D perspective display. The AI and EAI provide abstract representations of the horizon that do not contain depth information. Therefore pilots viewing these displays should not exhibit the OKCR. In addition, pilots are forced to develop and use a new mental model in order to interact with these displays. This mental model is not well established and may not hold up under stress and fatigue.

The 3-D perspective display contains perspective depth cues that allow its horizon image to be perceived as at a distance from the observer. Therefore pilots are expected to exhibit the OKCR while viewing the 3-D perspective display. The 3-D perspective display’s horizon image also provides spatial information in a manner that fits with the mental model humans have developed for moving through a three dimensional world.

The current research will manipulate display size. The AI and EAI are typically provided on displays that measure no more then four by four inches. The 3-D perspective display, however, is often seen on screens as large as ten by thirteen inches. Therefore both the EAI and the 3-D perspective display will be provided in both a five by five inch size and a ten by thirteen inch size. This display size manipulation will be done to remove the display size confound presented by the different standard sizes of the EAI and 3-D perspective display. It is important to note that this manipulation is not expected to create a significant change in the strength of the OKCR response. While the OKCR
seems to be affected by large changes in field of view the relatively small change of FOV from approximately 10° to 24° will probably not have a major impact on the strength of the OKCR response.

The current study will also look for evidence of roll reversals during sudden transitions from visual flight to instrument flight. This study will use a modified version of the lost wingman recovery task used by Patterson (1995) to track the number of roll reversals committed by pilots as they transition from VMC to IMC flight while using each of the three displays. It is believed that pilots viewing the moving-horizon AI and EAI will not exhibit the OKCR. As a result these pilots will be forced to switch from a world FOR to an aircraft FOR during the VMC to IMC transition. Consequently pilots viewing the moving-horizon AI and EAI should produce significantly more roll reversals then pilots viewing the 3-D perspective display.

Pilots viewing the 3-D perspective display should exhibit the OKCR. This orientation response may allow them to maintain a world FOR throughout the VMC to IMC transition. For that reason pilots viewing the 3-D perspective display should produce significantly less roll reversals then pilots viewing the AI and EAI.
Statement of the Hypothesis

Hypothesis 1: Subject OKCR response strength will vary as a function of display type with the out-the-window view generating the greatest response, followed by the 3-D display, followed by the conventional instruments.

Hypothesis 2: The display size manipulation will have a small but statistically nonsignificant effect on the strength of the OKCR response.

Hypothesis 3: Pilots will exhibit significantly fewer roll reversal errors during sudden VMC to IMC transitions while using the 3-D perspective display as compared to the conventional Attitude Indicator or the Electronic Attitude Indicator.
Method

Participants

Fifteen instrument-rated Embry-Riddle flight students were used as subjects for this study. Subjects were 19 to 22 years of age. Subject flight experience varied with four subjects having fewer than 130 flight hours, nine subjects having between 180 and 310 hours of flight time, and two subjects with 375 and 450 flight hours respectively. Fourteen of the fifteen subjects were male. All subjects had 20/20 vision or corrected to normal vision with contact lens. Subjects that required glasses were not able to participate in the study because the glasses interfered with the head-tracking equipment.

Tasks

Each pilot flew a flight profile that contained three phases including visual flight, a VMC to IMC transition, and instrument flight. Head-tracking data was collected throughout the flights. During the visual flight task the pilot rolled the aircraft from side to side to approximately ±70 degrees of bank while flying straight at about 1200 feet above ground level (AGL). The pilot used the out-the-window view to orient the aircraft relative to the horizon during this part of the test. Cockpit instrumentation was not visible during the visual flight task.

The VMC to IMC transition task was designed to force the pilot to switch from visual flight to instrument flight at an unexpected moment when the aircraft was at an extreme bank angle. At the instant of transition from visual flight to instrument flight the out-the-window view went blank and the instrument display appeared thus compelling the pilot to shift to instrument flight. The pilot was instructed that if they lost the out-the-
window view they were to transition to instruments and immediately bring the aircraft to
straight and level flight.

The transition points were randomized throughout the trials to prevent the pilot
from anticipating the moment of transition. For this purpose each roll maneuver was
broken into four periods. The first period was defined as a roll movement from 0° of
bank up to a maximum bank angle of –80 degrees. The second period was defined as a
roll movement from –80 degrees down to 0 degrees of bank. The third period consisted
of an increase in bank angle from 0° up to 80 degrees and the fourth period covered a
decrease in bank angle from 80 degrees down to 0 degrees. Each VMC to IMC transition
was randomly assigned to one of these four roll periods.

The transition task was designed to occur within a two-minute window. This
window was divided into five 24-second blocks. Each VMC to IMC transition point was
randomly assigned to a time block. The experimenter monitored pilot yoke movements
and the out-the-window view during each trial. When the pilot reached the appropriate
roll period within the appropriate time block the transition occurred. A time block and
roll period matrix allowed for timely execution of transitions throughout the experiment.

The IMC flight task began after the VMC to IMC transition was completed.
There was a possibility that the pilot might temporarily lose control of the aircraft due to
SD in the moments after the transition. For this reason the experimenter waited until it
was clear the pilot had adequate control of the aircraft before commencing the IMC flight
task. For the current study adequate aircraft control was defined as a return to straight
and level flight (both bank and pitch at approximately zero degrees) for more then five
seconds. At this point the pilot was given a verbal command to recommence rolling the
aircraft. The pilot rolled the aircraft from side to side to approximately ±70 degrees of bank while flying straight at about 1200 feet AGL. The pilot used the attitude display to orient the aircraft as the out-the-window view was not visible during the instrument flight task. The pilot continued this rolling maneuver until the researcher ended the trial.

**Apparatus**

This experiment was conducted in the Human Factors lab at Embry-Riddle Aeronautical University. There were five primary components in the experimental apparatus. The first component consisted of the *Elite iGATE* PC-based Aviation Training Device (PCATD) flight simulator hardware. This system provided controls typically found in a general aviation (GA) aircraft. A 17-inch flat panel display supplied the instrumentation used during the experiment. The flight simulator used *Elite* Electronic IFR Training Environment Version 7.0 software running on a Pentium-4 class PC. The *Elite* software provided aircraft responses to pilot control movements and generated aircraft position and state data. The *Elite* Data Communication Module Version 3.0 was used to record this simulator data.

The second component of the test equipment was the SVS research display system. This program ran on an SGI Intergraph Zx10 computer equipped with an *Intense-3D Wildcat 4210* video board. The SVS system generated all the instrument displays (AI, EAI, and SVS) shown to the pilots. Aircraft position and state data were provided to this computer from the primary simulator computer via a Local Area Network (LAN).
The third component was a generic out-the-window view generator provided by *Elite GenView* software running on a Pentium-4 class PC. Aircraft position and state data were passed to this computer from the primary simulator computer via a LAN.

The fourth component consisted of a head-tracking system designed by *Seeing Machines*. This passive camera-based head-tracking system used *FaceLAB 3.0* software running on a Pentium-4 class PC. Pilot head position data was collected and stored by this machine.

The fifth component consisted of a control computer running specially designed software that allowed the experimenter to simultaneously blank the out-the-window view and reveal the instruments as needed for the VMC to IMC transition task. See Appendix for more information about the *Switch Screen* program. This Pentium-2 class PC also generated a time log that was marked via keyboard inputs to indicate the beginning and end of data collection and to mark the point of VMC to IMC transition. This time log was used to parse the data files from the simulator and the head-tracking system at the end of the study.

*NTP FastTrack 1.0.0* was used as a network time protocol to synchronize the clocks on the control computer, head-tracking computer, and the primary simulator computer. This synchronization allowed the experimenter to merge individual data files from these three computers into a single data file for each subject and display condition.

**Experimental Design**

This experiment consisted of a within-subjects design with six levels of a single independent variable (display type). There were three display types including the
conventional Attitude indicator (AI), Electronic Attitude Indicator (EAI), and Synthetic Vision System (SVS). A display size manipulation was also built into the study with the EAI and the SVS displays provided in both a five by five inch size and a ten by thirteen inch size. The AI was provided in a single, four-inch square size. In addition, each pilot experienced an out-the-window view for the visual portion of each flight. During testing the pilots were provided only with attitude information. All other instrumentation was either removed or covered.

There were two dependent variables for this study. The strength of the OKCR response (degree of head tilt) during the visual flight task and instrument flight task and the number of roll reversals recorded during the VMC to IMC transition task. Head-tracking data was collected throughout the flights. This study used the same standard as Patterson (1995) to determine when a roll reversal occurred. This criterion states that a roll reversal has been committed when the pilot rolls the aircraft more then five degrees further in the direction of the bank (away from level) after the transition to instruments.

Procedure

The researcher briefed each participant regarding the general purpose of the study. Each subject read and signed an informed consent form. The researcher then described the flight tasks in detail and demonstrated the aircraft roll technique.

Once the subject was comfortably seated in the simulator they were allowed a few minutes of flight time to become accustomed to the response characteristics of the hardware and the flight model. A Bonanza flight model was used for this experiment. This aircraft is similar to flight models with which ERAU students are familiar but has
sufficient power to maintain altitude while being rolled continuously. Once the subject
was used to the handling characteristics of the simulator they were asked to practice
rolling the aircraft. The subject was then shown each of the five displays that would be
used during the experiment. The subject rolled the aircraft a few times while using each
display to become accustomed to the movement of the displays during roll maneuvers.

At this point the subject was asked to sit quietly while looking at the top center of
the instrument screen. The experimenter then performed a face modeling procedure to
allow the head-tracking equipment to function effectively. Given the obvious nature of
the face modeling process subjects were informed that the study would measure flight
performance and the equipment would help record their performance. This generic
explanation was intended to prevent subject awareness of the true nature of the
equipment and any adverse impact this would have on subject performance.

During each trial the pilot flew a flight profile that contained a visual flight task, a
VMC to IMC transition task, and an instrument flight task for each display type. For that
reason each pilot completed five flights. Each flight took approximately eight minutes
and aircraft state data and head-tracking data was collected throughout. The control
computer was used to mark three-minute sections of visual flight data and instrument
flight data collected during each flight. These data sections were used for the OKCR data
analysis. The control computer also marked the point of VMC to IMC transition. The
order of presentation of the display conditions was counterbalanced across the subject
pool to account for learning effects. There was a one-minute break between flights to
allow the researcher to switch display types and set up the hardware and software for the
next flight.
Results

The current study had two dependent variables including the strength of the OKCR response (degree of head tilt) during visual flight and instrument flight; and the number of roll reversals recorded during VMC to IMC transitions.

Aircraft data and subject data were collected at approximately 60 Hz by the Elite simulator and Seeing Machines head-tracking equipment. The raw data files from these two machines were merged along with the appropriate control computer files using their respective timestamps. The files were stripped of all unnecessary aircraft and subject parameters and reduced to a 10 Hz sampling rate. The resulting data files were then analyzed using linear regression and analysis of variance (ANOVA) procedures.

A visual inspection of the data plots revealed an overall negative slope to the data. This negative slope is a graphical representation of the OKCR. Keep in mind that the OKCR helps the pilot maintain a relatively level view of the horizon as the aircraft rolls. When the aircraft rolls in one direction the pilot’s head tilts in the opposite direction to compensate. As the aircraft rolls in a positive direction the pilot’s head tilts in a negative direction. Conversely as the aircraft rolls in a negative direction the pilot’s head tilts in a positive direction. This inverse relationship between aircraft roll and head tilt shows up on the graph as a line with a negative slope.

Figure 12. Mean display slopes.
Moreover, the degree of negative slope appeared to be affected by the display conditions with the out-the-window (OTW) view generating a steeper slope than the other displays. Figure twelve provides a graphical representation of the differences in mean slopes between the display conditions.

Descriptive statistics produced for these data show that the out-the-window condition did indeed generate the strongest OKCR response with a regression slope of \(-5.9\) degrees. The attitude indicator condition recorded the least slope at \(-1.9\) degrees. All other display types fell between these two scores. Standard deviations for all display conditions ranged from a high of 7.6 degrees for the Large SVS display to a minimum of 5.2 degrees for the out-the-window condition. Table one provides the regression slope values and standard deviations for each display condition.

<table>
<thead>
<tr>
<th>Display</th>
<th>Regression Slopes</th>
<th>SD</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Out-the-window (OTW)</td>
<td>-.059</td>
<td>.052</td>
<td>15</td>
</tr>
<tr>
<td>Attitude Indicator (AI)</td>
<td>-.019</td>
<td>.054</td>
<td>15</td>
</tr>
<tr>
<td>Small Electronic Attitude Indicator (SEAI)</td>
<td>-.029</td>
<td>.058</td>
<td>15</td>
</tr>
<tr>
<td>Large Electronic Attitude Indicator (LEAI)</td>
<td>-.037</td>
<td>.069</td>
<td>15</td>
</tr>
<tr>
<td>Small Synthetic Vision System (SSVS)</td>
<td>-.036</td>
<td>.062</td>
<td>15</td>
</tr>
<tr>
<td>Large Synthetic Vision System (LSVS)</td>
<td>-.047</td>
<td>.076</td>
<td>15</td>
</tr>
</tbody>
</table>

Individual regression analyses were conducted to generate regression equations for each subject and display combination. The slopes from these regression analyses were then placed in a subject/display matrix. A repeated measures ANOVA was conducted on the matrix to determine if there was any discernable relationship between amount of slope and display type. A number of assumptions underlie the use of the repeated measures ANOVA including homogeneity of variance, normality of data, and
sphericity. Myers and Well (1995) suggest a four to one ratio between variance scores as a limit for the homogeneity of variance assumption. The maximum variance between display conditions for the current research is 2.15 to 1. See table two.

Table 2.
Display type variances

<table>
<thead>
<tr>
<th>Display type</th>
<th>Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>OTW</td>
<td>.0027</td>
</tr>
<tr>
<td>AI</td>
<td>.0030</td>
</tr>
<tr>
<td>SEAI</td>
<td>.0034</td>
</tr>
<tr>
<td>LEAI</td>
<td>.0047</td>
</tr>
<tr>
<td>SSVS</td>
<td>.0038</td>
</tr>
<tr>
<td>LSVS</td>
<td>.0058</td>
</tr>
</tbody>
</table>

Field (2000) believes the Kolmogorov-Smirnov test provides an effective assessment of normality. A significance score of less than .05 on the Kolmogorov-Smirnov test indicates the data are not normal. The results of this test are provided in table three. This test showed that the OTW, AI, SEAI were normally distributed. The data for the LSVS approach normality and the distributions for the LEAI and SSVS were not normal.

Table 3.
Test of normality

<table>
<thead>
<tr>
<th>Display</th>
<th>Kolmogorov-Smirnov*</th>
</tr>
</thead>
<tbody>
<tr>
<td>OTW</td>
<td>.192 15 .141</td>
</tr>
<tr>
<td>AI</td>
<td>.218 15 .053</td>
</tr>
<tr>
<td>SEAI</td>
<td>.215 15 .061</td>
</tr>
<tr>
<td>LEAI</td>
<td>.255 15 .010</td>
</tr>
<tr>
<td>SSVS</td>
<td>.249 15 .013</td>
</tr>
<tr>
<td>LSVS</td>
<td>.224 15 .042</td>
</tr>
</tbody>
</table>

* Lilliefors Significance Correction

However, Myers and Well (1995) state that the F-test is not greatly affected by nonnormality unless the samples are very small and the deviation from normality is
extreme. Keppel (1991) is more specific stating that the F-test is resistant to deviations from normality when the distribution of scores are “symmetrical”, the samples sizes are equal, and the number of subjects is greater than twelve. If these conditions are not met Keppel suggests shifting the significance level to .025 or .01 to provide a correction for distortions in normality. The LSVS, LEAI, and SSVS display distributions do seem to meet Keppel’s requirements.

Sphericity is a measure of the homogeneity of variance of the differences between scores in a repeated measures test. Mauchly’s Test of Sphericity was significant indicating nonsphericity of the data. See table four.

Table 4. Mauchly's test of sphericity

<table>
<thead>
<tr>
<th>Within Subjects Effect</th>
<th>Mauchly's W</th>
<th>Approx. Chi-Square</th>
<th>df</th>
<th>Sig.</th>
<th>Epsilon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Display</td>
<td>.047</td>
<td>36.946</td>
<td>14</td>
<td>.001</td>
<td>.509</td>
</tr>
</tbody>
</table>

A lack of sphericity can lead to an inflation of Type I error rates. However, an \( \varepsilon \)- adjusted F test can help to compensate for type I error inflation. The Greenhouse-Geisser correction, a conservative form of the \( \varepsilon \)- adjusted F test, was used to interpret the repeated measures ANOVA results.

Table 5. Tests of within-subjects effects

<table>
<thead>
<tr>
<th>Source</th>
<th>Type III Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Display</td>
<td>Greenhouse-Geisser</td>
<td>.0150</td>
<td>5</td>
<td>.0059</td>
<td>9.113</td>
</tr>
<tr>
<td>Error (Display)</td>
<td>Greenhouse-Geisser</td>
<td>.0230</td>
<td>70</td>
<td>.0006</td>
<td></td>
</tr>
</tbody>
</table>
The tests of within-subjects effects indicate the main effect of display was significant, $F (5,70) = 9.11, p = .000$. See table five. The estimate of effect size, $\eta^2$, was .394 indicating that approximately 39.4% of the observed effect was due to the display manipulation.

Post hoc pairwise comparisons were conducted to determine where the significant differences between displays occurred. The Bonferroni correction was used for these tests to help prevent Type I error inflation. The results are provided in table six. The pairwise comparisons indicate that pilot head tilt for the out-the-window (OTW) condition was significantly greater then pilot head tilts recorded for the attitude indicator (AI), small electronic attitude indicator (SEAI), and small synthetic vision system (SSVS). Further comparisons show that pilot head tilt for the AI condition was significantly less then the SEAI condition but not significantly different from the LEAI, SSVS, and LSVS conditions. Pilot head tilt for the OTW condition was not significantly different from the large electronic attitude indicator (LEAI), or the large synthetic vision system (LSVS). Differences in display size did not yield any significant differences between the SEAI and LEAI displays or the SSVS and LSVS displays. Differences in display content (2D vs. 3D) did not yield significant differences between the SEAI and SSVS displays or the LEAI and LSVS displays.
Table 6.  
Pairwise comparisons

<table>
<thead>
<tr>
<th>Display</th>
<th>Mean Difference</th>
<th>Std. Error</th>
<th>Sig*</th>
<th>95% Confidence Interval for Differencea</th>
</tr>
</thead>
<tbody>
<tr>
<td>OTW</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AI</td>
<td>-.0406</td>
<td>.006</td>
<td>.000*</td>
<td>-.0611 - .0202</td>
</tr>
<tr>
<td>SEAI</td>
<td>-.0306</td>
<td>.007</td>
<td>.011*</td>
<td>-.0559 - .0054</td>
</tr>
<tr>
<td>LEAI</td>
<td>-.0226</td>
<td>.007</td>
<td>.100</td>
<td>-.0477 .0025</td>
</tr>
<tr>
<td>SSVS</td>
<td>-.0235</td>
<td>.006</td>
<td>.027*</td>
<td>-.0450 -.0019</td>
</tr>
<tr>
<td>LSVS</td>
<td>-.0124</td>
<td>.009</td>
<td>1.000</td>
<td>-.0446 .0198</td>
</tr>
<tr>
<td>AI</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SEAI</td>
<td>.0100</td>
<td>.003</td>
<td>.035*</td>
<td>.0005 .0195</td>
</tr>
<tr>
<td>LEAI</td>
<td>.0180</td>
<td>.007</td>
<td>.235</td>
<td>-.0051 .0411</td>
</tr>
<tr>
<td>SSVS</td>
<td>.0171</td>
<td>.005</td>
<td>.077</td>
<td>-.0011 .0354</td>
</tr>
<tr>
<td>LSVS</td>
<td>.0282</td>
<td>.008</td>
<td>.53</td>
<td>-.0003 .0567</td>
</tr>
<tr>
<td>SEAI</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LEAI</td>
<td>.0080</td>
<td>.008</td>
<td>1.000</td>
<td>-.0203 .0363</td>
</tr>
<tr>
<td>SSVS</td>
<td>.0071</td>
<td>.006</td>
<td>1.000</td>
<td>-.0146 .0289</td>
</tr>
<tr>
<td>LSVS</td>
<td>.0182</td>
<td>.009</td>
<td>.939</td>
<td>-.0136 .0500</td>
</tr>
<tr>
<td>LEAI</td>
<td>SSVS</td>
<td>-.0009</td>
<td>.005</td>
<td>1.000</td>
</tr>
<tr>
<td>LSVS</td>
<td>SSVS</td>
<td>.0102</td>
<td>.005</td>
<td>1.000</td>
</tr>
<tr>
<td>SSVS</td>
<td>LSVS</td>
<td>.0111</td>
<td>.005</td>
<td>.619</td>
</tr>
</tbody>
</table>

* indicates the mean difference is significant at the .05 level.  
a. Adjustment for multiple comparisons: Bonferroni.

The second part of the current experiment was designed to record the number of roll reversals committed by pilots transitioning from visual flight to instrument flight. This study used a five-degree criterion for roll reversals. This criterion states that if a pilot increases the aircraft’s roll angle by more than five degrees after the transition to instruments then they have committed a roll reversal. The bonanza aircraft flight model used for the experiment had a very slow roll rate. As a result the five-degree criterion netted only a single roll reversal (during the LSVS condition).

However, some participants exhibited a noticeable “startle reaction” at the moment of transition. This reaction was characterized by a rapid, momentary adjustment of the yoke angle as the subject transitioned from visual flight to the attitude display.
Given the slow reaction time of the aircraft coupled with the rather large control inputs required at the yoke, this reaction did not result in a measurable change in aircraft attitude. Experimenter observations of the startle reaction were recorded and the results are provided in table seven.

Table 7.
Subject startle reaction by display condition.

<table>
<thead>
<tr>
<th>Display type</th>
<th># of startle reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>AI</td>
<td>5</td>
</tr>
<tr>
<td>SEAI</td>
<td>1</td>
</tr>
<tr>
<td>LEAI</td>
<td>0</td>
</tr>
<tr>
<td>SSVS</td>
<td>3</td>
</tr>
<tr>
<td>LSVS</td>
<td>3</td>
</tr>
</tbody>
</table>

These results indicate that five of the fifteen pilots exhibited the startle reaction while using the AI. But three of the pilots had the same reaction while using the SSVS and the LSVS. Interestingly, only one pilot showed evidence of the reaction while using the SEAI and none of the pilots seemed to react while using the LEAI.

Discussion

The results of this study suggest that the type of display presented to pilots affects postural orientation responses in a manner consistent with previously established hypotheses. These results have implications for the OKCR, roll reversals, and spatial disorientation effects.
Previous researchers have found that pilots exhibit a relatively strong OKCR response while looking out the window and little or no OKCR response while looking at the moving horizon attitude indicator. Ambient visual theory suggests the OKCR response strength is affected by display size and depth information. An increase in display size should increase the strength of the OKCR response. Moreover, displays that contain depth information should produce a greater OKCR response than displays that do not contain depth information.

The current research tested three hypotheses. The first two hypotheses are based squarely on ambient vision theory. The first hypothesis stated that subject OKCR response strength would vary as a function of display type with the out-the-window view generating the greatest response, followed by the 3-D display, followed by the conventional instruments. This hypothesis was supported by the present study. Table eight compares pilot OKCR response (mean slopes) with the characteristics of the different display conditions.

<table>
<thead>
<tr>
<th>Display</th>
<th>Approximate Field of view</th>
<th>Depth Information</th>
<th>Mean Slopes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Out-the-window (OTW)</td>
<td>40°</td>
<td>Yes</td>
<td>-5.9°</td>
</tr>
<tr>
<td>Large Synthetic Vision System (LSVS)</td>
<td>30°</td>
<td>Yes</td>
<td>-4.7°</td>
</tr>
<tr>
<td>Large Electronic Attitude Indicator (LEAI)</td>
<td>30°</td>
<td>No</td>
<td>-3.7°</td>
</tr>
<tr>
<td>Small Synthetic Vision System (SSVS)</td>
<td>12°</td>
<td>Yes</td>
<td>-3.6°</td>
</tr>
<tr>
<td>Small Electronic Attitude Indicator (SEAI)</td>
<td>12°</td>
<td>No</td>
<td>-2.9°</td>
</tr>
<tr>
<td>Attitude Indicator (AI)</td>
<td>9°</td>
<td>No</td>
<td>-1.9°</td>
</tr>
</tbody>
</table>
The OKCR is a compensatory head movement so pilots tilt their heads in a direction opposite the roll of the aircraft to maintain a relatively level view of the horizon. This response produces a negatively sloped line on the data plot. The current study found head tilt results that are consistent with the anticipated OKCR response. The strength of the OKCR response (the mean slopes) seemed to vary as a function of the display conditions. The OTW view, which contains both the largest FOV (40°) and depth information, recorded the largest mean slope (-5.9°). The LSVS has a 30° FOV and depth information, recorded the second largest mean slope (-4.7°). This pattern continues down to the AI that has the smallest FOV (9°) and no depth information, which produced the least amount of slope (-1.9°). The pairwise comparison of the OTW view and the AI shows that these two display conditions were significantly different. This finding supports the results of previous OKCR studies and indicates that pilots exhibit a significantly stronger OKCR response to the OTW view then to the AI display.

The results for the LSVS display are less clear-cut. The pairwise comparison for the LSVS suggests that pilot OKCR response to the LSVS is similar to pilot OKCR response to the OTW view. This fits with ambient vision theory indicating that pilots are responding to the LSVS as they do with the OTW view. But the pairwise comparison between the LSVS and the AI yielded a value of .053 suggesting that they are not significantly different. A more sensitive test or additional participants may have demonstrated the expected effect. Interestingly, the LEAI, which has a 30° FOV but no depth information, recorded a larger slope than the SSVS that has a FOV of 12° and depth information. This suggests that perhaps display size has more of an effect on OKCR than the presence or absence of depth information.
The second hypothesis attempted to test effects of display size on the OKCR response. A review of prior OKCR research indicated that only large changes in display FOV would generate significant differences in the OKCR response. Ideally if one were to test this part of the ambient visual theory large changes in display size would be necessary. However, the current research was attempting to test an existing display system. So it was expected that, given the limited difference in the sizes of the available displays, there would only be a small change in the strength of the OKCR response. Therefore hypothesis two stated that the display size manipulation would have a small but statistically nonsignificant effect on the strength of the OKCR response. Hypothesis two was supported by the present study.

The EAI and SVS displays were tested in two sizes. The "small" size measured five inches square and subtended a 12° FOV. The "large" size measured ten inches by thirteen inches and subtended a 30° FOV. The large EAI condition produced a negative slope that was 0.8° steeper then the small EAI. This indicated a stronger OKCR response for the large EAI. While this was a measurable difference in OKCR response between the large EAI condition and the small EAI condition the difference was so small that it could easily be accounted for by the variability in the scores. The pairwise comparisons bear this out showing no significant difference between the OKCR response for the large EAI and the small EAI. The SVS displays produced similar results. The large SVS display recorded a negative slope that was 1.1° steeper then the small SVS display indicating a stronger OKCR response for the large SVS display. But, again, the difference between these two scores was quite small and the pairwise comparison
between the large SVS display and small SVS display yielded no significant differences in pilot OKCR response for the two displays.

Ambient visual theory suggests that displays that contain depth information may elicit a stronger OKCR response than displays that have no depth information. The current study attempted to test this idea by comparing pilot OKCR response with the EAI displays to pilot OKCR response with the SVS displays. The EAI provided the pilot with an abstract two-dimensional image of the horizon. The SVS display produced a 3-D perspective image of the horizon. The data hint at a connection between depth information and increased OKCR effect. For example, the small SVS display seemed to generate a 0.7° steeper negative slope than the small EAI display. However, this difference in slope is so small that it could easily be the result of variability in the scores. The pairwise comparisons indicated no significant difference in pilot OKCR response for the small EAI display and the small SVS display. Similar results were found with the comparison between the large EAI and large SVS displays. The large SVS display condition recorded a 1.0° steeper negative slope than the large EAI display. But, as before, the difference between these two scores was small and the pairwise comparison between the large EAI display and large SVS display yielded no significant differences in OKCR response between the two displays.

Subjective observation of the current data suggested a noticeable difference in the OKCR response of pilots in the present study when compared to the OKCR data collected in earlier studies. Previous research suggests the OKCR responds only to the rotation of the horizon image. Pilots exhibiting the OKCR tilt their heads in a direction opposite the roll of the aircraft and this results in a single negatively sloped line on the
data plots as seen in figure thirteen. Note the OKCR plot indicates there is almost no head tilt when the aircraft is at zero degrees of roll.

Pilots in the current study, however, continued to tilt their head in the direction of the roll even as the aircraft rolled through zero degrees and on to the maximum roll angle. They would hold this head tilt until just before the maximum roll angle was reached. The pilot would then rotate the yoke to maximum opposite lock while simultaneously tilting their head in the new roll direction. These findings suggest the OKCR may not be mediated purely by visual stimuli as previously thought. The top row in figure fourteen shows the head movement that would be expected if the OKCR were affected only by visual stimuli. The bottom row in figure fourteen shows the head movement that was observed in the current experiment.

Figure 13. Typical OKCR data plot. Adapted with permission from Gallimore et al. (2001).
Figure 14. Comparison of expected (Row A) and observed (B) OKCR responses.

The first set of pictures (A1 and B1) show the pilot just finishing a left roll and beginning a right-hand roll. At this point in both images the pilot's head is aligned with the horizon as expected. In the second set of pictures (A2 and B2) the pilot is continuing to roll right and passing through zero degrees of roll. If the OKCR is affected only by the visual image then the pilot's head should be aligned with the horizon as seen in picture A2. Pilots in the current study seemed to align more with the yoke then with the horizon as seen in B2. In pictures A3 and B3 the pilot is still rolling right and is about to begin a left hand roll. Visual mediation of the OKCR response would suggest that the pilot's head should still be aligned with the horizon as seen in picture A3. Pilots in the current study were still aligned with the yoke. However, the amount of right-hand head tilt was reduced as shown in picture B3. This lessening of the head tilt would suggest that pilot head tilt might be a function of both the rotation of the horizon image and the position of the yoke. In pictures A4 and B4 the pilot has begun the left-hand roll. It is only at this
point, when the yoke had been rotated to the left, that pilots tilted their heads to the left and fully aligned with the horizon image.

This pattern of pilot responses creates the elliptical shape seen on the plot in figure fifteen. The ellipse in figure fifteen shows that, as the aircraft rolled right (from –80 degrees to +80 degrees) the pilot maintained a relatively constant positive (right) head tilt throughout the roll. As the aircraft rolled left (+80 degrees to –80 degrees) the pilot maintained a relatively constant negative (left) head tilt. Pilots exhibited, on average, 6.9° of constant head tilt in the direction of the aircraft roll during roll maneuvers.

Notice that the ellipse in figure fifteen is tilted. The slope of the entire ellipse indicates the overall OKCR response. The heavy dashed line is provided to help emphasize the general slope of the ellipse. As the OKCR response increases the overall negative slope of the ellipse increases as well. If the OKCR were not occurring the ellipse would have a negligible slope and the heavy dashed line would be essentially horizontal.

This study is the first to find evidence of a relatively constant head tilt throughout a roll maneuver. The constant head tilt is an important finding that suggests the OKCR is affected by more than just the visual stimulus of the horizon. The current study differed from earlier OKCR research in a number of ways. These differences may provide

Figure 15. Raw data plot from current study.
additional clues as to why the constant head tilt was seen in this study and not in previous studies.

In previous OKCR research pilots flew from waypoint to waypoint. A waypoint is an arbitrary point in space and time where the pilot changes heading or altitude. When flying between waypoints a pilot follows a predetermined pattern of left and right turns. Each turn is usually separated in time by at least a minute. One drawback of flying between waypoints is a lack of data collected for extreme bank angles. Previous researchers found that pilots spent most of the time flying straight and level to the next waypoint. As a result most of the data collected contained bank angles between five and negative five degrees.

To solve this problem the current research design called for the pilot to continuously roll the aircraft from side to side. This was done in an attempt to collect an equal amount of roll data throughout the entire roll range. It was hoped that this procedure would help to reduce the variability in the extreme bank angle data and provide a much more consistent picture of pilot head tilt for all bank angles. However, the dynamic nature of this task may be causing this constant head tilt effect. Other aspects of the current test may also play a role in generating the constant head tilt effect.

The flight model used in the current study may be creating or intensifying the constant head tilt. In most previous OKCR research pilots flew military aircraft or rotorcraft. These aircraft are highly responsive and roll very quickly. The current research used a simulation with a bonanza flight model that has a very slow roll rate. Subjective observation of pilot control inputs during the current research simulation flights indicated that the simulator response was consistently a second or more behind the
control input of the pilot. This control lag may be causing the constant head tilt. It seemed as if pilots were tilting their heads in an attempt to get the aircraft to move quicker.

The flight controls used in the current study may affect the constant head tilt effect. In previous research pilots have flown aircraft and rotorcraft using a control stick. The control stick requires a relatively small amount of side-to-side control movement during roll maneuvers. During the current research pilots used a general aviation simulator equipped with a yoke. The yoke required large, rotational movements during roll maneuvers. Given the slow roll rate of the aircraft and the rhythmic nature of the task, pilots were required to rotate the yoke to its maximum angle throughout the flight. The yoke was spring-loaded and thus constantly resisted pilot control inputs. It may be that, given the resistance of the yoke and the large amount of movement required, pilots might be adopting a physical movement to assist them in turning the yoke back and forth. Therefore the constant head tilt may be an attempt to provide leverage and assist the pilot in rotating the yoke.

The current research has helped to validate the presence of the OKCR in pilots performing a simulator based flight task. The constant roll paradigm of the current research has shown that the OKCR does occur in very dynamic flight conditions. More importantly, the constant head tilt effect suggests that while the OKCR may be primarily mediated by the visual image of the horizon it seems to also be affected by other factors as well.
Roll reversals

The third hypothesis tested in the current research stated that pilots would exhibit significantly fewer roll reversal errors during sudden VMC to IMC transitions while using the 3-D perspective display as compared to the conventional attitude indicator or the electronic attitude indicator. The current research was only able to detect one roll reversal using Patterson's five-degree criteria.

There are two likely reasons for why this study did not find more roll reversals. A roll reversal is a momentary disorientation event that results in a pilot rolling the aircraft in the wrong direction. Pilots typically catch this mistake very quickly. The flight model used in this study required large amounts of control input at the yoke in order to alter the roll attitude of the aircraft. In addition, this study used an aircraft model that had a very slow roll rate. If a pilot had become disoriented and turned in the wrong direction the aircraft would have rolled only one or two degrees before the pilot corrected the mistake. This small roll deviation is less than the five-degree criteria used in the test. One possible way to compensate for this in future tests would be to track yoke control inputs rather than the roll response of the aircraft. Reducing the roll reversal criterion from five degrees to three or two degrees might also help researchers detect roll reversals when testing aircraft with slow roll rates.

The roll reversal manipulation used in the current study may not have been strong enough to elicit roll reversals. The test procedure used in this study was different in some respects to the roll reversal procedure used in previous studies. In most other studies the experimental design placed the aircraft into a more extreme unusual attitude before forcing the pilot to transition to instruments. In this study the only attitude change was in
roll while aircraft pitch remained relatively constant. It may be that this relatively weak manipulation of aircraft attitude was not effective at disorienting the pilot. It was originally thought that the repeated rolling action might disorient the pilot however this does not seem to be the case. In fact, the rhythmic pattern of the flight task may have even provided a cue to the pilot as to the direction required to bring the aircraft to straight and level flight.

The startle reflex observed during testing suggested that some sort of conflict or confusion was occurring at the moment of transition. Pilots using the AI did exhibit the highest number of startle reactions with 5 of the 15 pilots reacting in this manner. During the current test 3 of the 15 pilots exhibited the startle reflex while using both the large SVS display and small SVS display. However, only 1 of the 15 pilots showed evidence of a startle reaction while using the small EAI and none of the pilots exhibited the startle reaction while using the large EAI. These findings are contrary to what was expected and do not support the third hypothesis.

Pilots in the current study have the most experience with the standard attitude indicator. Yet they experienced the greatest number of startle reactions while using the AI. It is believed the pilots used in this study have little if any experience using the EAI. Even so they exhibited the fewest number of startle reactions while using the EAI. Therefore, familiarity with instrumentation cannot be used as an explanation to account for these results.

It was originally believed that pilots using the EAI and AI would need to switch from a world FOR to an aircraft FOR during VMC to IMC transitions. This was thought to be the underlying cause of the roll reversals. Conversely, the pilots using the SVS
displays would use a world FOR during both VMC and IMC flight and thus experience fewer roll reversals. The test results do not bear this out. Therefore, frame of reference transitions may not account for this finding either. Perhaps the startle reaction observed during the current study is caused by another phenomenon.

Conclusions and Recommendations for Future Research

The current research supports the findings of previous OKCR work. Pilots seem to exhibit differences in the strength of OKCR head tilt based on the type of display being viewed; such as significantly more head tilt during visual flight with the OTW view as compared to instrument flight using the moving horizon AI. The results of the current research also suggest that pilots viewing a synthetic vision system display may indeed be exhibiting the OKCR response.

The constant head tilt observed in the current study is an important finding that suggests the OKCR is not mediated solely by the rotation of the horizon image. This phenomenon requires further investigation. There are a number of factors that could be influencing this constant head tilt effect. The current study used a bonanza flight model, which has a slow roll rate. As a result the aircraft motion and position lagged over a second behind pilot control input. During the test subjects seemed to be attempting to get the aircraft to roll quicker by leaning in the direction they wanted the aircraft to go. Varying the amount of lag time between pilot control input and aircraft response could reveal a correlation between aircraft lag and pilot constant head tilt.

The flight task used in the current study required pilots to input maximum yoke rotation in order to roll the aircraft from side to side. The large, circular motion of the
yoke along with the resistance of the yoke to pilot input may have contributed to the
constant head tilt. A control stick, by comparison, requires a small amount of side-to-
side movement. A comparison of pilot reaction while using a control stick and a yoke
may reveal a relationship between head tilt and control motion.

The rhythmic nature of the current flight task may also play a role in generating
the constant head tilt and lack of disorientation during transitions from visual flight to
instrument flight. A comparison of pilot response to a rhythmic turning task and a
random turning task may reveal a correlation between the rhythm of a task and constant
head tilt.

The current study found little evidence of roll reversals. This is most likely due to
a number of factors related to the aircraft and the experimental design. The aircraft used
in this study rolled slowly and attitude changes required large amounts of control input.
These characteristics greatly reduced the chances of recording a five-degree deviation in
roll. As mentioned earlier, reducing the roll reversal criterion to a lower value or
recording yoke inputs instead of attitude changes might help researchers detect roll
reversals when testing aircraft with slow roll rates.

The roll reversal manipulation used in the current study may not have been strong
enough to elicit roll reversals. In fact, rolling the aircraft from side to side may have
assisted pilots in maintaining their orientation. Future roll reversal tests may benefit from
using a more random flight task. In addition, placing the pilot and aircraft into a more
extreme attitude before forcing a transition from visual flight to instrument flight may
also help elicit roll reversals.
The current study proposed that OKCR is an expression of ambient vision. Ambient vision has a number of clearly defined characteristics that can be easily tested. Ambient vision seems to respond to changes in the pilot's field of view. Therefore varying a pilot's field of view should cause changes in the OKCR with larger fields of view eliciting more OKCR response. Changes in light levels do not affect ambient vision. A study varying the illumination of a horizon image should show no change in OKCR response to diminishing light levels down to the threshold of light detection. Ambient vision is not affected by image clarity. A study varying the clarity of the horizon image should show no change in pilot OKCR response. Ambient vision appears to be mediated by background visual images rather than foreground images. Therefore a study that places the horizon image on a foreground display should elicit less OKCR response than the same image projected on a background display.

More research is needed to determine if the OKCR is an expression the ambient visual system and if a synthetic vision system does, in fact, elicit the OKCR response. The link between the OKCR and prevention of SD must also be verified. The ambient visual function has many characteristics that may help to prevent spatial disorientation in the cockpit. Ambient vision functions effectively in low light conditions and is not affected by blurred images. These characteristics would be well suited for difficult conditions such as nighttime flying in turbulence. The ambient visual system functions in parallel with the focal visual system. This would allow pilots to maintain orientation via ambient vision while simultaneously using focal vision to concentrate on other important information in the cockpit. The automatic, instinctive nature of the ambient visual response is resistant to the fatigue and stress that often breaks down the learned
skills required for conventional instrument flight. Finally, an OKCR response to the SVS system may allow pilots to transition to instruments while using a world frame of reference. This would help to eliminate SD effects caused by the shift from a world FOR to an aircraft FOR required of pilots transitioning from visual flight to instrument flight while using conventional instruments. More research should be conducted because the many benefits of an OKCR/ambient visual response to a synthetic vision system display are too powerful to ignore.
References


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Appendix

There were two requirements in the experiment that demanded a software developer. The first was that experimenter must be able black out the “out-the-window view” and “heads down” displays alternately. The second requirement was that all collected data must be merged so the results could be processed by the necessary statistical software.

Switch Screen

Switch Screen was developed to give the experimenter the ability to control the screens of two computers from a control station. Throughout the experiment only one screen could be visible. When the experimenter pressed the designated the key on the control computer, the two displays would immediately switch their state: the visible one became dark, while the dark one became visible.

In order to provide this functionality, two programs were created. The server software resided on the control computer and sent messages to any running instances of the client on computers driving the displays. Figure one illustrates the computer and software configuration. The server sent messages to each display to switch its state. Any client whose state was visible would go dark. The opposite would occur if the client’s state were initially dark when the message was sent.

In addition to the primary function mentioned above, additional functions were developed. Switch Screen time stamped and logged each message sent to a client. It also provided keys that allowed the experimenter to mark the start and stop point of the experiment in the log.
Figure 1 – Configuration of the computers and software

Log Merging

The most time consuming task, at least from perspective of the software development, was merging the three software logs into a single source. The Eye Track log, Elite log, and Switch Screen log (their location in the system configuration is shown in Figure 1) stored information in different formats. This provided two challenges. The first challenge was to ensure that the timestamps on all of the logs were synchronized. The second challenge was merging logs that were at different sample rates.

The timestamp used in each log was not only in a different format, but also represented a different measurement of time. The Eye Track log used Greenwich Mean
Time (GMT), the Elite log used the Elite system's uptime, and the Switch Screen log used Eastern Standard Time (EST). The first and last logs (Eye Tracker Switch Screen) were synchronized by simply converting EST to GMT. The Elite log, however, provided more of a challenge.

The difficulty with the Elite log was that it did not use an absolute timestamp, like GMT. Uptime, the number of milliseconds since the computer was turned on, is an arbitrary number that changed every time the Elite computer was turned off. Therefore, a program was developed that retrieved the uptime of the system and compared it to the current EST. This was then written into a fourth log, the Uptime log. The four logs were then merged.

It was during the actual merging of the files where the second challenge was visible. Each of the four logs stored data different rates. The solution was to find a rate that was equal to or lower than the rate of all of the logs and use that rate to create the merged source. After that, an entry was retrieved from each log for each time determined by the common rate.

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