AD-A281 869

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE

3. REPORT TYPE AND DATES COVERED
THESIS/~~DISSERTATION~~

4. TITLE AND SUBTITLE
AVIATION SPATIAL ORIENTATION IN RELATIONSHIP TO HEAD POSITION, ATTITUDE INTERPRETATION, AND CONTROL

5. FUNDING NUMBERS

6. AUTHOR(S)
DARYL RAYMOND SMITH

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
AFIT Student Attending:
WRIGHT STATE UNIVERSITY

8. PERFORMING ORGANIZATION REPORT NUMBER
AFIT/CI/CIA-
94-087

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
DEPARTMENT OF THE AIR FORCE
AFIT/CI
2950 P STREET
WRIGHT-PATTERSON AFB OH 45433-7765

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

DTIC ELECTE JUL 21 1994 S G D

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for Public Release IAW 190-1
Distribution Unlimited
MICHAEL M. BRICKER, SMSgt, USAF
Chief Administration

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Best Available Copy

11296

94-22788

94 7 20 019

14. SUBJECT TERMS

15. NUMBER OF PAGES
102

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT

18. SECURITY CLASSIFICATION OF THIS PAGE

19. SECURITY CLASSIFICATION OF ABSTRACT

20. LIMITATION OF

NSN 7540-01-280-5500

94-087

AVIATION SPATIAL ORIENTATION

IN RELATIONSHIP TO

HEAD POSITION, ATTITUDE INTERPRETATION, AND CONTROL

Accesion For		
NTIS CRA&I	X	
DTIC TAB	☐	
Unannounced	☐	
Justification		
By		
Distribution /		
Availability Codes		
Dist	Avail and / or Special	
A-1		

A thesis submitted in partial fulfillment
of the requirement for the degree of
Master of Science in Engineering

By

Daryl Raymond Smith
B.S., United States Air Force Academy, 1984

1994
Wright State University

WRIGHT STATE UNIVERSITY

SCHOOL OF GRADUATE STUDIES

June 16, 1994

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY Daryl Raymond Smith ENTITLED Aviation Spatial Orientation in Relationship to Head Position, Attitude Interpretation, and Control BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF Master of Science in Engineering.

Thesis Director

Department Chair

Committee on Final Examination

Anthony J. Cacioppo, Ph.D.

Jennie J. Gallimore, Ph.D.

Chandler A. Phillips, M.D.

Joseph F. Thomas, Jr., Ph.D.
Dean, School of Graduate Studies

ABSTRACT

Smith, Daryl Raymond. M.S., Department of Biomedical and Human Factors Engineering, Wright State University, 1994. Aviation Spatial Orientation in Relationship to Head Position, Attitude Interpretation, and Control.

Aircraft instrument design theory assumes pilots maintain head alignment with the aircraft during turn and bank maneuvers. As a result, the outside view through the windscreen is thought to be of a moving horizon. The attitude indicator used in today's aircraft, displays moving horizon symbology thought to accurately represent pilot spatial orientation. Recently, an optokinetic collic neck reflex was documented which indicates that pilots align their heads with the horizon rather than the axis of the aircraft while manually flying the aircraft. If this is the case, then pilots orient about a fixed rather than moving horizon, implying current attitude instruments inaccurately present spatial information. The purpose of this study was to determine if the optokinetic collic neck reflex has an affect upon pilots while monitoring the autopilot and if so, what that affect is in relation to manual flight. Findings will help determine if the optokinetic collic reflex is transferable to other flight crewmembers. Sixteen military pilots flew two 13 minute VFR low level routes in a large dome flight simulator. Head position in relation to aircraft bank angle was recorded by a head tracker device. During one low level route the pilot had a supervisory role as the autopilot flew the aircraft (passive). While the other route was flown manually by the pilot (active). Results indicate that the optokinetic collic reflex caused similar head tilt in both the active and passive flight phases. However, the reflex had a faster onset rate in the passive condition. Applications to attitude indicator, HUD, and HMD design are discussed in light of these findings.

TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

TABLE OF CONTENTS (CONTINUED)

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENTS

As is often the case, many deserve thanks for what the one accomplishes. Humanly speaking, one deserves more than all the others. My wonderful wife Laura has made this work possible through her steadfast support and encouragement. Thank you and I love you.

Thanks also to committee members Dr. Phillips and Dr. Gallimore who was peppered with enough questions for a lifetime. Time is precious, thanks for yours. Much gratitude is due Mr. Terry Christian for flexibility and support at the MS-1 Simulator. You came through in the clutch and I believe the Air Force will benefit by your foresight. To Lieutenant George Hinman, a keen mind and one of the hardest working, dedicated persons I have ever run across. Your work was brilliant. Lastly, Dr. C, you epitomize what a professor and department chair should be. The student comes first. You have set the example for me at the Air Force Academy. Myself, Wright State and the Air Force owe you much for your visionary leadership.

Finally, and most importantly, I owe thanks to Almighty God who has given me eyes to see, a mind with which to think, and a body to carry out purposeful action. He deserves the credit for anything of value I may accomplish on this earth.

1.0 INTRODUCTION

1.1 The Problem

Spatial disorientation as applied to aviation is of critical importance to members of the aviation community, from the Federal Aviation Administration in the civil sector to military leaders in all four branches of service. Not only are the aviation organizations interested in the area, it is of primary concern to the flight crews. The reason for concern is that spatial disorientation costs many lives and the loss of millions of dollars in equipment annually. Before presenting evidence for this claim, we will define the term spatial disorientation. Kirkham, Collins, Grape, Simpson, and Wallace (1978) defined spatial disorientation as, "an incorrect self-appraisal of the attitude or motion of the pilot and his plane with respect to the earth." Simple stated, the inability of the pilot to correctly interpret aircraft attitude.

Spatial disorientation has contributed to great loss of life and resources over the years. In the 1980's alone, the United States Air Force had 81 Class A mishaps directly attributed to spatial disorientation (Lyons, Ercoline, Freeman, and Gillingham 1994). These resulted in the loss of 115 lives and a cost of 539 million dollars. Civilian aviation has suffered equally, from 1968-1975 spatial disorientation was the third highest cause of fatal accidents in small general aviation aircraft (Kirkham et al. 1978). Because the military operates most high performance aircraft in the U.S., and in more hostile and dynamic environments, this research will focus on military type aircraft, however, results may be inferred to the civilian community.

Fitts and Jones (1947) stated, and it is generally accepted, that proper design of orientational instruments can help reduce the chances of spatial disorientation from occurring. To design instruments properly one must be aware of the user's frame of reference. Here lies one problem in the development of cockpit orientational instruments. Sanders and McCormick (1993) describe the traditional model which crystallizes the long held assumption in aviation that as the pilot banks the aircraft, his head remains aligned with his body. This assumption has rarely been challenged, but rather held as well established fact. Actually, little research has been conducted to see if this phenomenon actually occurs. Patterson (1994) in his study of pilot head motion in a non-moving simulator, found that the pilot does not keep the head aligned with the axis of his body in a turn. He reported that as pilots banked the aircraft, they consistently and without exception tilted the head in the opposite direction of rotation in an attempt to stabilize the horizon on the retina. This finding casts serious doubt on the validity of current design philosophy of pilot attitude indicators which are responsible for much of the pilot's spatial orientation information in the cockpit. These indicators have specifically been designed resting on the assumption that the pilot's head remains aligned with the airframe while maneuvering the aircraft. Perhaps this assumption is incorrect and has lead to poor design of the indicators contributing to the problem of spatial disorientation. Patterson's (1994) findings suggest that the pilot will tilt his head in order to keep the horizon in a horizontal position on the retina to the greatest degree possible.

1.2 Objectives

Patterson (1994) studied pilots actively controlling the aircraft, however, the act of passive observation was not addressed. was performed with the pilot actively controlling the aircraft. This study has three objectives. The first is to investigate if the head tilt phenomenon takes place in other flight crewmembers. We do not know what occurs under states of passive control. An example would be an F-111 Weapons System Operator (WSO) who sits next to the pilot and shares the same perspective out the cockpit. Since the WSO does not actively fly the aircraft, but navigates and operates the weapon systems, do they experience the same frame of reference, through head tilt, as the pilot? If not, then the two will have differing frames of reference which could lead to confusion on direction for navigation and target information exchanged between the two crewmembers. This may also explain the causes behind the higher incidence of airsickness in non-pilot crewmembers. The second objective is to simply validate Patterson's groundbreaking work through replication. The third objective, is to investigate the underlying assumptions, or causes, behind the head tilt. Patterson discovered the head tilt, and suggests the cause behind it is a natural automatic reflex he labeled the optokinetic collic reflex. But is there more to the phenomenon? Specifically, is head tilt partly a function of the operator's control loop and if it is, does this affect the pilot differently when he is actively flying versus passively observing the autopilot as it executes the flight profile? This leads us to tracking theory as well as supervisory control issues.

Prior to undertaking the experimental work, this investigation will consider earlier work on spatial disorientation, document the historical origins of the pilot's attitude indicators, pursue an understanding of the mechanisms of the vestibular and visual sensory inputs and reflexes, and examine tracking theory and supervisory control in order to understand the active versus passive states in the aircraft and their possible affect upon pilot performance.

2.0 BACKGROUND

2.1 Spatial Disorientation Defined

In the previous section, a working definition of spatial disorientation was presented. Before proceeding, it is important to examine this concept more closely. The late Kent Gillingham was an Air Force expert on spatial disorientation. He defined the overall term spatial disorientation as, "a state characterized by an erroneous orientational percept, that is, an erroneous sense of one's position and motion relative to the plane of the earth's surface." (Gillingham 1992). Citing Air Force Manual 51-37, Instrument Flying, as a backdrop he added the following definition. "...a useful operational definition of spatial disorientation: it is an erroneous sense of the magnitude or direction of any of the aircraft control and performance flight parameters." Air Force Manual 51-37 defines a control parameter as indicative of aircraft attitude (pitch, yaw, bank), power or thrust. Performance parameters would include heading, velocity, airspeed, etc.

Kirkham, Collins, Grape, Simpson, and Wallace (1978) offer a working definition. "Spatial disorientation in aviation refers to an incorrect self-appraisal of the attitude or motion of the pilot and his plane with respect to the earth." The keys words in this definition are "incorrect self-appraisal". Presumably the pilot is receiving correct information from his instruments and the outside visual world, however if the pilot misinterprets the instrument providing the information or perhaps relies on an unreliable input such as the vestibular system, spatial disorientation may occur. However these inputs are received and calculated, the pilot has an *incorrect self-appraisal* which put him in dangers path. Suffice it to say, there are many viable and accurate ways to define spatial disorientation. For the purposes of this study we will use Kirkham's definition. Basically, spatial disorientation is the inability of the pilot to correctly interpret aircraft attitude.

2.2 The Problem of Spatial Disorientation

Aviation accident statistics have been collected since the 1950's. Here we discover evidence linking the deadly influence of spatial disorientation to aircraft accidents. Barnum and Bonner (1971) conducted an epidemiology of USAF spatial disorientation aircraft accidents from 1958 through 1968. They found that, "...192 pilots most of whom were highly qualified, lost their lives due to disorientation." From their data they profile the next pilot predicted to be involved in a spatial disorientation accident (see Table 2.1).

Table 2.1: Profile of the next pilot involved in spatial disorientation accident Barnum and Bonner (1971)

10 years in the cockpit
1500 hrs of first pilot/instructor time
Fighter pilot
Flown 25 times in 3 mos. prior to accident

Their findings were surprising in that most considered a new or inexperienced pilot to be most susceptible to spatial disorientation. Which prompts the question, why would an experienced pilot be susceptible to spatial disorientation? We will address this question later in this study.

The authors also looked at the most susceptible type of aircraft. Not surprisingly they found that fighters and jet trainers accounted for 84% of spatial disorientation accidents. This is in part due to mission profile, angular acceleration, and speed in these types of aircraft. Disorientation inducing activities like formation flying in weather, inflight air refueling, aerobatics, and ordinance delivery were involved in 48% of all disorientation accidents. Formation flying alone accounted for 21% of disorientation accidents. It is noteworthy that two of these types of flying, inflight aerial refueling and formation flying, give the pilot a moving aircraft perspective. That is, as the wing aircraft or refueling aircraft pilot flies, their attention is focused on the lead aircraft as it moves against the background. We will address the issue of moving aircraft versus moving horizon in the next section. Suffice it to say that this moving aircraft perspective does not match the standard attitude presentation of a moving horizon display. This discrepancy may be a source of spatial disorientation.

It is clear that spatial disorientation is a problem in military aviation. But, what about general aviation where pilots generally lack the training and proficiency of military pilots? Though the training and proficiency of pilots may not be as good, general aviation aircraft are not as demanding to fly. They are typically slower and do not subject the pilot to as great a linear or angular acceleration. Most general aviation aircraft are categorized as small, under 12,500 pounds, well under that of an Air Force fighter plane.

Kirkham et al. (1978) studied the effect of spatial disorientation in general aviation using 1968-1975 statistics compiled by the National Transportation Safety Board (NTSB). The authors found spatial disorientation to be the third highest cause of fatal accidents in small aircraft and closely related to the second, which was continued VFR (visual flight rules) flight into adverse weather. Lyons, Ercoline, Freeman, and Gillingham (1994) pointed out that the relationship of spatial disorientation to this second leading cause requires clarification. They state, ' If the actual contribution of SD to the latter accident category (continued flight into VFR weather) were to be made explicit, the proportion of civilian aircraft accidents attributed to SD would undoubtedly be much higher." Spatial disorientation was a cause or factor in 16% of all fatal accidents. A cause is defined as a direct causation of the aircraft accident. Whereas factor may be thought of as a contributing influence to the accident. Sobering was the fact that 90% of the time if spatial disorientation was ascribed as a cause or factor to an accident, it was a fatal one. It is in fatal accidents that spatial disorientation assumes a clearly important role. Fifteen percent of the total fatal accidents involving spatial disorientation involved instrument rated pilots, which is similar to Air Force numbers over the same period. Kirkham et al. (1978) summarized by saying, "Accident data and testimony of numerous pilots who have had nonfatal brushes with spatial disorientation signify unequivocally that this phenomenon continues to be a serious problem in aviation." To negate the effects of spatial disorientation the authors emphasize proficiency and recency in use of flight instruments.

TABLE 2.2: USAF accident rates from 1950's-1990's.

YEARS	TOT ACC	SD ACC	% TOT ACC	RATE
1958-1968	4,679	281	6 %	.35
1980-1987	524	61	12 %	.23
1988-1989	109	13	12 %	.19
1990-1991	91	13	14 %	.18

TOT ACC: Total accidents
SD ACC: Spatial disorientation accidents
% TOT ACC: SD Proportion of Total Accidents
RATE: Accident rate per 100,000 Flying Hours

A recent epidemiology of USAF spatial disorientation accidents was accomplished by Lyons et al. (1994). They nicely summarize Air Force accident rates from the 1950's through the early 1990's. Part of their results can be seen in Table 2.2. They focused on major accidents from the period of 1980-1991. A major accident is defined by the Air Force as those resulting in a loss of life or more than the following dollar amounts; until 1982 greater than $200,000, 1982-89 greater than $500,000, after 1989 greater than $1,000,000.

A number of facts are obvious from the Table. The incident of proportion of accidents attributed to spatial disorientation is increasing. There could be several reasons for this. First of all, modern Air Force aircraft have become more complex and higher performing. Furthermore, the missions have become more complex and challenging, such as night operations with night vision goggles (NVG's) and more air-to-ground missions.

Additionally, with increased awareness of spatial disorientation, flight surgeons and others on accident investigation boards may be more likely to attribute spatial disorientation as a cause or factor in an accident. However the investigators meticulously went over the accident boards findings to determine if spatial disorientation was unfairly left out of the contributing factors. They found instances where spatial disorientation should have been listed and was not. Faulty reporting undoubtedly played some role in the differences over the years, but what exactly this role is, is not clear. However, it is apparent that the proportion of total accidents attributed to spatial disorientation is definitely <u>not</u> going down! One other note regarding the data. The authors determined the one-sided binomial probability of the rate of accidents declining from the 1958-68 period to the 1980-91 period by chance to be .001. The overall accident rate in the Air Force is decreasing, but the percentage of the accidents that are occurring that are connected to spatial disorientation are increasing.

As mentioned above, one possible explanation for the increased rate of accidents attributed to spatial disorientation is the increased complexity of today's aircraft. As Kuipers, Kappers, van Holten, van Bergen, and Oosterveld (1990) pointed out, "the present generation fighter planes are very advanced and give the pilot more, instead of less, workload. They also allow a short range, high Gz, dogfight, in which there is hardly time for a good crosscheck (of attitude information). Because of overload, the aviator looses the total picture of his position."

Gillingham (1992) makes similar observations. The phenomenal ability of today's aircraft to change spatial orientation parameters quickly (pitch, roll, acceleration, etc.) present a substantial challenge for the pilot to accurately assess these changes. The clear canopy, of which the F-16 bubble canopy is the best example, is an advantage in looking for enemy aircraft, but a disadvantage in making one more susceptible to illusions of an ambient vision origin. Electronic systems which make the aircraft capable of flying in poor weather conditions and at night also expose the pilot to conditions making spatial orientation assessment more difficult and thereby increasing the odds of spatial disorientation .

Lyons et al. (1994) also declared there to be a consensus that spatial disorientation represents a major problem in aviation. This is consistent with Kirkham et al. (1978) findings in the seventies and points out the continuing nagging nature of the problem of spatial disorientation.

Lyons et al. (1994) point out the relationship between spatial disorientation and loss of situation awareness (LSA) also needs clarification. LSA is caused by inadequate cockpit attention due to fixation, etc., which can lead to spatial disorientation. The close relationship between the two is evident. The authors warn against the historical tendency to consider these two in the same category in aircraft accident reporting. For example, if these categories are combined, then 76% of all major accidents from 1980-89 would be in this one category. However, their strong relationship cannot be ignored.

The profile of the average pilot who is involved in a spatial disorientation accident has not changed much from the 1960's (see Table 2.3 from Lyons et al. 1994)). In 1990-

91, 12 of the 13 total Air Force spatial disorientation accidents occurred in fighter aircraft. Nine of the thirteen were fatal.

Kuipers et al. (1990) interviewed 209 fighter pilots from the Royal Netherlands Air Force (R.N.L.A.F.) to obtain information pertaining to aircraft spatial disorientation.

TABLE 2.3: Profile of the next pilot involved in spatial disorientation accident Lyons et al. (1994)

33 years old
Fighter pilot
1,687 total flying hours
635 hours in the specific aircraft

In their study, they focused on the most vivid or substantial case of spatial disorientation in each pilot's flying career as determined by the pilot. They found that pilots of all ages and experience levels had experienced spatial disorientation. In those incidents, where experience played a role, some younger, inexperienced pilots had difficulties with the aircraft complexity. This created distraction and high workload. Yet, some experienced pilots had overconfidence which led to spatial disorientation.

Gillingham (1992) summarizes the high cost of spatial disorientation. "Spatial disorientation is the largest single cause of Class A (major) aircraft mishaps attributable to operator error in the United States Air Force (USAF)." During the 10-year period 1980 - 1989, spatial disorientation was listed as a cause or factor in approximately one-eighth of all major USAF accidents, or 8 per year. If only operator-error mishaps involving fighter type aircraft are considered, the ratio is one-fourth, or 5 to 6 per year. If only operator-error mishaps involving the F-15 and F-16 are used, one-third of such mishaps, or 2 to 3 per year are related to spatial disorientation. The annual cost to the Air Force is around 100 million dollars, higher in some years. More tragically, twelve people on average lost their lives in spatial disorientation accidents every year in that period. Factor in the other branches of the U.S. military, military aircraft worldwide, civilian aircraft losses domestically and internationally, and the dimension of the cost becomes enormous to imagine.

As if these proportions are not staggering, one must consider the conservative nature of safety investigation reports. Unless there is clear evidence, spatial disorientation is not listed as a causal or contributing factor in an aircraft accident. For instance if poor crew coordination led to loss of situational awareness which ultimately resulted in ground impact, spatial disorientation may not be listed as a cause or factor in the accident. However, if the pilot had consistently paid attention to his attitude parameters such as pitch and bank, the loss of situational awareness probably would not have occurred. In other words, if they would not have been spatially disoriented they may not have lost their situational awareness. Bearing this in mind Gillingham states, "Thus, we can infer that SD causes many more USAF aircraft mishaps than the SD-specific incidence statistics would lead us to believe-probably two to three times as many."

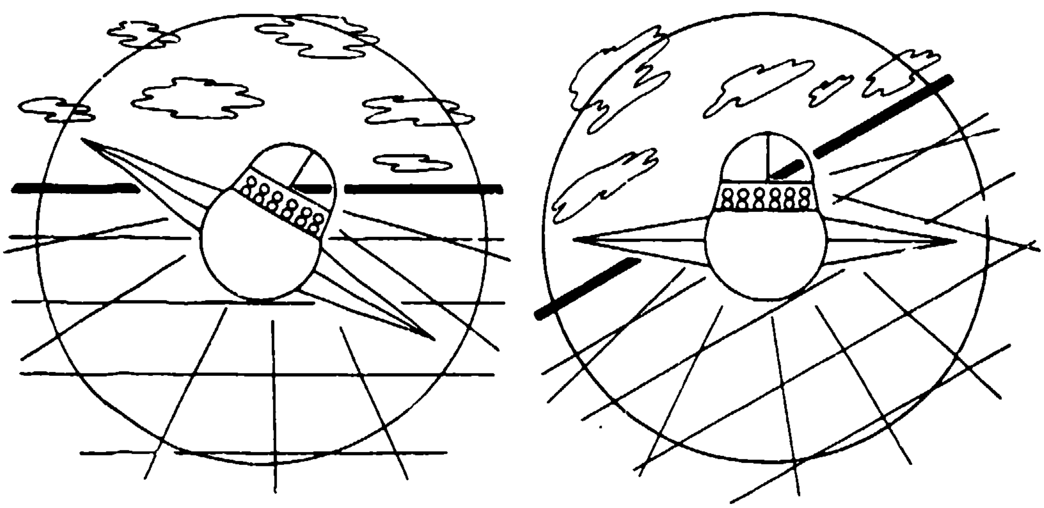
The severity of the problem is readily apparent. What can be done about it and how does the positioning of the pilot's head in flight play into all of this? Each of these issues will be discussed, but first the historical origins of situational awareness and attitude information will be considered.

2.3 Historical Origins

The pilot's orientation in flight has been important every since Orville Wright lifted off the beach at Kitty Hawk. The primary concern to him and his brother Wilbur that day were slight control movements to keep their Wright flyer in an upright and controllable condition, maneuvering only every so slightly. As their flying and technical expertise improved, so did their flying machines. With this improvement came more aggressive maneuvers in the pitch, yaw, and roll axis. Until the 1920's, flying was confined to visual flight conditions. Instrumentation was limited to information concerning aircraft condition such as engine temperature. For orientation, the pilot was left to his visual and vestibular senses. The 1918 Air Service Medical book reported on the importance of the pilot possessing a "good" vestibular sense to ensure he was competent to fly. The inference being that a well honed vestibular sense would ensure solid flying performance. The book reports several rudimentary tests conducted to test the vestibular sense, such as hitting the pilot in the head with a mallet. If he regained consciousness within 15 seconds he was considered to have a good vestibular sense and could make an excellent pilot. We now recognize that factors contributing to spatial disorientation are more complex than information provided by the vestibular system. Pilots are now taught not to trust or rely on the vestibular system, but to depend on their instruments for spatial orientation information.

The 1920's saw the advent of "blind flying" now known as instrument flying. The ability to fly in instrument flight rule conditions (IFR) was made possible by the development of gyroscopic flight instruments such as turn indicator and directional gyros. The most important instrument developed was the attitude indicator, or what is now often referred to as the ADI (attitude direction indicator). The roots of such instruments can be traced to Billy Mitchell's bold claims that he and a small band of aviators could sink the mighty Ostfriesland, a captured World War I German battleship. The naval authorities scoffed at such an idea, the battleship was the most powerful weapon of the era. Since by treaty the Ostfriesland must be sunk, authorities in Washington gave approval to Mitchell's test. Of course in front of horrified Naval dignitaries, the Ostfriesland was indeed sunk by Mitchell's aircraft in a matter of a couple of hours, in July 1921. Overshadowed by the publicity of the sinking, was the fact that the Sperry Corporation developed the first artificial horizon for Mitchell's run. Mitchell had been concerned about the possibility of bad weather on the day of the test and or the potential loss of a clear horizon line due to misty ocean conditions . To avoid the embarrassment of having to cancel the test for weather, Mitchell approached Sperry about the possibility of developing an orientational instrument to allow him to fly in clouds and fog. Their answer was the artificial horizon.

James Doolittle, who later led the famed raid on Tokyo in World War II, proved the utility of the new instrument on September 24, 1929. Doolittle accomplished the first totally "blind flight" by taking off, flying approximately twenty miles, and landing solely with the use of instruments. From this point forward a debate has raged as to the proper display format for this instrument. Generally, there have been two schools of thought, they are pictured in Figure 2.1. The most common instrument is the Moving Horizon or inside-out display. Several names for the instrument are used, but this investigation will use the term Moving Horizon. With this indicator the aircraft symbol is fixed while the horizon line rotates as the pilot turns and pitches the aircraft. Sanders and McCormick (1993) state the rationale behind this display, "this type of display is congruent with the pilot's frame of reference". Is this statement accurate? Before exploring it's validity, it's origin should be examined.



Moving Aircraft	Moving Horizon
Moving Aircraft/ Fixed Horizon	Moving Horizon/ Fixed Aircraft
Outside in	Inside out
Fly-from	Fly-to
Moving pointer	Moving card or tape
Aircraft referenced	Earth referenced
Space stabilized	Aircraft Stabilized

FIGURE 2.1: Basic aircraft attitude indicators and names adapted from Johnson and Roscoe (1972)

The first argument found in literature in favor of the Moving Horizon being congruent with the pilot's frame of reference was put forth in 1936 by John Poppen, a naval flight surgeon. His statements summarize today's design philosophy. The following is his basic argument in support of the Moving Horizon indicator. "One essential principle of flying instruments has not been sufficiently stressed. This is the nature of the representation it is designed to produce. We might say the kind of picture it draws. This is very well exemplified in the Sperry Horizon. *As we look at this instrument we see a picture of the exact relationship the airplane bears toward the horizon. It gives us the impression that we are actually looking at the real horizon.* If the airplane is banked to the right we see the left wing above the horizon and the right below, just as they appear in clear weather. This immeasurably reduces the mental effort of interpreting just what the instrument is trying to tell us. *It is a picture exactly like what we would see if we looked at the real horizon through a small window. It is a normal picture.*" (italics added) Poppen states clearly the primary arguments proposed for the Moving Horizon until the present. Underlying Poppen's argument is an assumption that the pilot does not move his head in a turn or pitch of the aircraft. This is important to highlight. If this assumption is true, the remainder of his argument is sound. However, if false, his arguments lose validity.

One would think this assumption would have been rigorously tested. This was found not to be the case. No tests of this hypothesis could be found through 1993. Whether Poppen was responsible for this assumption or was influenced by Doolittle or engineers at Sperry is not clear. It is clear however that this assumption has been propagated to the present, cited by multiple sources as evidence favoring the Moving Horizon (Sanders and McCormick 1993; Wickens 1992; Roscoe, Johnson, and Williges 1980). The investigation of this assumption is the crux of this proposed research..

Patterson (1994) found the assumption of a fixed head to be erroneous. In his study, pilots consistently and without exception tilted their head to maintain reference to the horizon while flying a realistic 360 degree view simulator. Serious doubt was cast upon Poppen's claims. This study intends to validate Patterson's work. Additionally, the question, are Patterson's findings transferable to other flight crew positions, will be investigated by observing the pilot's head response when they are not actively controlling the aircraft. Finally, exploration of factors which may attenuate or accentuate the head tilt will be examined which could lead to possible additional underlying causes of or influences on the head tilt reflex. Specifics on these methods will be given in Section 4. First a discussion of the two types of attitude displays currently available.

2.4 Moving Horizon versus the Moving Aircraft Display

The main argument in favor of the moving horizon display as mentioned earlier is the realism proponents claim it provides. The importance of pictorial realism of displays is highlighted by Roscoe, Corl, and Jensen (1981) as a key principal in the design of representational displays. Part of this principle maintains, "that a display should present a spatial analog, or image, of the real world,...", (Sanders and McCormick 1993). Poppen realized this in 1936 (he used the term "normal pictures" for pictorial realism) when he stated, "The principle of "normal pictures" should be zealously maintained in the design of all flying instruments. Remembering, again, the tremendous part played by the conscious mental interpretation of just what we see, anything which will simplify this step is highly to be desired." This is sound reasoning and is an argument for the moving horizon if the assumption of a still head is accurate. The ramifications of an incorrect assumption are obvious.

One of the biggest arguments against the Moving Horizon indicator is the fact that it violates the principle of compatible motion. Sanders and McCormick (1993) and Wickens (1992) point out this obvious fact. The principle of compatible motion states that if the aircraft were banked to the right, then the display should also move to the rignt. This is not the case with the Moving Horizon, when the aircraft is banked to the right, as pictured in Figure 2.1, the horizon (the only moving part of the attitude indicator) moves to the left. Many have suggested that this may cause reversal error. "Reversal errors are the result of misinterpreting an instrument indication and making a control movement that aggravates rather than corrects an undesirable condition" (Johnson and Roscoe 1972). As early as 1947, Fitts and Jones in their classic work studied 270 pilot errors in reading and interpreting flight instruments. He found that 12.2 % of all errors had the artificial horizon or attitude indicator as a contributive factor. 8.15% of all piloting errors were reversal errors. Of the 22 reversal errors, 19 were due to misinterpreting the direction of bank. He noted the violation of the compatibility of motion principle and claimed many of the "pilot errors" are really due to the design characteristics of aircraft instruments. He suggested developing simplified instruments that would eliminate some of the mental steps required in interpreting present instruments such as the attitude indicator. In another classic article, Johnson and Roscoe (1972) claim that fatalities, accident reports, films, and everyday experience of students and instructors indicate a high estimate of momentary and persistent control reversals associated with the misinterpreting of conventional attitude and steering displays. The frequency is higher than recognized and the consequences include increased pilot training requirements, decreased operational effectiveness, and losses of lives and equipment. They add, "...pilots do make errors in using the gyro horizon display. The problem is that, although this number is relatively small, the consequence of such errors are often tragic, and the amount of overlearning associated with the use of this display dictates that the number should be closer to zero." Patterson (1994) hypothesized this to be the cause of reversal errors in his experiment when the pilot suddenly lost visual references while flying formation wing position and attempted to transition to instruments. A significant percentage of accidents and incidences of spatial disorientation occur when aircraft suddenly enter instrument conditions (Roscoe 1989; Kuipers et al. 1990; Lyons et al. 1994).

Another argument against the Moving Horizon Indicator is perceptual interpretation. An observer may perceive himself as stationary in a moving surround (egocentric motion perception) or he may perceive himself as moving in a stable surrounding (exocentric motion perception) (Brandt, Dichgans, and Koenig 1972). The Moving Horizon Indicator assumes a egocentric motion perception. However, Brandt et al. (1972) found that peripheral vision predominates central vision to give the observer the exocentric motion perception. The determination of an egocentric versus an exocentric motion perception depends on the location of the stimulus. If the stimulus is found in the central visual field an egocentric perception will result. However, if the central and peripheral fields are stimulated (as is the case out the pilots window) the exocentric perception results. They found this to be true when manipulating the surround to give an equal area to both central and peripheral vision. Normally, the peripheral garners a larger share of the surround. They also found the peripheral driven exocentric perception to dominate without the associated vestibular cues which one would get if actually turning an aircraft. "Indeed, uniform motion filling the entire visual field, even without objective body motion, invariably leads to exocentric self-motion sensation." Exocentric motion perception appears to be the more appropriate perception model for the pilot, a model which the Moving Horizon indicator violates.

The main argument lodged against the Moving Aircraft Display is that it violates the principle of pictorial realism. As Sanders and McCormick (1993) state, "The problem is that the pilot sitting in the cockpit does not see the real horizon (in a turn) 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. We have already seen that this conventional wisdom is in jeopardy. The Moving Aircraft display definitely has the principle of compatible motion in it's favor. When the aircraft is banked to the right, the display aircraft (the only moving portion of the display) also banks to the right (Fig. 2.1). It has been suggested that this compatibility should aid in reducing reversal error (Fitts and Jones 1947; Johnson and Roscoe 1972).

Research results have been mixed as to which is the superior display. Many studies have shown that novices consistently perform better in flying tasks with the Moving Aircraft (Browne 1945; Loucks 1947; Nygaard and Roscoe 1953; Gardner 1954; Matheny, Dougherty, and Willis 1963). Casperson of Dunlap and Associates, Inc. (1955) showed that pilots who had not flown for an average of 5.8 years (averages of 2,556 flight hours and 300 hours of instrument time) performed better with the Moving Aircraft display in a jet simulator. For example, control reversals using the Moving Horizon display were 3.6 times the number of the Moving Aircraft control reversals. The subjects also showed a significantly better recovery time from unusual attitudes using the Moving Aircraft display. This is surprising considering their previous experience and training was strictly with the Moving Horizon indicator. Casperson contributed this to the notion that the Moving Aircraft is the "more natural" display. Other studies have also shown that current pilots show little or no better performance with the Moving Horizon versus the Moving Aircraft (Browne 1945: Roscoe, Wilson, and Deming 1954; Gardner 1954; Roscoe, Hopkins, and McCurley 1955; Weisz, Elkind, Pierstorff, and Sprague 1960) This is surprising considering the fact that the pilots have flown with such a display for a number of years and with very intensive training.

Not all the evidence is in favor of the Moving Aircraft. Gardner and Lacey (1954) showed the Moving Horizon superior in a test of forty Air Force pilots with a minimum of 1500 hours flying time and 150 hours instrument time in a Link trainer. Roscoe and Williges (1975) demonstrated that the Moving Horizon seems to do much better in actual flying conditions than in simulations. Sixteen Naval ROTC cadets flying a Beechcraft C-

45H showed a significantly better ability in tracking a randomly generated command flight path, with disturbed attitude tracking, using a Moving Horizon display versus the Moving Aircraft display. However, recovery from unusual attitudes were superior with the Moving Aircraft display. Fitts and Jones (1947) suggested that the argument over the best display system had yet to be settled. This was nearly 20 years after the Moving Horizon was in use. Johnson and Roscoe (1972) declared the issue had not been settled 25 years after Fitts and Jones. I contend the issue has not been settled in the 20 plus years since Johnson and Roscoe, especially in light of Patterson's work (1994). Some would argue what with the strong convention in place, it would be difficult to transition from the Moving Horizon. This may not be the case. As Casperson's (1955) work indicated, experienced pilots seem to make the transition to the Moving Aircraft display easily.

Alternatives to the Moving Horizon and Moving Aircraft displays have been proposed. Fogel (1959) points out that these two are but opposite ends of a spectrum when it comes to attitude presentation. He suggests a frequency separated display, now known as the kinalog display, where the initial turn of the aircraft would result in a compatible initial movement of the aircraft symbol, and after the turn was stabilized the display would then rotate by moving the horizon to a tilted position then resembling the Moving Horizon display. He suggested the initial movement of the aircraft in theory would overcome the problem of the principle of compatibility. Roscoe and Williges (1975) tested this display in flight and subjects reported it to be a bit confusing and did not perform as well as with traditional instruments in tracking a randomly generated flight path and recovering from sublimal unusual attitudes. However, Roscoe and

Williges (1975) slightly modified the display and found it to be more effective than the Moving Aircraft display in a disturbed attitude tracking task. The experiment used a randomly generated flight path with sixteen Naval ROTC cadets as subjects. The display had equivalent performance to the Moving Horizon and showed promised in unusual attitude recovery. Ince, Williges, and Roscoe (1975) found in a simulator study, that this modified frequency separated display had superior disturbed attitude tracking performance and better recovery times for unusual attitudes recoveries versus the Moving Horizon and Moving Aircraft displays using flight naive subjects. Beringer, Williges, and Roscoe (1975) found that highly experienced pilots could easily learn to use the frequency separated display, and after little practice performed better with it for certain flight tasks.

Obviously an important element has been left out of the experimentation to this point. All the studies referenced were performed under the assumption that the pilot's head remains in a fixed position aligned with the airframe during aircraft bank. If it is can be shown that pilots naturally and consistently tilt their heads, then that would change the argument entirely and could explain some of the mixed experimental results we have seen thus far. It may be that the frequency separated display, if designed correctly, will provide the most pictorial realism and superior performance of any display possible; however, this should be confirmed through research.

2.5 Visual and Vestibular Responses

Patterson (1994) identified six responses which play into the pilot's spatial orientation equation. They have been compiled in tabular form (Table 2.4) for the reader's convenience and should be referenced throughout this discussion. These responses can be synergistic or antagonistic and they seem to override one another in a hierarchical arrangement that is not yet understood. For simplicity these responses may divided into the following categories determined by the primary (though not exclusive) driving areas of each particular response. There are two vestibular driven responses, three visually driven, and one receptor driven response. Each response will be examined in turn.

Friederici and Levelt (1987) investigated spatial orientation in 1g and micro g conditions. Their data support the theory that unambiguous spatial assignment is achieved by a cognitive weighting of different perceptual cues. On earth, gravity is the dominant cue, while in space (during weightlessness) it is retinal information that plays the dominant role in spatial assignment. Furthermore, in weightlessness, visual frame information and body axis orientation are largely ignored in providing spatial orientation. Most likely, in an aircraft there are several cues which are weighted to determine spatial orientation.

Before examining the reflexes, some general observations on vision and orientation should be made. Gillingham and Wolfe (1986) pointed out the ambient vision (as opposed to focal vision) is primarily involved with orientating oneself in the environment and seems to be independent of focal vision. Focal vision serves to orient the perceived object relative to oneself, while ambient vision orients oneself relative to the perceived environment. The retinal image of a moving object or environment can be stabilized by appropriate eye movements. These eye movements provide gross stabilization of the retinal image which aids object recognition and spatial disorientation by enhancing visual acuity.

The visually controlled eye movements which provide image stabilization can be characterized by slow pursuit movements followed by saccadic (or rapid) eye movements. This pattern of reflexive slow tracking and fast back tracking is known as optokinetic nystagmus and will be examined further (Gillingham and Wolfe 1986).

The vestibular system also plays a role in orientation and will be reviewed only briefly as a working understanding of the system is assumed. The vestibular system consists of the semi-circular canals and the otoliths organs. Each play a role in pilot orientation, but the otoliths play the major role. The semi-circular canals convert inertial torques into information about angular motion of the head. The otoliths translate gravitational and inertial forces into spatial orientation information, specifically information about position and linear motion of the head (Graybiel 1974). Young and Oman (1984) put it succinctly, on the earth the otoliths signal head orientation with respect to the vertical. The otoliths are composed of the ultricle and saccule. Of the two, the utricular otolith is responsible for more information about position and movement of the head (Dorland 1988). Howard (1982) makes the following observation, "Such an organ is clearly suited to respond to displacements of the heavy otoliths (the heavy calcite

TABLE 2.4: Reflexes experienced in flight

GROUP or Name	DEFINITION & EXAMPLE	DRIVER
VESTIBULAR		
Vestibular-ocular	Tilt head and eyes rotate (eye torsion) to stay fixed on point. Fig. 2.2	Semi-circular canals Facilitated by otoliths Rate dependent
Vestibular-collic	Otoliths displace. Tilt head to stabilize. Vision out of the loop. Car driver Fig. 2.3	Otoliths
VISUAL		
Optokinetic nystagmus	Whole vision field moves, eyes rotate same direction as field to stabilize. Opposite rotation of vestibular-ocular and slower. Pilot's eyes rotate to stabilize peripheral as horizon tilts.	Peripheral vision
Pseudo-vestibular collic (Young) **Optokinetic collic** (Patterson)	Tilt the head to stabilize the peripheral. Opposite tilt from vestibular-collic. Head tilt reflex seen in pilots in a bank. Fovea on the line, horizon in the periphery.	Peripheral vision
Foveal Pursuit	Tracking a target with the fovea. Eye will chase a moving finger.	Central vision
JOINT RECEPTOR		
Cervico-ocular	Bend neck and eye adjust accordingly. Head stationary (in vice) move trunk aft and eyes rotate upward. Vice-versa.	Receptors in the neck

crystals or otoconia inside the utricles and saccule) induced by changes in the extent and direction of the linear acceleration of the head,brought about by changes in the linear velocity of the body or in the direction of motion of the body or by a tilt of the head with respect to gravity." The response of the otoliths to these changes in the extent and direction of the linear acceleration of the head will play a role in several of the responses we look at, and especially in the vestibular-collic and pseudo-vestibular collic reflexes. Gillingham and Wolfe's (1986) cardinal principle for the vestibular system mechanics is as follows: angular accelerations are the physiologic stimuli for the semi-circular canals while linear accelerations and gravity are the stimuli for the otoliths. The stimulation of vestibular organs in flight is often outside the designed frequency response of the organs which leads to orientational illusions in flight (Gillingham and Wolfe 1986).

The human body can consciously or subconsciously be oriented. Gillingham and Wolfe (1986) describe it well, "Conscious orientational percepts thus can be either natural or derived, depending on the source of the orientation information and the perceptual process involved: one can experience both natural and derived conscious orientational percepts at the same time." An example would be a pilot whose eyes and instruments tell him he is level while the vestibular system tells him he is in bank, this condition is known as the leans. Although Howard (1982) has provided service in collocating the factors which play into human visual orientation, more work in this area is needed.

2.5.1 Vestibular Responses

The vestibular ocular response occurs when the human tilts the head, and the eyes rotate about the visual axis opposite the motion of the head to stay fixed on a point. This response is induced by the semicircular canals, but facilitated by the otoliths , and is rate dependent (Jones 1965; Howard 1982; Gillingham and Wolfe 1986). Jones (1965) states, "Yet within limits the eyes usually manage to achieve the necessary intermittent stabilization of the retinal image, largely by means of a complex series of automatic neuromuscular mechanisms...". He further points out that man has "high eye in skull actuation ability" (the ability of the eye to rotate and move in the head) which allows him to move the eyeball dynamically. Howard (1982) reports that this torsion (rotation of the eye) is 10% to 20% of head tilt for angles up to 30° and evidence suggests a shearing force acting on the ultricles drives this countertorsion. Gillingham and Wolfe (1986) give an excellent illustration of this response (Fig. 2.2). As seen in the figure, as the subject tilts the head, the eyes have a counter-torsion which allow the subject to stay focused on an object, such as a word. Gillingham and Wolfe (1986) contend that this is the body's primary system to stabilize the retinal image, yet it may be overridden at times by the optokinetic nystagmus reflex, as Patterson (1994) suggested. When the movement of the eye is characterized as a torqued rotation it is sometimes referred to specifically as ocular countertorsion reflex (Gillingham and Wolfe 1986).

The second vestibular based response is the vestibular-collic response. As the otoliths of the inner ear are displaced by the change of the linear acceleration of the head, the person repositions the head to stabilize the head in equilibrium (Outerbridge and Jones 1971; Gillingham and Wolfe 1986). This response is obviously driven by the otoliths and the visual system is out of the loop (Howard 1982). An example of the vestibular-collic response is pictured in Figure 2.3. As the car driver enters a turn to the left, the otoliths are displaced to the right by the linear motion. To compensate, the driver leans to his left, or into the turn, to bring his otoliths back into line. This stimulation of

FIGURE 2.2: The vestibular-ocular reflex.
As the head tilts left, the eyes rotate right to assume a new angular position about the visual axis. From Gillingham and Wolfe (1986)

the otoliths by constant linear acceleration induces deviations in a direction which depends on the direction of the stimulus (Howard 1982). Gillingham and Wolfe (1986) state that the vestibular-collic reflex is not as effective as the vestibular-ocular reflex in stabilizing the retinal image. However, the two usually work together in a synergistic fashion.

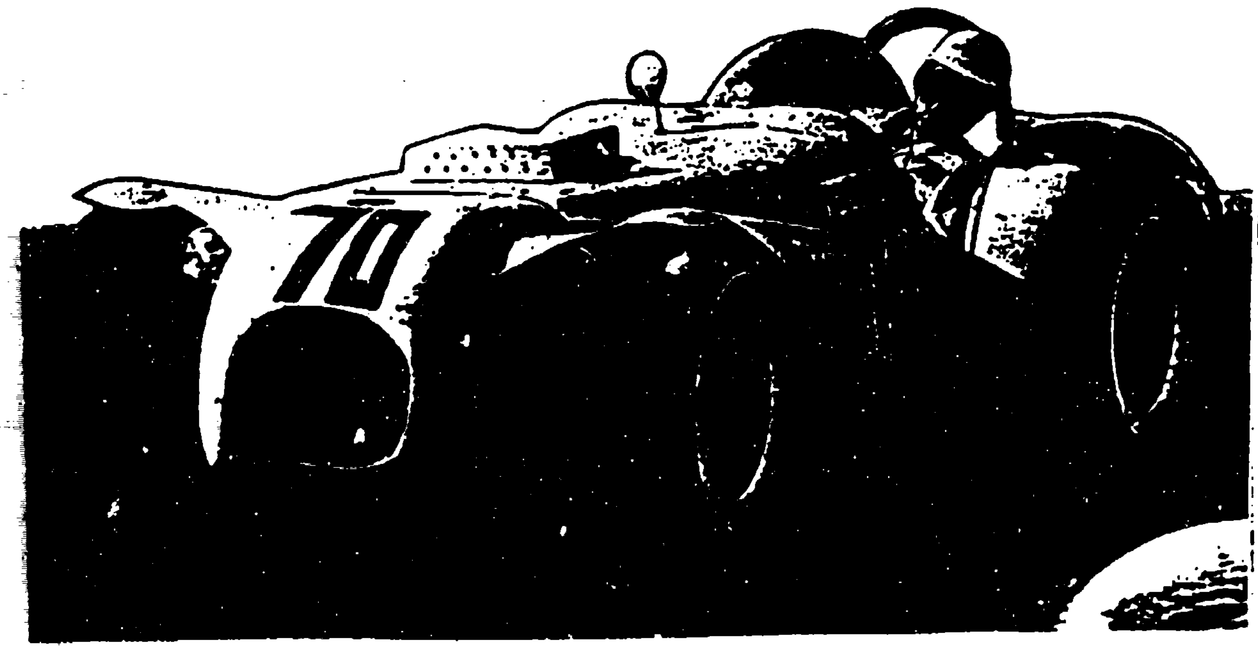


FIGURE 2.3: Car driver exhibiting the vestibular-collic response

2.5.2 Visual Responses

In the interplay between the visual and vestibular systems, the visual system seems to override the vestibular system in flight, especially in visual flight conditions. Gillingham and Wolfe (1986) describe visual dominance, "...visual dominance, the ability to obtain and use spatial orientation cues from the visual environment despite the presence of potentially very strong vestibular cues. Vestibular suppression seems to be exerted, in fact, through visual dominance, as it disappears in the absence of vision."

In optokinetic nystagmus (OKN) the eye moves to stabilize the visual field. A more specific type of OKN is optokinetic torsion which is the torsional equivalent to vertical and horizontal optokinetic nystagmus (Howard 1982). I will use these terms interchangeably as is common in the literature. The torsional movement of the eye is elicited by a rotation of the visual scene in the frontal plane about the fixation point (Howard 1982, Young, Shelhammer, and Modestino 1986). This eye torsion is *opposite* that of the vestibular ocular response. With OKN the entire visual field is moving while the head may or may not be stationary, while with the vestibular-ocular response, the head tilts and the eyes rotate to stabilize a visual field which may or may not be stationary. The eye rotates in the direction of the field movement in an attempt to stabilize the visual field (Howard 1982). This response is driven by peripheral vision (Brandt et al. 1972). Gillingham and Wolfe (1986) pointed out that foveal vision is not primarily involved with orientating oneself in the environment, but rather the peripheral vision drives it. Besides consisting of an opposite direction of eye torsion, OKN is slower than the vestibular-ocular response and therefore not as effective (Howard 1982). For example, it is easier to move the head and read (vestibular-ocular) , than to move the print and read (OKN). An operational example of OKN can be seen in aviation. As a pilot banks the aircraft, the eyes rotate to stabilize the peripheral as the entire horizon rotates in front of him. Like the vestibular-ocular reflex above, the prime purpose of this reflex is to stabilize the image as a whole, not to maintain the image on the fovea. Howard (1982) pointed out that this reflex is very difficult to inhibit consciously. Furthermore, the cooperation between OKN and vestibular systems to stabilize the retinal image when the head moves suggests they share certain neural components which are most likely situated in the vestibular nuclei. This is a good example of the complementary roles of various orientational systems of the body.

Another visually induced reflex is the pseudo-vestibular collic (Young et al. 1986) reflex. Young et al. (1986) refer to this as a postural stabilization reaction which results in head and trunk tilt in the direction of a rotating visual field. This phenomenon occurs when the visual field is rotated and the human tilts the head in the direction of the rotation to stabilize the movement of the peripheral field. It should be pointed out that this reflex is *opposite* that of the vestibular-collic reflex and indeed the input of the otoliths must be overridden for this opposite tilt to take place. Figure 2.4 illustrates the reflex in a motorcycle rider. As the rider turns to the left, his head tilts to the right to help him remain oriented. This reflex occurs in conjunction with the OKN reflex. Brandt et al. (1972) showed the powerful influence of visual motion on perceived body orientation. They concluded that the peripheral retina dominates this function. They also emphasized the importance of peripheral vision for dynamic spatial orientation, "dynamic spatial orientation relies on moving stimuli projected into the peripheral visual field..." To build on the previous example, as the pilot banks the aircraft the eyes rotate in the direction of the rotating field and the pilots head will tilt in the direction of rotation in an attempt to stabilize the horizon line. In this scenario the pilot's eyes are focused on the horizon and as it moves in his peripheral vision, the OKN and pseudo-vestibular collic reflexes are evoked.

Patterson (1994) has labeled the pseudo-vestibular collic reflex the optokinetic collic reflex. Patterson's term is more technically correct, as the reflex seems to be elicited primarily through the visual or optic system and the term readily identifies the triggering mechanism of the reflex. Whereas Young's term, pseudo-vestibular collic,

FIGURE 2.4: Motorcycle rider displaying the optokinetic collic response

could be mistaken for a vestibular induced reflex. I will use both terms, with emphasis on Patterson's more technically correct term, optokinetic collic reflex. Both vestibular-collic and pseudo-vestibular coilic or optokinetic collic reflex result in head tilt, but they are opposite in direction and triggered by different mechanisms.. The reason for the opposite movement of the eye and head from the vestibularly driven responses is likely to relate to visual dominance.

Another visually driven response is foveal pursuit (Howard 1982; Patterson 1994). Foveal pursuit eye movements seek to maintain the image of interest on the fovea. The goal is to stabilize the image of the object of interest rather than the whole visual scene which is the role of vestibular-ocular and OKN eye movements (Howard 1982). It follows that central (or foveal) vision drives this response. A human will track a moving target with foveal vision. For example, the eye will chase a moving finger to keep it in focus. While most of the reflexes discussed are automatic, this response is not, since high level decision processes at the cortical level are involved (Howard 1982). However, the.

vestibular inputs "mesh" with those of the visual pursuit system to maintain effective visual performance as the observer moves about

2.5.3 Receptor Driven Response

There are joint receptors in the neck which influence the orientation of the human eye (White 1982). The receptors can elicit a cervico-ocular response. This response occurs as the head is held stationary and the torso is moved fore or aft. However, as Howard (1982) notes, no eye torsion will occur, only movement in the horizontal or vertical plane. For example, if a human's head is put in a stationary position and immobilized, then the trunk is moved aft, the eyes will rotate skyward and vice-versa. "The horizontal and vertical responses are induced by stimulation of the joint receptors in the neck" (Howard 1982). This cervico-ocular reflex is sometimes referred to as a spino-ocular reflex, though technically there are differences between the two. "Cervico-ocular and vestibular-ocular cooperate in achieving visual stability during head movements" (Dichgans 1974). This occurs because neurons originating in proprioceptors in the neck project directly and indirectly into visual and vestibular centers (Howard 1982).

2.5.4 Relationship of Responses

We have noted that reflexes act in a synergistic or antagonistic fashion depending on the particular stimulus. For example, the joint receptors in the neck combine with the vestibular and visual inputs to form inputs into eye and head movements for acquiring targets off to the side (Howard 1982). To summarize, a person determines the position of the head through visual inputs, including eye torsion. The joint receptors in the neck and ultricles register head position with respect to the body. Finally, the angle of the head with respect to gravity is determined by the otoliths (Young, Oman, and Dichgans 1975; Howard 1982).

One may ask, aren't pilot head movements undesirable, as they may lead to coriolis effects and other pilot illusions? Research has shown that pilot head movement may lead to disorientation, especially at 2 g's or greater (Gilson, Guedry, Hixson, and Niven 1973). Such research invariably cites military manuals, such as Air Force Manual 51-37, which discourage head movements during banked turns. For example, when a pilot turns his head to adjust a radio frequency while in a high g turn (i.e. greater than 1 g) the pilot may experience a tumbling sensation because the semi-circular canals have been re-stimulated in addition to the otoliths. This is known as the coriolis response or effect. However, often such research and references apply when there are no visual references, or instrument flight rule (IFR) conditions. However, under visual flight rule (VFR) conditions, head movement is natural and desirable.

2.6 Control Theory

As Young et al. (1986) pointed out, the pseudo vestibular-collic reflex (or Patterson's term optokinetic collic reflex) can be induced in a passive observer. Brandt et al. (1972) placed subjects inside a rotating drum which allowed circular motion of the entire surrounding. This led to an apparent self motion known as circularvection which is indistinguishable from actual chair rotation. As subjects observed the rotating scene, the pseudo vestibular-collic reflex was induced. Young et al. (1986) found the same response in weightlessness on Spacelab 1. Clearly pseudo vestibular-collic is a natural reflex, but when piloting an aircraft is it also more than just a reflex? Patterson's (1994) work seems to indicate it may be, and this needs to be investigated.

Figure 2.5 shows a simple tracking loop. In any control loop there is a specified input which drives the output (Sanders and McCormick 1993). The curves of the road (the input) specify the path to be followed by the car (the output). The input on a display is often referred to as the target, while the output is referred to as the cursor. Input is typically received directly from the environment and sensed by the human eye (or other sensors). Output is reflected (observed) by the outward behavior of the system, such as the movement of the car along the road. Both control input (e.g. the approach runway) and output (e.g. position of the aircraft) of VFR flying can be read by the eyes using outside visual references. The display contains the target which is the desired position and the cursor which is the actual position. The difference between the target and the cursor is the error. The operator perceives what the display is presenting, makes decisions, and then outputs a response to a control stick or whatever the control device may be (Fig 2.5). The device takes that response and transforms it through wires, cables, etc., to the control service such as the ailerons on an aircraft. The system then responds to the control input with feedback traveling to the display to present the new cursor position.

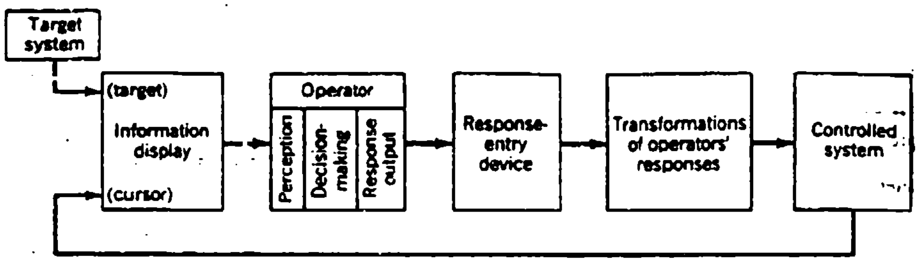


FIGURE 2.5: A simple tracking loop
from Knight (1987)

The complexity of a control system relationship is called the control order (Adams 1989). The simplest control order is position, where the relationship between control action and system output is linear and proportional. For example, as the target moves left 5 inches, the operator moves the control device left .5 inches to track. Position is known as a zero order control system. First order systems are based on the first integration of position, which is velocity. The control movement defines a velocity output for the system. Second order systems are based on the second integration, which is acceleration. In this case, a control movement defines an acceleration output for the system. As a general rule, as the order of the system increases above first order, so does the difficulty of the tracking task and a decrease in performance occurs (Wickens 1986). However, under constant velocities or accelerations, higher order dynamics may be easier because they relieve the operator of certain duties (i.e. tracking an accelerating missile).

The operator must process the display information, before a control input can be made. This results in a lag. Lag time of zero or first order systems is 150 to 300 msec. Lag time of second order systems is 400 to 500 msec (Wickens 1992). Increased lag time decreases tracking performance (Poulton 1974; Adams 1989). Sluggish controls or systems are another source of lag. For example, the captain of a oil tanker turns the control wheel which moves the rudder of the tanker, but the response of the tanker turning is very sluggish. Fighter type aircraft do not suffer from sluggish controls, but some larger aircraft such as bombers and transports do.

There are two main types of tracking displays, the pursuit and compensatory displays. In pursuit tracking, both the target and cursor are displayed which translates to the input, output and error all being displayed in one place. One is able to ascertain if error is induced by movement of the controlled element (e.g. the aircraft) or due to movement of the target (e.g. the lead aircraft in formation). With compensatory displays only the error is displayed. Therefore, one cannot easily derive if the error was due to output of the operator or some outside force acting on the input. A pilot flying in visual flight rule conditions (VFR) uses the outside world as a pursuit display. "The operators of many systems are expected to make control responses to bring about the desired operation of the system as implied by the input (...such as the flight path of an airplane)" (Sanders and McCormick 1993).

Pursuit displays have consistently proved superior to compensatory displays in tracking tasks (Poulton 1952; Briggs 1962; Briggs and Rockway 1966; Pew 1974). Adams (1989) presents two possible reasons for this superiority. The operator's knowledge of the results of actions is better with a pursuit display, which is a strong determinant in human learning. These displays give a clear knowledge of the results about the corrective actions. Secondly, these displays allow the operator to see the input and any regularities about them. The ability to anticipate regularities of input is a key to tracking. Therefore, we find the characteristics of the input signal (e.g. speed of change) is a determinant of tracking plus what the operator knows in advance (known as preview) about the signal (e.g. how it will vary) both affect the ability to track effectively. An example would be a car driver who knows it will be a winding road from experience and can also see the curves coming in clear (as opposed to foggy) conditions.

As mentioned above, one way to deal with lag and to improve tracking performance in general, is through prediction and anticipation (Sanders and McCormick 1993; Wickens 1992; Adams 1989). Prediction and anticipation can in turn be divided into two areas; predicting input and predicting system output. Reid and Drewell (1972) showed that predicting command input improves tracking performance. Future input is most accurately available when there is preview. As in the previous example, the car driver who sees the road in the clear versus foggy, or other obscured conditions, will track better. For pilots, flight path previewed tens of seconds into the future will be useful (Wickens 1992). This preview helps compensate for mental processing lags in the operator.

The second area of prediction and anticipation is predicting future trajectory of the system output. Predictive displays and quickening of displays are effective techniques. However, this is outside the area of interest of this investigation.

As Wickens (1992) states, "The source of all information necessary to implement the corrective response is the display.. For the automobile driver, the display is simply the field of view through the windshield,...". So in other words, to correctly track the target cursor and error, one must have a display to give the information necessary for the tracking task. The display can be the outside world as we see in the automobile. This is also the case for aircraft flying in visual flight conditions. The majority of information necessary to fly a course is outside the canopy of the aircraft. Of course, under instrument conditions this is not the case as the pilot cannot use outside visual references due to weather etc. and is forced to fly by the use of instruments.

Sheridan (1987) has developed the concept of supervisory control to explain the behavior of human beings in relation to computers and other automated systems. The modern aircraft is definitely an automated system. He draws an analogy of this interaction to that of a supervisor who plans and then delegates to subordinates specific tasks to be done. The subordinates accomplish the tasks and then report back the results to the supervisor who in turn makes decisions based on the new status of the system.

Sheridan (1987) lists five major categories of behavior that are a part of the supervisory role: planning, teaching, monitoring, intervening, and learning. The operator plans goals and strategies for the system. Teaching is actually inputting or directed the system in "what" to do. Monitoring is obviously ensuring the system carries out the instructions in a correct manner and intervening by the operator occurs when the system is not performing correctly. Finally, the operator learns through experience with the system, how best to employ the it the next time.

Rasmussen (1983) categorized three types of behavior which may be applied to supervisory control. The behaviors are from simple to complex: skill-based, rule-based, and knowledge-based. Skill-based behavior is well practiced, nearly effortless behavior such as riding a bicycle. The role that information plays in skill-based behavior is that of a signal. The signal indicates whether performance is adequate and or when to initiate a behavior. Machines often perform skill-based behavior better or at least as well as humans, especially in tedious repetitive tasks.

Rule-based behavior is controlled by stored rules or "know-how" or "rules of thumb". Examples would be cookbook recipes or rules developed through prior experience such as, "pump the accelerator twice to best start this car". Information for rule-based behavior serves as signs. One must interpret a sign to discover its meaning. The interpretation allows one to select and or modify rules which apply to the particular situation. When an aircraft is flying at 150 knots this may be a good approach speed for landing, but nearly a stall speed at high altitude. The situation therefore dictates the rule-based behavior to follow, continue the approach or push up the throttles. Machines can be programmed to exercise rule-based behavior through if-then loops, etc. Humans apply this type of behavior effectively.

The final and most complex type of behavior is knowledge-based behavior. This behavior requires high level decision making, planning, evaluation, goal setting, and situational awareness. Such behavior is seen in unfamiliar or unexpected environments where previous experience provides little help. An example would be a pilot traveling over the ocean for the first time when a hydraulic failure and bad weather are encountered. Information serves as a symbol or symbols in knowledge-based behavior. These symbols are necessary for reasoning and serve as a piece of the operator's mental model of the system. Machines are generally poor at this level of behavior, but are improving. This is a strong area of the human operator. As Sanders and McCormick (1993) point out, these behaviors are not discrete, but rather operate on a continuum, each being used differently and often simultaneously depending on the scenario.

Using Sheridan's (1987) supervisory control theory in conjunction with Rasmussen's (1983) taxonomies of behavior, I will examine the role of a pilot flying in VFR conditions. A well trained pilot uses skill-based behavior to actual fly (or track) his aircraft along a route. Simultaneously, he may click off an insignificant written message on his display using rule-based behavior. Finally, he may be formulating a contingency plan in case of bad weather at his destination airport. The actual control of the aircraft is almost effortless in this scenario, especially if no turbulence is present.

Let's look at the same scenario, but this time the pilot programs the autopilot to do the actual flying of the aircraft. This situation is a classic supervisory control scenario. This changes the behaviors at work. The skill-based behavior is replaced in the operator by the autopilot. This leaves the pilot free to concentrate on other rule-based or knowledge-based behaviors. In other words, on higher level tasks. His supervisory control of the autopilot demands that he initially teach (i.e. program the autopilot) but for the majority of time monitor the autopilot's performance and intervene if necessary in case of malfunction. These roles require higher level behavior. Finally, the pilot learns each time he uses the autopilot how to best employ is on subsequent missions.

2.7 Summary

In this section, spatial disorientation has been addressed, focusing on the origins of the phenomenon, the high costs which result, and the associated displays used to help minimize its effects. Or better put, the displays which have been offered to help keep the pilot oriented with the aircraft and environment. The physiological responses which affect the pilot's ability to remain spatially oriented have been examined. Finally, the concept of supervisory control was introduced as it relates to the pilot actively flying or simply monitoring the autopilot as it flies the aircraft.

3.0 DEVELOPMENT OF HYPOTHESIS

Inherent to the success of the tracking loop is the correct reading or perception of the display. Often, this is an underlying assumption of the tracking loop. The vast majority of literature discussing tracking loops assumes that the display is in the optimum (or at least adequate) position to be read and interpreted by the operator. Pew (1974) points out that operators will follow pursuit behavior when possible, that is they will read or follow the input closely and compensate for errors when they build up. However, if the display is not read correctly, the subsequent tracking effort will suffer. As mentioned above, as a driver rounds a corner in an automobile, his head tilts in response to the otoliths driving the vestibular-collic reflex. This is the natural response and in all likelihood allows the driver to feel more comfortable as he tracks the vehicle along the road. In the same way, it is likely that the aircraft pilot exhibiting Patterson's (1994) optokinetic collic reflex is doing so not only as part of a natural reaction, but also as an aid to reading the display (the outside world) and thus to feel more comfortable and track the aircraft more proficiently than would be possible without the head tilt. Furthermore, the attentional resources required to fly visually may demand more head tilt. The input and output must be read correctly to properly accomplish the flying task. It is postulated that to read the input and output most effectively, the pilot must tilt his head.

Not only will head tilt allow the display to be read and interpreted correctly, but it is theorized that it will also allow proper preview to occur, increasing performance. These two concepts, reading/interpreting and preview are closely related. Good preview allows one to read and interpret more efficiently and effectively. If the pilot is to get the proper preview to predict command input the head tilt can prove helpful. As stated earlier, this preview helps compensate for mental processing lags in the operator and in the flying environment. Flight path preview of tens of seconds into the future can be very helpful (Wickens 1992). An analogous situation can be taken from the automobile. Imagine driving a car lying in a horizontal position with the feet near the passenger door and the head near the driver's door. It is easy to imagine the resulting difficulty in properly previewing the road and correctly tracking the automobile along the road. In the same way, the pilot's head tilt allows him the proper perspective with which to preview, track, and remain spatially oriented in the aircraft.

Combining Rasmussen's (1983) three types of behavior with Sheridan's (1987) supervisory control theory allows a conceptual model to be built to help explain head tilt in the supervisory control flying situation. Because the skill-based behavior has dropped out of the operator's loop and is performed by the autopilot, the requirement to precisely read the display (i.e. the outside visual scene) is not as stringent. This is because the feedback required on the display for the pilot to fly the aircraft correctly is not required for the autopilot to fly (or track) the aircraft. In the monitoring role, it is not necessary for the pilot to closely observe the outside environment so that he may fly the aircraft correctly. He must simply monitor the autopilot, through the outside visual world, and through instruments such as the altimeter, to ensure it is performing correctly. The optokinetic collic reflex is a natural response, however, it may be that the pilot's requirement to precisely read the display (i.e. the outside visual world) may lead to a greater optokinetic collic reflex than would be found if the pilot was performing only higher level supervisory control where information is at the sign or symbol level. In other words, when the autopilot flies, reading the information at the skill level is not required as the information is treated at the rule or knowledge level. It is hypothesized that the rule and knowledge levels demand less precision than does processing the visual display at the skill level. Therefore, if there is no requirement to read the display as precisely, less head tilt should result.

One can see that reading signals, signs, and symbols in the aircraft and through the canopy display are closely related to reading/interpreting and previewing the display. These all interconnect and act in a synergistic fashion. The hypothesis that active control

PATTERSON MODEL	**SMITH ACTIVE**	**SMITH PASSIVE**
Movement of Visual Field	Movement of Visual Field	Movement of Visual Field
⇓	⇓	⇓
Optokinetic reflex	Optokinetic reflex	Optokinetic reflex
⇓	⇓	⇓
Spatially Oriented knowledge)	Read display (skill)	Read display (rule,
	⇓	⇓
	Preview	Preview (slight)
	⇓	⇓
	Improved tracking	Spatially Oriented
	⇓	
	Spatially Oriented	

FIGURE 3.1: Conceptual model of pilot orientational processes

will result in greater degrees of head tilt than passive control can be pictorially seen in Figure 3.1. The ultimate goal of the head tilt may be to track correctly as well as to stay spatially oriented, as Patterson hypothesized.

Passive control should be subject to the optokinetic collic reflex, but not to the degree that occurs under active control. There should be a significant statistical difference between the active and passive states at greater than twenty degrees of aircraft bank. Furthermore, both active and passive states should differ significantly from zero head tilt.

4.0 METHOD

4.1 Experimental Design

The experiment was a three-factor mixed design with within-subjects and repeated measures on two factors and between-subjects on the other factor. The between-subject factor was type of aircraft experience (TYPEACFT), Fighter or Heavy. The first within-subject factor was the control (CONTROL) of the aircraft with two levels, ACTIVE (pilot flying) or PASSIVE (autopilot flying). The other within-subjects factor was aircraft bank angle (BANK) which was divided into five degree increments left and right from 0 to 90 (18 levels) for ease of data analysis using ANOVA techniques. This resulted in a 2 X 2 X 36 mixed design. Figure 4.1 shows the experimental design. The order of presentation of CONTROL was counterbalanced. For each experimental session the subject flew the aircraft and observed the autopilot fly the aircraft through a visual flight rules (VFR) low level route.

There was one dependent variable in the experiment. The head roll position of the subject, specifically the head angle measured from the vertical toward each shoulder. This variable was easily measured by the MS-1's head tracker apparatus attached to the pilot's helmet. Data was collected twice per second. This is a rate near the limit of the collection system and yet allows ample sampling in a turn and results in a manageable data output. Each time a pilot was in a particular BANK the head roll was added to that

BANK. The head rolls were then averaged in that BANK for that pilot and a head roll mean (HRMEAN) score resulted. In turn, the 16 subject's HRMEAN scores were averaged to arrive at a cell mean (CELLMEAN) score for each BANK. The HRMEAN scores were used to achieve a balanced ANOVA procedure. As a backup, a video recording of the pilot's head and instruments was made, to permit digitized analysis if required. Data was also collected on the other two axis of pilot head movement, however the side-to-side roll angle was the primary interest of this study.

4.2 Subjects

Sixteen subjects from the United States Air Force participated in the experiment. Most pilots were stationed or worked at Wright Patterson AFB Ohio. One pilot was stationed at Springfield Air National Guard Base. There was no remuneration to the subjects for their participation. All subjects were or had been military instrument rated pilots. A current rating in an aircraft was not required, however all had military flight experience in the last three years. Nine of the subjects were actively flying military aircraft. Three of the pilots had left the service in the past three years. The pilots had flown a variety of aircraft. Eight were categorized as Fighter type pilots (primary flying had been in a fighter, reconnaissance, or military trainer), while the other eight were categorized as Heavy type pilots (tanker, bomber, cargo, or transport aircraft). None of the subjects participated in the Patterson (1994) study to preclude confounding this work.

4.3 Apparatus

The simulator used for the experiment was the Mission Simulator One (MS-1) located in Building 145 in Area B, Wright Patterson AFB, Ohio. The Control Integration and Assessment Branch of Wright Laboratory performs highly realistic simulations using the MS-1.

Physically the MS-1 consists of a 40-foot sphere with an interior projection surface and a stationary cockpit at its center. The simulator produces realistic aircraft sound and projects a 360 degree field-of-view. The subject sat in the generic fighter cockpit, based loosely on the F-15 cockpit design.

A Polhemus 3SPACE Tracker System was used to monitor pilot head movement. The head tracker sensor was attached to the pilot's helmet. The head tracking source in the simulator cockpit emits a low frequency magnetic field. By attaching the head tracker sensor to the helmet, the apparatus was able to detect movement in the magnetic field and record head pitch, roll, and yaw angles to a .001 degree level. The apparatus was calibrated two working days prior to the study and two working days after the completion of the study. The head tracking apparatus was dedicated to this experiment for the duration of the study. More specific information on the Polhemus 3SPACE Tracker System and calibration results can be found in Appendix A.

4.4 Tasks

Low level routes were flown at 400 knots indicated airspeed (KIAS) and at 500 feet above ground level (AGL). Verbal corrections were given at 300' AGL (to preclude

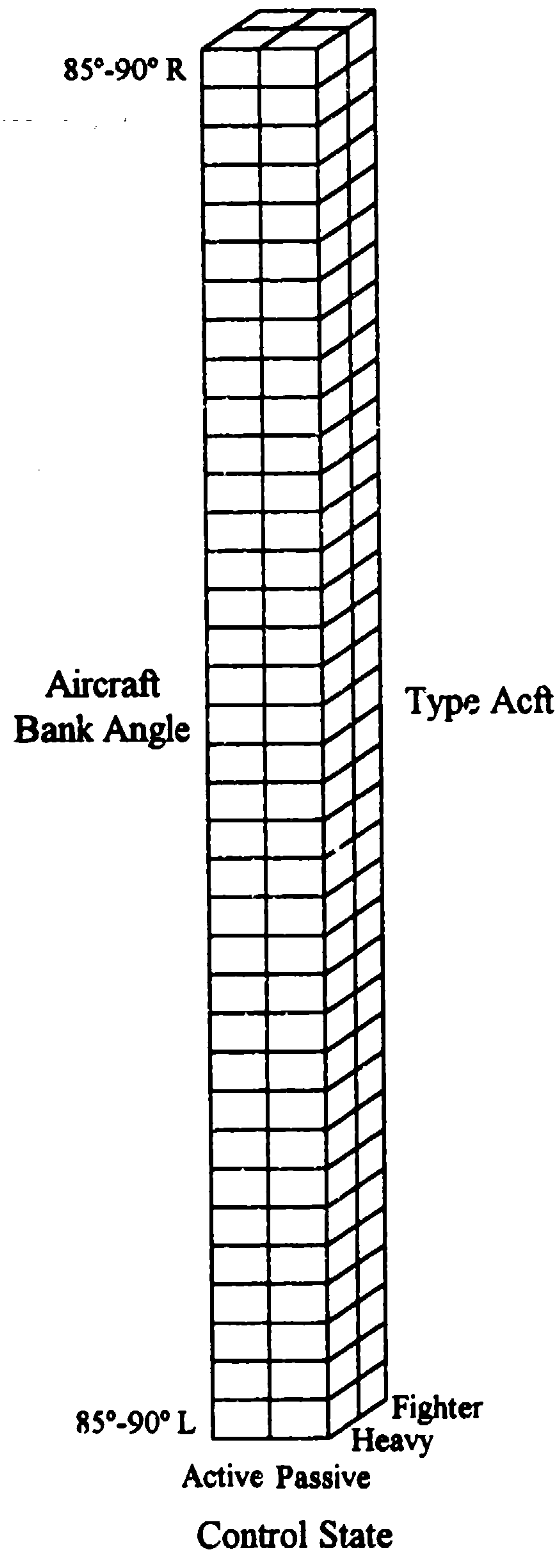


Figure 4.1: Experimental Design

ground impact) and 900' AGL (to preclude loss of terrain acuity) to the subjects. Altitude inside this range ensured proper simulation of actual low level routes. The experimenter acted as the navigator or "backseater" during the simulated flight.

The first task described will be the active control condition (ACTIVE). In this condition, the pilot flew the aircraft. Following the warm-up period, the subject was repositioned on the runway and accomplished a takeoff. Once the subject was flying straight and level toward Point 2, experimental data collection began. Subjects were told to fly to Point 2 shown on their navigational display. To ensure the pilot did not fixate on the navigational instruments, vector prompts and turn corrections were given over the headphone by the experimenter. As the flight continued, the subject was instructed to acquire landmarks such as bridges, houses, etc., and to clear for other aircraft and birds to again ensure the vision remained focused out of the cockpit. Subjects flew through a total of 6 points, with head tracker data and aircraft performance (pitch, roll , yaw, airspeed, altitude) data being collected every half second throughout the route. The route required approximately 13 minutes to fly. The simulated terrain was based on that of the area around Nellis AFB. Typical terrain consisted of desert, hills, ridges, canyons, and lakes.

The second task described is the passive control task (PASSIVE). In this condition the autopilot flew the simulator while the subject acted as navigator. The subject acquired and described landmarks, ensured the autopilot was navigating correctly to the next point, and cleared for other aircraft and birds. These tasks are analogous to those of a F-111 navigator, who is seated next to the pilot in the two-man cockpit.

In the passive control task, the simulator was frozen and the aircraft positioned on the runway. The subject was reminded of the tasks and then the autopilot performed the takeoff and flew a low level route similar to the one described above. Data collection began once the aircraft was level and heading for the first Point. Data on aircraft bank and pilot head roll position was again taken every half second for the route. This route also took approximately 13 minutes. Data collection was terminated as the autopilot crossed the final waypoint, Nellis AFB. Subjects always flew the same route for ACTIVE and a different route for PASSIVE. This could potentially be a small confound and is expounded upon in the Discussion Section.

4.5 Procedure

Subjects were asked to fill out a short, background questionnaire to record such data as total flight hours, aircraft flown and hours, low level time, and any instructor rating (Appendix B). The questionnaire also ensured the subject did not participate in Patterson's study (1994). Following the questionnaire, subjects were briefed on the upcoming simulator flight and any questions were answered. Cockpit instruments were reviewed and are shown in Figure 4.2. Instruments included an airspeed indicator in knots indicated airspeed (KIAS), a digital readout of KIAS, a Moving Horizon attitude indicator, a vertical velocity indicator (VVI), an altimeter in mean sea level (MSL), and a digital readout of altitude in feet above ground level (AGL). Below the attitude indicator was a navigation display with circled waypoints and two adjustable range circle markers. These instrument were presented on a cathode ray tube screen (CRT). Emphasis was made on the importance of flying the simulator visually (i.e. without constant referencing of aircraft instruments) as would be done on an actual low-level flight. Subjects were instructed to accomplish turns as if this was an actual fighter low level flight and no particular degree of bank was prescribed by the experimenter.

Subjects were then taken into the simulator and strapped into the seat. The experimenter assisted with the donning of the heimet and familiarized the subject with the cockpit. At this point, the experimenter returned to the control room where contact was established with the subject via headphones and through a video camera mounted behind the cockpit seat.

The subject was positioned onto the runway and instructed to perform a takeoff, the experimenter offered verbal assistance if needed as the takeoff was of no interest to the experiment. Once the subject was airborne, flight was accomplished over sample terrain to become accustomed to the aircraft controls and visual display of the dome simulator This warm-up period lasted from 10 to 15 minutes. It was imperative that the subject feel proficient in handling the simulator, as it was not possible for subjects to return for further trials. The warm-up period was not terminated until the subject declared they felt comfortable handling the simulator.

Once the warm-up period was complete, the simulator was put on freeze and the aircraft was repositioned on the runway for the first task. As stated previously, the experiment was counterbalanced so that half the subjects began with the ACTIVE portion followed by the PASSIVE condition.

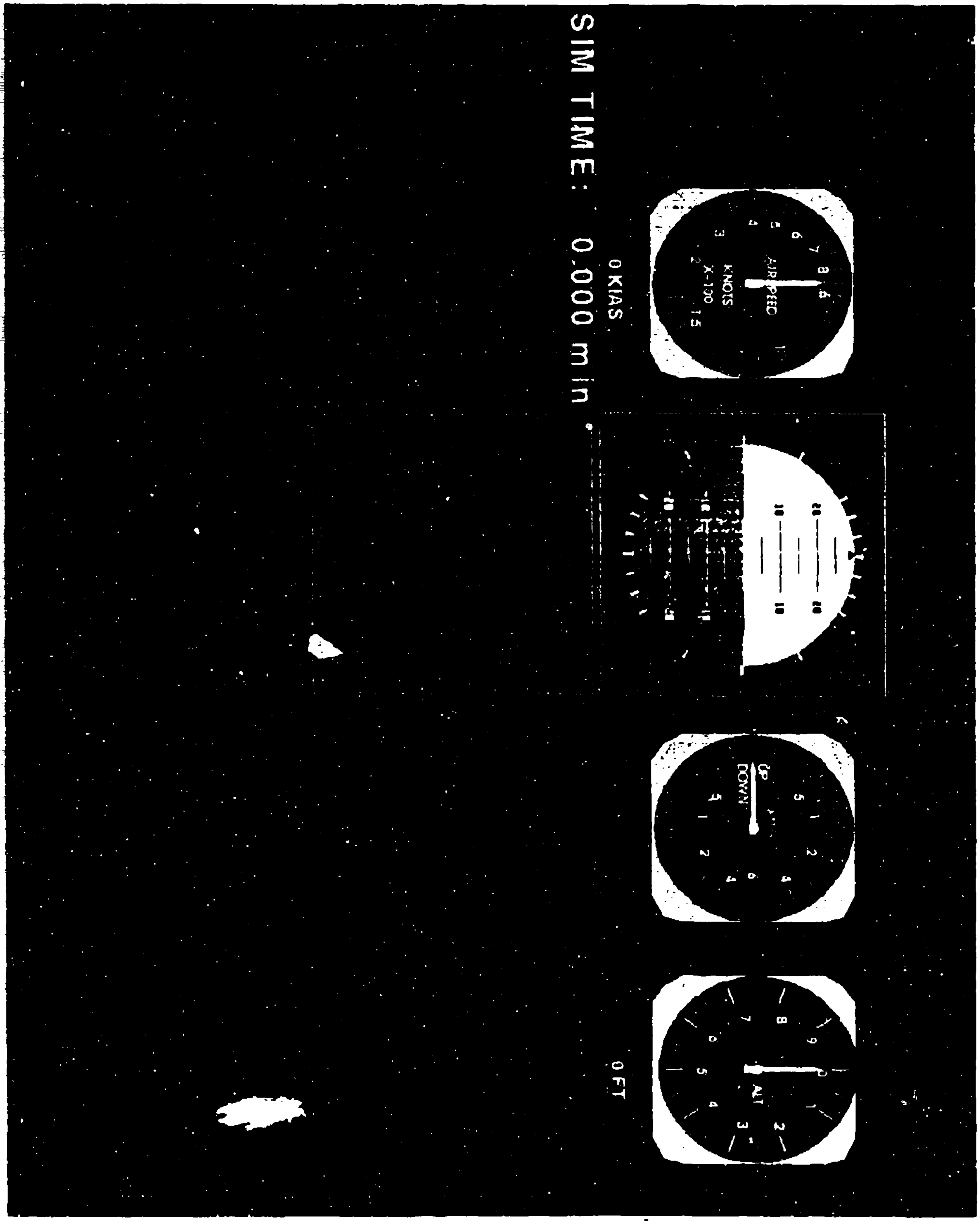


Figure 4.2: Cockpit Instruments

Following the termination of data collection, the autopilot maneuvered for and accomplished a visual landing. Data collected in this phase was not used as part of the experiment. Upon landing, the simulator phase of the experiment was over. Debriefing took place and any questions answered.

5.0 RESULTS

Experimental data was analyzed using the Statistical Analysis System (SAS) release 6.09 on a DEC Model 4000 MODEL 610 mainframe computer. An ANOVA was performed for the dependent variable, the head tilt of the subject (HRMEAN). While subjects flew the simulator, aircraft bank and subject's head tilt were sampled every 0.5 seconds. The subject's head tilt for a particular aircraft bank were all tallied and averaged to compute a Head Roll Mean (HRMEAN) score. For example, a subject during the active flying control state (ACTIVE) may have used 20-24.999 degrees of right aircraft bank a total of 50 times. The head tilts during these 50 times would be averaged to acquire the HRMEAN for 20-24.999 degrees of bank. The HRMEAN was then used in the ANOVA computations. The sixteen subject's HRMEAN scores were averaged for each cell (or BANK, 20-24.999 right would be one BANK) resulting in the CELLMEAN score for that particular BANK and CONTROL. Additionally, regression analysis was performed on the slope of the regression line of the head tilt of the subjects in the passive and active states. Main effects and interactions were evaluated using a significance criterion of 0.05.

5.1 Raw Data

A sample of the raw data is located in Appendix C. Furthermore, the raw data is graphically presented in the Appendix. It is emphasized that no statistical analyses for the purpose of drawing conclusions was performed on the data. The data is presented merely to give the reader and experimenter a starting point to begin actual statistical analysis.

5.2 Missing Values

Subjects used each of the levels of BANK a unique number of times. To compensate for the varying amount of data points at each BANK, HRMEAN was used as opposed to individual data entries at each BANK in order to achieve a balanced ANOVA. However, not all the subjects used all of the available BANK while in ACTIVE. Because no specific bank angles were dictated by the experimenter some subjects were more conservative and did not use the highest bank angles available for right turns. Three subjects did not use 75° to 80° right bank, five subjects did not use 80° to 85° right bank, and six subjects did not use 85° to 90° right bank. As a result, there are no HRMEAN values for those subjects at those BANKs. To compensate for three of the BANKs not having 16 HRMEANs, the Proc GLM feature of SAS was used. This procedure compensates for a small number of missing data points and allows the ANOVA to be run in a balanced manner.

5.3 Warm-up

Fourteen of the 16 subjects reported feeling comfortable in the simulator and ready to begin the actual runs in fifteen minutes or less. One subject took 18.7 minutes while the other took 19.8 minutes. Both of the subjects had not flown an Air Force aircraft in over one year. It was stressed to subjects in the pre-brief that the warm-up period was fifteen minutes, but not to proceed to the actual runs until they felt comfortable.

5.4 Type of Aircraft

The predominant type of aircraft the subject had flown, Fighter or Heavy, was found not to be statistically significant ($F(1,14) = .5609$, $p = .5609$). Additionally, there were no significant interactions between TYPEACFT and the other two independent variables. Therefore, the data were pooled, leaving a two factor, CONTROL and BANK, within-subjects factorial design. The ANOVA for the three factor design is shown in Table 5.1.

5.5 Effects on Head Tilt

The CELLMEANs are plotted in Figure 5.1. The figure indicates that PASSIVE CONTROL seems to yield greater head tilt angles for both left and right turns. ANOVA techniques were used to investigate if there were indeed statistical differences. For ease of calculation and explanation, left aircraft and right aircraft bank were analyzed separately. Additionally, more left turns were required for the low level route,

TABLE 5.1: ANOVA summary for three factor design.

Source	df	MS	F	*p*
Typeacft	1	115.8852	0.35	.5609
Subject(Typeacft)	14	326.5554		
Bank	35	4347.6887	124.72	.0001
Typeacft x Bank	35	6.8464	0.20	1.0000
Subject(Typeacft) x Bank	490	34.8583		
Control	1	0.4178	0.00	.9526
Typeacft x Control	1	76.8846	0.67	.4256
Subject(Typeacft) x Control	14	114.1528		
Bank x Control	35	51.8451	5.21	.0001
Typeacft x Bank x Control	35	8.7622	0.88	.6667
Subj(Typeacft) x Bank x Control	476	9.9485		

resulting in a greater sample pool. The results of the ANOVA for left aircraft bank are shown in Table 5.2, results of right aircraft bank are shown in Table 5.3.

5.6 Interaction of Bank Angle and Control State

Left aircraft banks showed a significant interaction between CONTROL and BANK (right turns were marginally significant) and significant main effects occured with both CONTROL and BANK. Figure 5.1 allows inspection of both right and left aircraft CELLMEANs. In both left and right banks, the interaction is an ordinal one, with the PASSIVE resulting in greater head tilt.

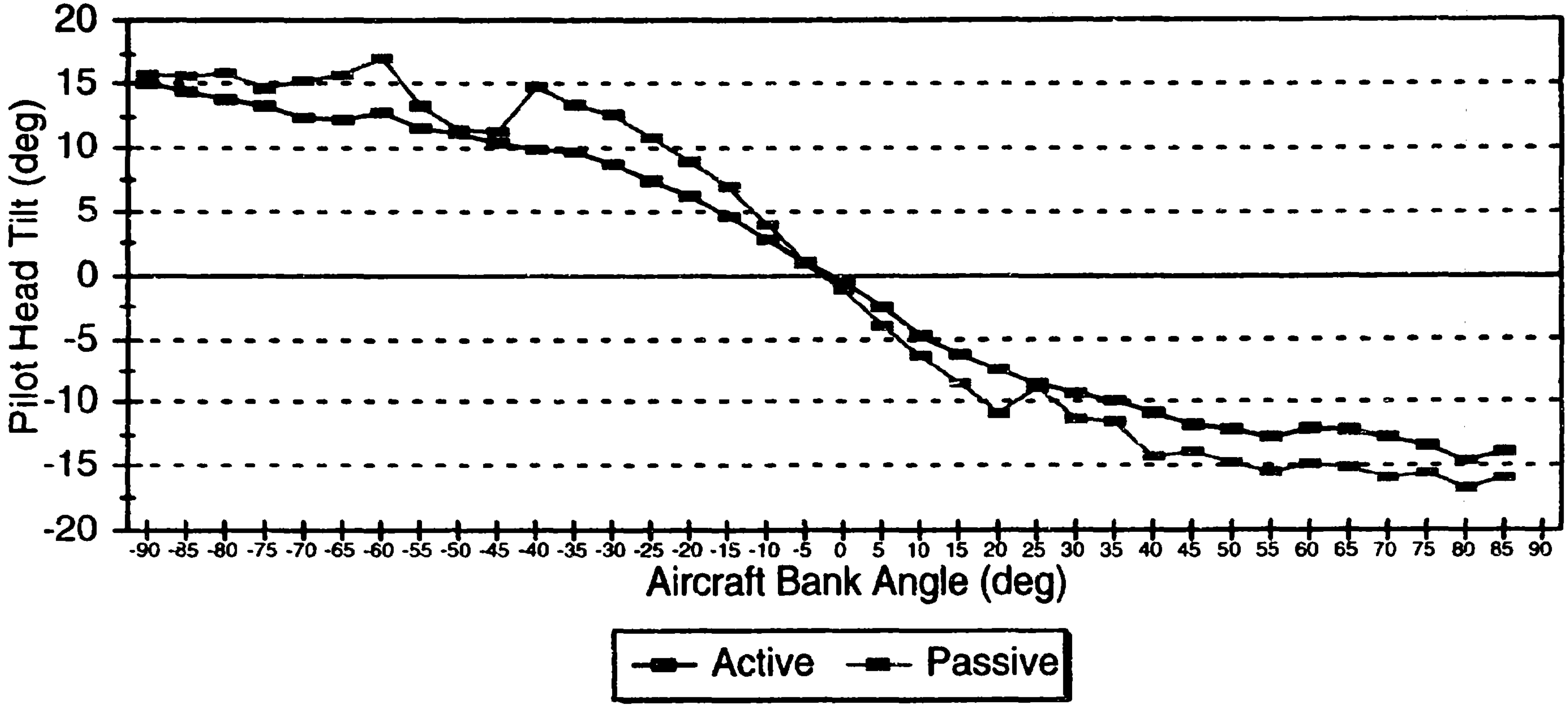


FIGURE 5.1: Plot of mean head tilt at each bank for active and passive control

TABLE 5.2: ANOVA summary for left aircraft bank.

Source	df	MS	F	*p*
Subject	15	691.5402		
Control	1	750.3738	4.80	.0446*
Subject x Control	15	156.2981		
Bank	17	562.4325	48.29	.0001*
Subject x Bank	255	11.6467		
Control x Bank	17	16.9679	1.92	.0167*
Subject x Control x Bank	255	8.8265		

* *Denotes significance at* $p < 0.05$

TABLE 5.3: ANOVA summary for right aircraft bank.

Source	df	MS	F	*p*
Subject	15	397.6506		
Control	1	703.9263	9.30	.0081*
Subject x Control	15	75.7145		
Bank	17	561.5801	48.99	.0001*
Subject x Bank	255	11.4629		
Control x Bank	17	6.6377	1.63	.0569**
Subject x Control x Bank	241***	4.0644		

* *Denotes significance at* $p < 0.05$ ** *Denotes marginal significance*

***Three cells from a total of 14 subjects were not used, as a result df does not total 255.

5.7 Main Effects of Bank and Control

To determine the locus of interaction and significant main effects, a series of t-tests was performed between ACTIVE and PASSIVE at each BANK. The results are shown in Tables 5.4 and 5.5 for left and right aircraft banks respectively. Due to the large number of t-tests run, 18, the results were not significant at a family wise alpha rate of .05. As shown in the tables, bank angles between 15 and 40 degrees indicate the greatest potential for there to be an actual difference between ACTIVE and PASSIVE for leftBANKs. While bank angles 15 to 25 degrees, hold the greatest potential for the right BANKs. As mentioned earlier, more left aircraft rolls where dictated by the low level route, resulting in a larger sample size and smaller variance in HRMEAN. This in turn results in a more reliable CELLMEAN estimate and a better ability to separate differences with confidence in left BANK. Additionally, more small aircraft bank angles were used by the pilots, resulting in a smaller sample size of steeper bank angles and therefore a less reliable estimate of the true cell mean and a decreased ability to separate differences.

5.8 Slope of the Regression Line

These results seem to indicate that with bank angles up to roughly 40 degrees that PASSIVE results in a greater head tilt. To specifically address this question, a regression analysis was accomplished on the slopes of the two lines in their nearly linear regions. This is the region from 30 degrees left aircraft bank to 30 degrees right aircraft bank (see Figure 5.1). The linear regression line was fit by the method of least squares. The correlation coefficient of the ACTIVE and PASSIVE lines was .9959 and .9785 respectively, indicating an excellent fit. The plotted regression lines are shown in Figure 5.2. The figure includes 35 degrees of bank simply to ease the plotting process. Results of the regression analysis are shown in Table 5.6. The slope of the PASSIVE line is greater than the slope of the ACTIVE line ($p \leq .0001$).

TABLE 5.4: T-tests between ACTIVE and PASSIVE, left BANK

Bank	T-test *p* value	Bank	T-test *p* value
0 - 5 (4.999)*	.9313	45 - 50	.8871
5 - 10 (9.999)*	.1175	50 - 55	.4015
10 -15	.0397	55 - 60	.0844
15 - 20	.0209	60 - 65	.1611
20 - 25	.0108	65 - 70	.2341
25 - 30	.0146	70 - 75	.6001
30 - 35	.0140	75 - 80	.4717
35 - 40	.0126	80 - 85	.6788
40 - 45	.6460	85 - 90	.8063

* As denoted in the first two cells, the right hand value is actually: value - .001. Data is presented in the above manner for ease of understanding.

TABLE 5.5: T-tests between ACTIVE and PASSIVE, right BANK

Bank	T-test *p* value	Bank	T-test *p* value
0 - 5 (4.999)*	.2704	45 - 50	.2251
5 - 10 (9.999)*	.0612	50 - 55	.1183
10 -15	.0728	55 - 60	.1485
15 - 20	.0271	60 - 65	.1762
20 - 25	.0075	65 - 70	.1627
25 - 30	.7974	70 - 75	.1211
30 - 35	.1024	75 - 80	.2958
35 - 40	.2769	80 - 85	.3560
40 - 45	.0648	85 - 90	.3137

* As denoted in the first two cells, the right hand value is actually: value - .001. Data is presented in the above manner for ease of understanding.

TABLE 5.6: Regression analysis of slopes

Slope of ACTIVE = -1.6542 Slope of PASSIVE = -2.2619
t (20) = 5.461, $p \leq .0001$

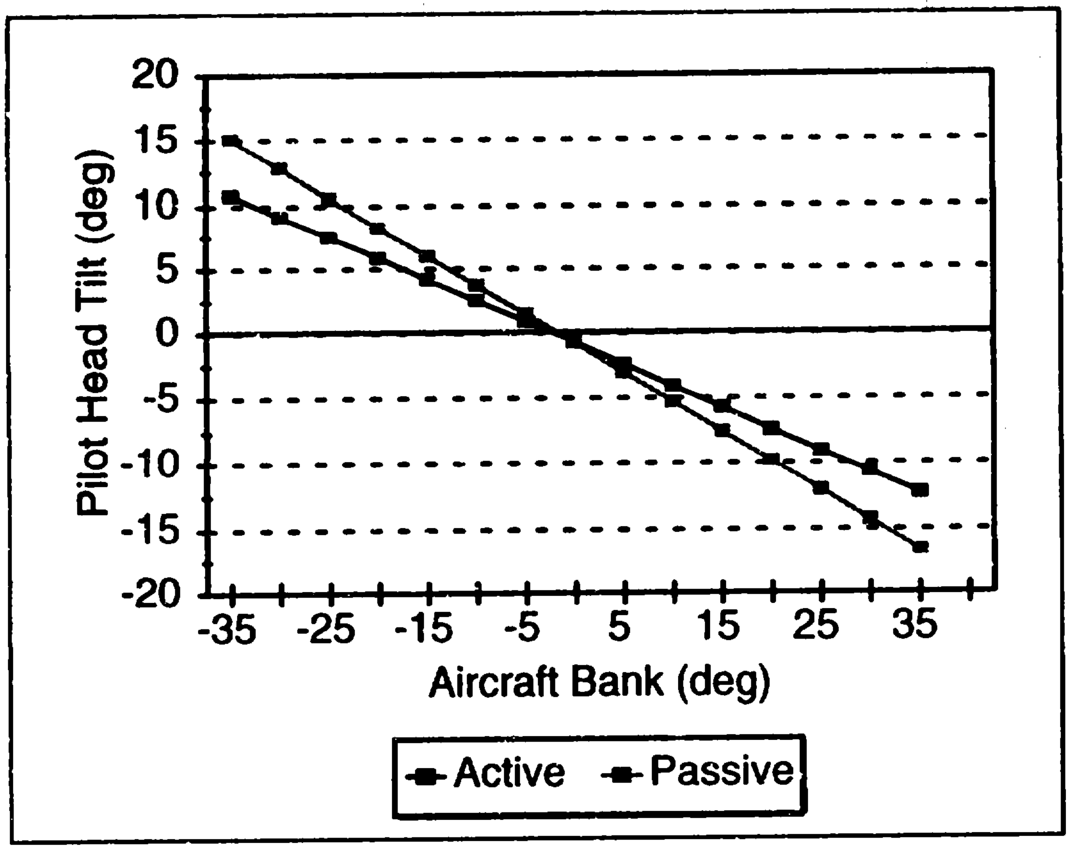


FIGURE 5.2: Plot of active and passive linear regression lines.

6.0 DISCUSSION

The results of this experiment indicate that the degree of pilot head tilt may be affected by the control state of the pilot. Though a difference in the two states was predicted, the degree and direction of difference was surprising. This section will discuss the significant effects and their relationship to the experimental hypothesis.

6.1 The Optokinetic Collic Reflex

As found by Patterson (1994), the optokinetic collic reflex was again elicited by rotation of the horizon (caused by aircraft bank) when pilots actively fly. This is not surprising, but does help validate Patterson's work.

Furthermore, the optokinetic collic reflex was also elicited in pilots not actively flying the simulator. This scenario was intended to simulate the supervisory role of the pilot as the autopilot carries out the actual control functions. In addition, the pilot performed duties commonly assigned to a navigator to test for the transfer of the reflex to other crew positions. The presence of the response in the PASSIVE state indicates that the response is transferable to other crewmembers and the pilot continues to exhibit this reflex while in a supervisory role.

The fact that all subjects were pilots could be seen as a possible confound in establishing transfer to other crew positions. However, several non-pilots were tested in a pilot study and all strongly exhibited the optokinetic collic reflex. It is safe to assume that the reflex is not unique to pilots.

6.2 Interaction of Control State and Bank

The interaction of CONTROL and BANK is an ordinal one as seen in the Results section. PASSIVE CELLMEAN consistently and without exception resulted in greater head tilt than ACTIVE CELLMEAN at greater than 5 degrees of bank, though not at a statistically significant level at each bank. To clarify, individual t-tests at left aircraft roll showed significant differences between 10 and 40 degrees, while right banks showed differences between 15 and 25 degrees of bank. However, due to the large number of t-tests run, 18, the results were not significant at a family wise alpha rate of .05. Perhaps with a larger sample size, specifically more turns accomplished, these differences would become significant using a family wise rate. Furthermore, if an equal number of left and right turns were accomplished, the right BANK may well have showed significance at the same bank angles as left BANK.

The second procedure used to analyze the data, regression, did show a clearly significant statistically difference between ACTIVE and PASSIVE from 30 degrees left bank to 30 degrees right bank, in the region where head tilt increases almost linearly from zero. It can be said with confidence that PASSIVE results in greater head tilt in this region. This was surprising. The hypothesis had been that the task of actively flying would require greater head tilt to track and preview effectively. This does not seem to be the case. Rather, it seems that either passive control accentuates head tilt, or active control attenuates head tilt, or both.

There could be two explanations for this difference. The most obvious is that these head tilt angles are well under the maximum capable tilt of the subject. Therefore, there is a range of tilt available where ACTIVE attenuation or PASSIVE accentuation can take place. While at higher angles of aircraft bank, the head tilt is closer to the maximum possible tilt. So under active and passive conditions, pilot's head tilts reach maximum at higher angles of aircraft bank and no difference between the conditions is found.

The second explanation is that the onset rates of the two conditions differ. It is possible that a substantial number of head tilts recorded in this region of difference were made as the pilot transitioned to a larger aircraft bank angle. If the rate of change of PASSIVE is greater than ACTIVE, then larger angles of head tilt would be recorded for PASSIVE. For example, during a turn of the aircraft from 0 to 90 degrees left, with a sampling rate every 0.5 seconds, the pilot's head position may be measured 3 to 4 times. An example scenario using actual data is given in Table 6.1.

It is obvious from the actual CELLMEAN values listed in Table 6.1, that as the aircraft bank continues to increase, the difference between ACTIVE and PASSIVE decreases. The transition between banks occurred often and could explain the difference in the slopes of the two lines.

TABLE 6.1: Example scenario of left aircraft roll and sample rates

TIME (ELAPSED)	AIRCRAFT ROLL	PASSIVE	ACTIVE	STATE OF AIRCRAFT
0 sec	0°	.2°R	.1°R	Turn to begin
.5 sec	25°L	12.6°R	8.6°R	Turn in progress
1.0 sec	50°L	13.3°R	11.6°R	Turn in progress
1.5 sec	75°L	14.6°R	13.3°R	Turn in progress
2.0 sec	90°L	15.7°R	15°R	Turn completed

L = Left R = Right

It is likely that both explanations contribute to the differences noted between the two control states. It is not possible to make a definitive judgment. It would be possible to conduct an experiment to study this question in detail. Specifically, an apparatus would be required to measure the rate of change of head tilt for both ACTIVE and PASSIVE. Though the head tilts do differ significantly, the difference between head tilt angles is not great in absolute value, therefore the time and expense of such a project may not be warranted.

It could be possible that there is also a statistically significant difference between ACTIVE and PASSIVE at higher angles of aircraft bank, but these differences were not discovered due to the smaller sample sizes in the higher bank angle regions. If these differences do exist, it would lend credence to the idea that attenuation of accentuation is occurring. This topic is discussed further under the Higher Aircraft Bank Angles section.

6.3 Accentuate or Attenuate

Regardless of whether the difference is due to differing onset rates of head tilt or simply to attenuation or accentuation at bank angles less than forty degrees, or both, the underlying cause of either explanation should be addressed. There could be several possible causes. The underlying cause may be the fact that a reflex does not require cognitive activity. For example, if one touches a hot stove, the hand is pulled away before the mind can compute that the stove is hot. In the experimental condition, the task of manually flying an aircraft requires a higher degree of cognitive activity than passively observing while accomplishing clearing and navigational tasks. Perhaps it is this greater cognitive activity which causes or influences an attenuation of the optokinetic collic reflex. Wickens Resource Model (1992) provides a model for this explanation. ACTIVE requires central processing on the part of the subject. Whereas, a pure reflex uses only sensory resources which is the case with passive control. Therefore, ACTIVE requires more resources of the human operator, and therefore an attenuation of the optokinetic collic reflex. This would explain the steeper slope of the PASSIVE.

If this is the case, under actual flight conditions the navigator, or pilot not flying, may have a higher cognitive load than was simulated by this experiment which in turn may bring the actual PASSIVE slope closer to the ACTIVE. However, the additional cognitive load of flying under actual conditions may also be greater than that simulated in the study, with the end result being a difference in the two slopes due to differences in cognitive loading.

The subject did not know how much bank angle the autopilot would use, but only when the autopilot would begin the turn. As a result, the subject may have over anticipated the degree of bank angle to be used, which resulted in the steeper slope of the PASSIVE line. The optokinetic reflex seems to be induced by the rotation of the horizon in the peripheral vision which would indicate strictly a response reflex, therefore it is unlikely that this anticipation could be the cause. However, this explanation cannot be ruled out.

Another potential cause could be the motor output required by the ACTIVE state in controlling the aircraft stick. The PASSIVE state of course, required no motor output. This motor output could attenuate the ACTIVE response for similar reasons as discussed under cognitive loading. There is a greater "drain" on available resources resulting in attenuation. At a physiological level, the upper motor neural traffic (caused by perception, cognition, and motor output), could have an influence on the response reflex arc.

It is likely that there are a combination of causes for the difference between the slopes of ACTIVE and PASSIVE. It is not possible from this research to point to a conclusive answer to this question. However, it provides opportunity for further research.

6.4 Higher Aircraft Bank Angles

No significant differences in head tilt could be found with aircraft bank angles above forty degrees. There could be several reason for this. First of all, as mentioned above, as head tilt approaches 15 degrees it begins to taper off. This corresponds to the region near forty degrees of aircraft bank. The head is capable of tilting roughly 30 degrees, depending on the subject. Most subjects recorded sample head rolls above 20 degrees, while a few recorded tilts of over 30 degrees. However, head tilts above 15 degrees begin to be uncomfortable and as a result we see mean head tilts around 15 degrees at the higher aircraft bank angles (above 60 degrees). This level of comfort may correspond to the near equality of head tilt between ACTIVE and PASSIVE at higher aircraft banks.

The second explanation is a statistical one. As higher aircraft banks were approached, the HRMEAN's of subjects had a smaller sample size and larger variance. Simply put, subjects did not use higher bank angles as often as lower bank angles, therefore the number of observations in these regions was lower. With a decrease in sample size and increase in variance, the result is a less reliable estimate of HRMEAN. In turn, the sixteen HRMEAN's used to compute CELLMEAN for each bank also had a higher variance. So at these higher banks we cannot separate ACTIVE and PASSIVE with as much confidence. For example at 10 - 15 degrees left bank, the CELLMEAN standard deviation was 2.8, while at 80 - 85 degrees the CELLMEAN standard deviation was 6.7. It should be noted that some subjects had HRMEAN scores of over 20 degrees at higher aircraft banks (above 75 degrees), but the sample size was small.

6.5 Exhibiting the Expected Behavior

All subjects exhibited the optokinetic collic reflex in the correct direction. However, four of the subjects did not exhibit the degree of head tilt of the other twelve subjects. Before explaining the Dependent Variable during debrief, subjects were questioned in general about their philosophy of VFR flight and their dependence on the attitude indicator. From Patterson's (1994) study, it is clear that close reliance on the attitude indicator will diminish the optokinetic collic reflex. The first subject relayed that since it had been nearly two years since an actual flight, the top of the glare shield was used as a large attitude indicator to "drag across the horizon" to ensure turns were kept level. The subject in question had completed one year of flight training before entering a non-flying job. This subject's experience level was the lowest of any subject used in the study.

The second subject reported feeling queasy during the warm-up period. Remembering that a similar experience was once brought on by excessive head movement in a simulator, the subject decided to limit head movement as much as possible during the rest of the simulator period.

The third subject reported being told during pilot training never to move the head. This principle was strongly reinforced by several instructors. The subject reported consciously remembering this instruction during the flight in the simulator. This is an example of instruction that is inappropriate in light of the optokinetic collic reflex.

The final subject is a bit of a mystery. No explanation could be found for the decreased level of head tilt versus the other subjects. It should be emphasized that the subject did systematically tilt the head in the correct direction, but not to the degree of the majority of the subjects.

6.6 Implications of Research

It is clear that optokinetic collic reflex was again a shown to be an important and constant factor in simulator flight. Patterson's (1994) work had been successfully replicated in part.

It also seems clear that the optokinetic collic reflex is a phenomenon which may be experienced by all flight crewmembers and also by the pilot while not actually flying. This is a positive finding and greatly simplifies the process of designing instruments for flight crews and understanding the means by which crewmembers remain spatially oriented. It should be emphasized that the implications to non-pilot crewmembers include only those with a similar field of view to that of the pilot, in other words, in a cockpit with side by side seating. If the navigator were seated behind the pilot, as in a tandem cockpit, the affect of the optokinetic reflex may be different. In the tandem configuration, the crewmember in the rear would have the central vision blocked by the front crewmember's helmet and ejection seat while looking straight ahead. However, since the optokinetic reflex is driven by the peripheral vision, it is likely that the optokinetic reflex would still be strong as the peripheral vision is not obstructed in a tandem cockpit arrangement.

The fact that the optokinetic collic reflex appears transferable to other crewmembers seems to minimize its possibility as a factor in the larger incidence of air sickness in non-pilot aircrew members. Had there been a large difference between ACTIVE and PASSIVE the possible association with motion sickness would be clear as each crewmember would have a different head position. This study indicates similar head position between crewmembers. However, the optokinetic reflex may be relate in some not yet understood way to motion sickness in non-pilot crewmembers and therefore cannot be dismissed as a possible factor.

During this experiment in the PASSIVE condition, the subject spent the majority of time looking at the visual representation. In an actual flight conditions on a low level mission, the navigator would spend a great deal of time acquiring landmarks and clearing for aircraft, both requiring a scan of the visual filed. However, the navigator would have other tasks requiring the vision to be inside the cockpit such as cross-checking charts and instruments. The percentage of time the eyes were in or out of the cockpit, would depend on the particular mission and navigator. However, this study indicates that when the navigator's eyes are outside the cockpit, the optokinetic reflex will result in a head tilt. When the eyes are inside the cockpit and the horizon is not visible, the head tilt will probably disappear or be minimized depending on the time inside the cockpit. This movement of the eyes from inside to outside the cockpit could be a factor in the airsickness question.

The most immediate implication of this research is to make aircrew members aware of the optokinetic collic reflex so they can correctly assess their ability to remain spatially oriented. If crewmembers understand their frame of reference and what is going on in their orientation process they will perhaps be better able to remain oriented. This understanding will also help crewmembers appreciate why the attitude indicator is difficult to interpret at times, as it does not always reliably replicate their view of the world.

Another ramification of increased understanding is to change poor instructional techniques. As stated earlier, one subject reported being told not to move his head in flight during Air Force pilot training. Student pilots should not be told to keep their head aligned with the body during VFR flight. The tilt is caused by the optokinetic collic reflex and is a natural movement. Attempting to "short circuit" this reflex will not aid in spatial orientation. Under instrument conditions, the optokinetic collic reflex is not induced and therefore it is helpful and proper to instruct a student not to turn the head. There is not a natural desire to do so and tilting the head can be disorienting under these IFR conditions.

The optokinetic reflex may explain the mixed experimental results of attitude indicator studies. Many of these tests were conducted with no visual references, while some included the visual picture. The study of the most effective indicator would definitely be influenced by the use of either IFR or VFR conditions, since Patterson's results (1994) showed the optokinetic reflex to be absent during IFR conditions. It also seems clear that if the optokinetic reflex is considered, that neither the Moving Horizon or the Moving Aircraft display enjoy the advantage of pictorial realism.

A long term implication is the re-design of the attitude indicator. The re-design should take into account the optokinetic collic reflex and its affect on what the pilot actually sees in flight. The optokinetic nystagmus eye rotation must also be considered, and is discussed in a following section. The frequency separated display tested by Roscoe and Williges (1975) holds promise for the new design. As a recommendation, the horizon line on the indicator should remain horizontal, until approximately 30 degrees of bank when it should begin to move as the pilot actually sees the world. At this 30 degree point, the head tilt and eye rotation is assumed to be unable to compensate for aircraft bank and the pilot would actually begin to see the horizon moving. This design should produce an indicator which possesses pictorial realism in addition to compatibility of motion.

The degree of difference in the head tilt between ACTIVE and PASSIVE, while definitely significant at angles less than thirty degrees of aircraft bank, does not seem to be of the magnitude to cause design problems. For example, design of HMD's for aircrew members could likely compensate easily for the difference in the two control states. Of course the degree of optokinetic nystagmus during active and passive conditions is not known and would need to be considered in HMD design. It is important, however to design HMD's with the optokinetic collic reflex in the equation. To design such helmets assuming a head remaining aligned with the body axis could be disorienting.

Finally, there is a potential safety problem with the current HUD system used in military fighter aircraft (Patterson, personal communication). These HUD's are designed with an approximately 4 to 5 inch "viewing box" where the pilot can read the display. If the optokinetic collic reflex causes head tilts in flight similar to those found in this study, it is likely the pilot will be out of this viewing box in steep bank turns. This would remove vital, and perhaps life-saving information, from the pilot. One example is the "pull-up" indicator which alerts the pilot of imminent ground collision and the need to raise the nose. To regain the information the pilot must tilt the head back into the box, or reference the head's down display. Some information is relayed audibly, but auditory information is often lost under stress. Re-design of the HUD viewing angle deserves strong consideration in light of this research.

6.7 Future Research

Does the optokinetic collic reflex occur in actual flight conditions? This is the next research question which needs to be addressed. The answer is almost assuredly, yes. Two pieces of evidence point to this conclusion. First, the otoliths are the primary influence on most pilot reflexes. Otoliths are affected in flight very similar to the way they are on earth. They are influenced primarily by the direction of gravity. On the earth that is obviously in the vertical direction which is in line with the body axis while standing or sitting erect. In a coordinated turn in flight, 1-g also acts in line with the body axis. Semi-circular canals affects on the reflexes is not as great, though they do have an influence. The semi-circular canals are affected much differently in flight than on earth and could theoretically influence the head tilt.

The second strands of evidence are actual observations. Video recordings of inflight head movements of the Blue Angels Aerobatics Team, clearly show the optokinetic collic reflex at work. Patterson's (personal communication) personal observations in Naval aircraft led to his study. In addition, personal observations were relayed to the experimenter during the debrief sessions of this study. An F-16 pilot reported being in the back seat of an F-16 the month prior to the experiment and noticing the pilot in the front seat consistently tilting the head in each turn. The pilot made the following statement, "I thought wow, I wonder if I do that, and then I forgot about it, I guess I do." The quote also shows the subconscious character of the reflex.

The second area of research needs to occur in the area of eye measurement of the optokinetic nystagmus. It is theorized that optokinetic nystagmus works in conjunction with the optokinetic collic reflex to stabilize the retinal image of the horizon. It must be determined conclusively to what degree the eye does rotate to aid in this stabilization. From there it can be determined at what point the horizon begins to tilt on the pilots retinal image. This can in turn be used in the design of an attitude indicator which will present a more realistic picture of what the pilot actually sees in flight.

6.8 Limitations of Research

The following recommendations would prove helpful in the replication of this experiment. The low level routes used in this study proved very successful in eliciting the optokinetic collic reflex. Due to time and cost constraints, low levels were limited to two thirteen minute sessions. This limited the number of turns available to establish a realistic route. With increased time, more turns could be added, increasing sample size in the higher bank turns. This would provide a better ability to distinguish actual differences between ACTIVE and PASSIVE at higher BANK. This experiment suggests there may be differences in this region. If possible, the same number of left and right turns should be accomplished so that meaningful comparisons can be made between the two. The active route of this study required approximately 9 left turns and 6 right turns. While the passive route required approximately seven for both right and left.

As mentioned in the Method section, each pilot flew the same route for the ACTIVE and PASSIVE conditions. Ideally, the routes should have been counterbalanced with eight pilots flying one route actively while the others flew the alternate route. This is possibly a small confound. Time and cost dictated the use of only one ACTIVE and one PASSIVE route. Any confound should be minimal as the routes were flown over similar terrain, based on the Nellis AFB region in Nevada. The terrain was rocky desert with small bluffs and hills which rose and fell gradually. The PASSIVE route did contain a lake region, but the majority of time was spent over the desert terrain. To eliminate any possible confound, replication of the study should counterbalance the two routes.

Another area of improvement would be in the use of the autopilot. The autopilot had a tendency to use either 40 degrees or less of aircraft bank or greater than 75 degrees bank. This left a small sample size for the area from 40 to 75 degrees and is evident in Figure 5.1 where CELLMEAN values are not consistent.

7.0 CONCLUSIONS

The results of this study indicate that the optokinetic collic reflex, and resulting head tilt, is affected by the control state of the pilot. When the pilot is not actively flying the aircraft, a greater head tilt occurs. This finding is seems to be limited to aircraft bank angles from roughly 10 to 40 degrees both left and right. Whether this difference is due to accentuation of the passive state or attenuation of the active state is not clear. It is theorized that it is the latter.

No statistically significant differences could be found between the control states at aircraft bank angles above 40 degrees, though the pilot's sample head tilt means were higher for the passive than the active control state. Perhaps if the sample size in this region were increased, statistically significant differences would be found.

Besides the obvious fact that the optokinetic collic reflex remains strong while the pilot is in a supervisory role, it also seems clear that the head tilt is transferable to other non-pilot crewmembers. This is welcomed information and greatly simplifies the understanding of aircrew spatial orientation, by providing a consistent frame of reference between crewmembers.

The most immediate need for further research is actual flight test of the optokinetic collic reflex. It is strongly suspected that the optokinetic collic reflex will also be found to be strong during actual flight conditions, due to its dependence on the otoliths which function very similarly on the ground and in coordinated flight.

Another important area of research to be pursued is reliable measurement of the optokinetic nystagmus eye torsion which is thought to aid, along with the optokinetic collic reflex, in stabilization of the horizon on the retinal image. This will require sophisticated and precision eye measuring equipment.

Armed with information on the optokinetic collic reflex and the torsion parameters of optokinetic nystagmus, a better design of the attitude indicator is within reach. The traditional attitude indicator can be improved and the frequency separated display will make an excellent starting point. Determination must be made as to the proper angle at which the horizon should begin to move, following the immediate movement of the aircraft symbol. Complicated phase angle relationships will probably be involved.

The effects of optokinetic collic reflex on the design of HMDs demands careful attention, as this new area of technology does not suffer from years of tradition and should be designed properly from the beginning.

Operational implications include education of the pilot and flying world on the existence of the optokinetic collic reflex and its affect on spatial orientation. In particular, poor instructional techniques concerning VFR flying and head movement should be corrected, especially at the initial training level and through periodic flying refresher courses.

The issue of the HUD and it's viewing box is potentially the most pressing safety implication and should be acted upon immediately after successful flight experimentation on the optokinetic collic reflex. Short-term steps should include precautionary messages distributed to flight crew on the potential for loss of the HUD and the resulting loss of the life saving warning message, "Pull Up". Monthly Squadron Safety Meetings would also be an excellent arena in which to provide this advisory. The long term solution is better design of the HUD, to allow for an expanded viewing box to take into account pilot head tilt. This will not be an easy task, but a critical improvement to make.

APPENDICES

APPENDIX

A. Head Tracker System

The head tracker system used for this experiment was the Polhemus 3SPACE system. A short synopsis is provided below for the benefit of the reader. Some of the details of the Air Force configuration of the system are proprietary. More complete detail of the system can be obtained by contacting the manufacturer Kaiser Aerospace & Electronics Company headquartered in Colchester, VT. The contents of this appendix were condensed from the 3SPACE User's Manual.

The 3SPACE system utilizes low-frequency, magnetic field technology to determine the position and orientation of a sensor in relation to a source or other specified reference frame. This provides a full six-degree-of-freedom measurement device. The information can be transmitted to a host in ASCII or BINARY format. The ASCII format was used for this experiment.

The tracker has a variety of possible applications. For this study the tracker was configured with a system electronics unit (SEU), one source, and one sensor. A system electronics unit contains all the hardware and software necessary for the 3SPACE system to compute the position and orientation of the sensors. The SEU contains analog circuitry to generate and sense the electromagnetic fields, and digitize the sensed analog signal. It also contains a central processor to control the analog circuitry and perform all necessary computations.

The source generates the low-frequency magnetic field measured by the sensor. There may be on or two sources, identified as SOURCE 1 and SOURCE 2, each connected to the SEU by a cable. For this study only SOURCE 1 was used. It was mounted above the pilot's helmet on a calibrated source mount. The mount in turn was attached to a support structure. The mounting system is depicted in Figure A1.

The sensor senses the low-frequency magnetic field generated by the source. There may be one to four sensors each connected to the SEU by a cable. This study used only one sensor. The sensors are pictured in Figure A2.

The post-experiment calibration charts are included as Figures A3 to A5. Complete calibration readings are extensive and not feasible to include in the appendix. They may be obtained by contacting the author.

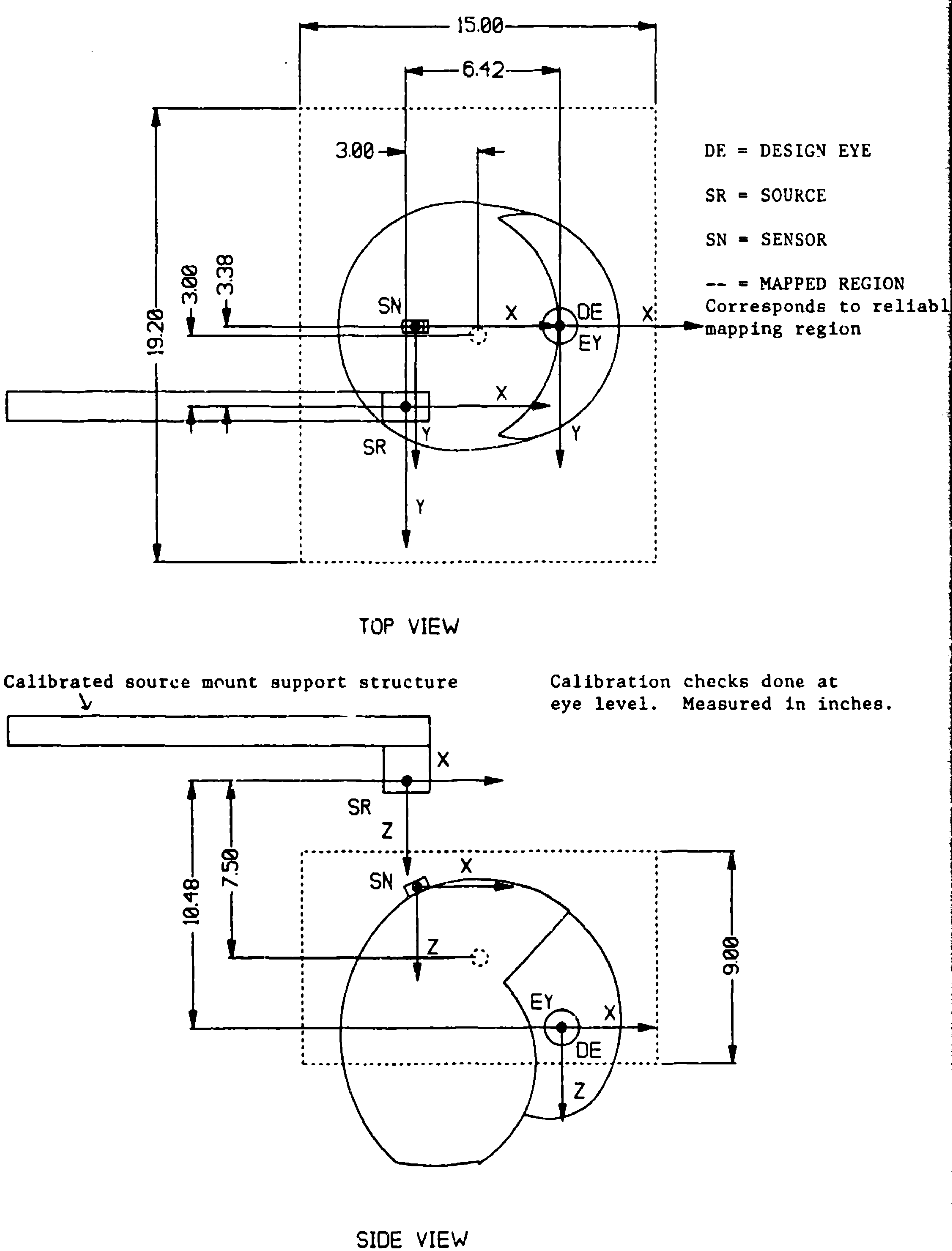


FIGURE A1: MS-1 head tracker mapping volume.

SYSTEM ELECTRONICS UNIT (SEU)

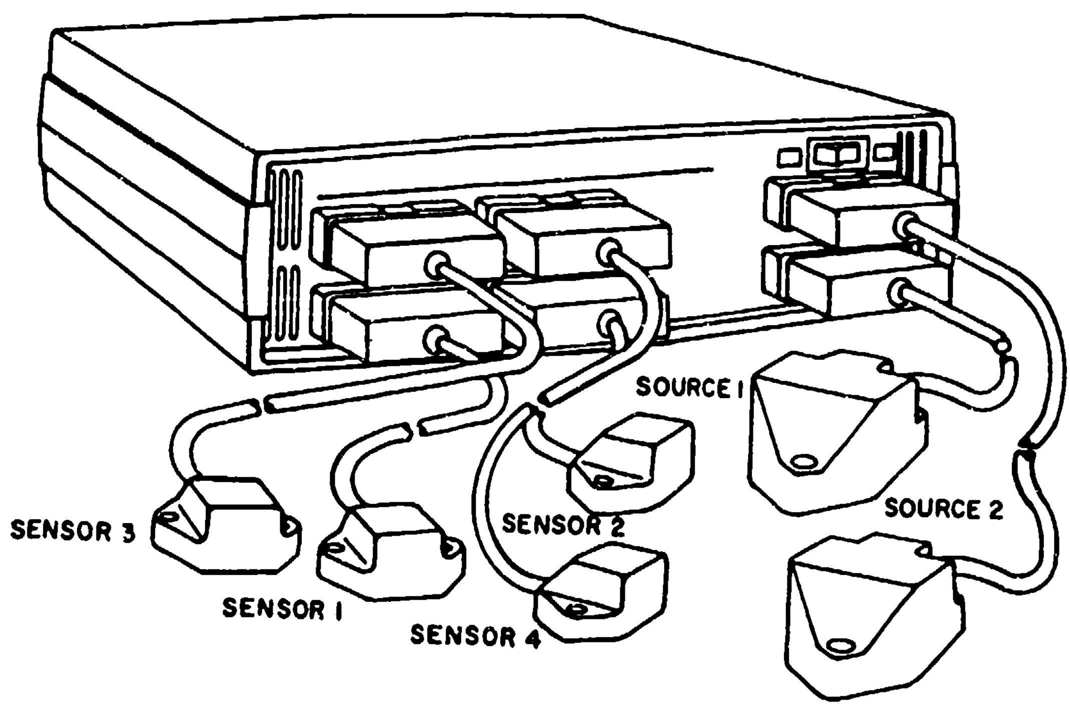


FIGURE A2: 3SPACE tracker system.

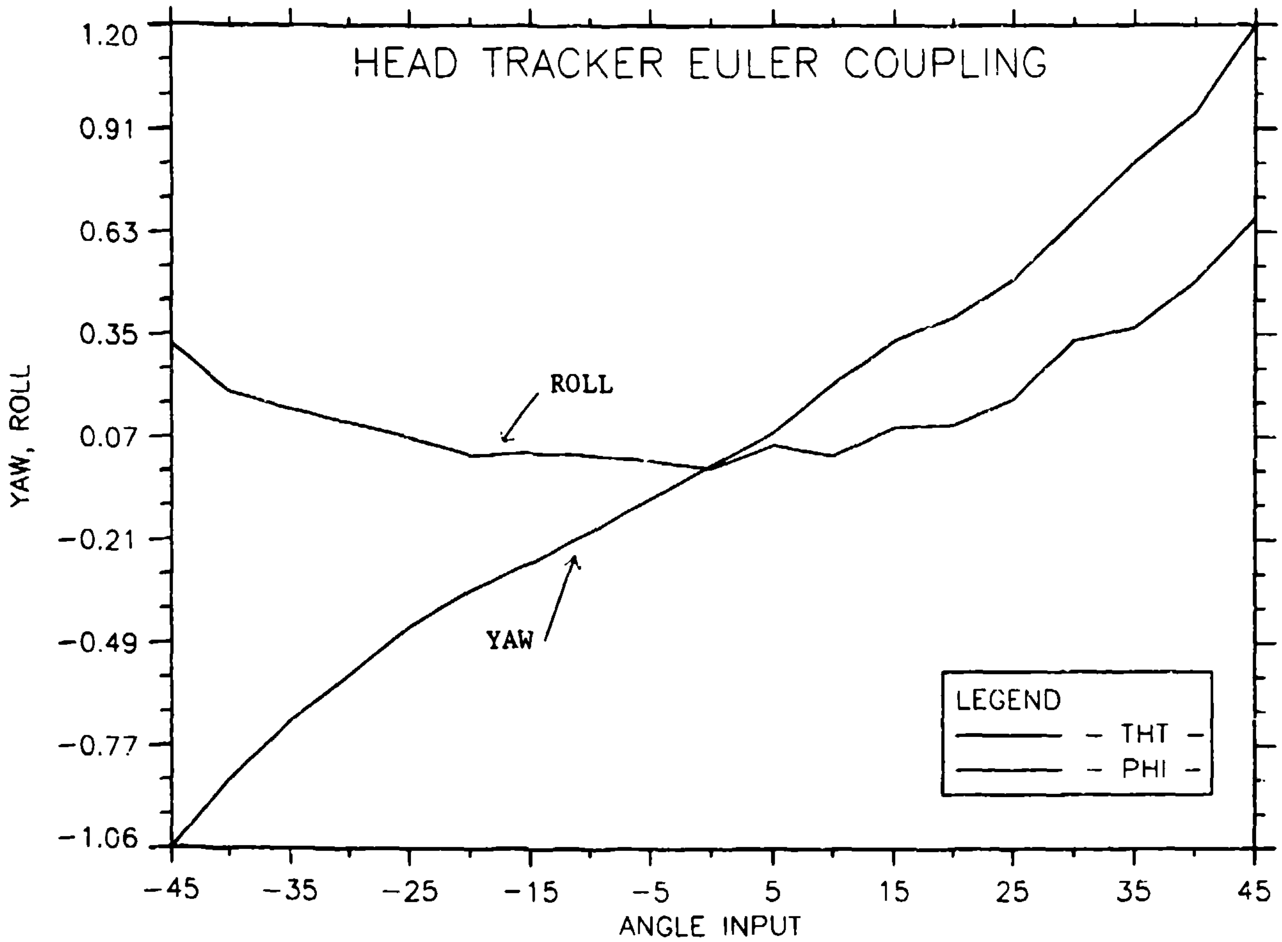


FIGURE A3: Pitch calibration chart

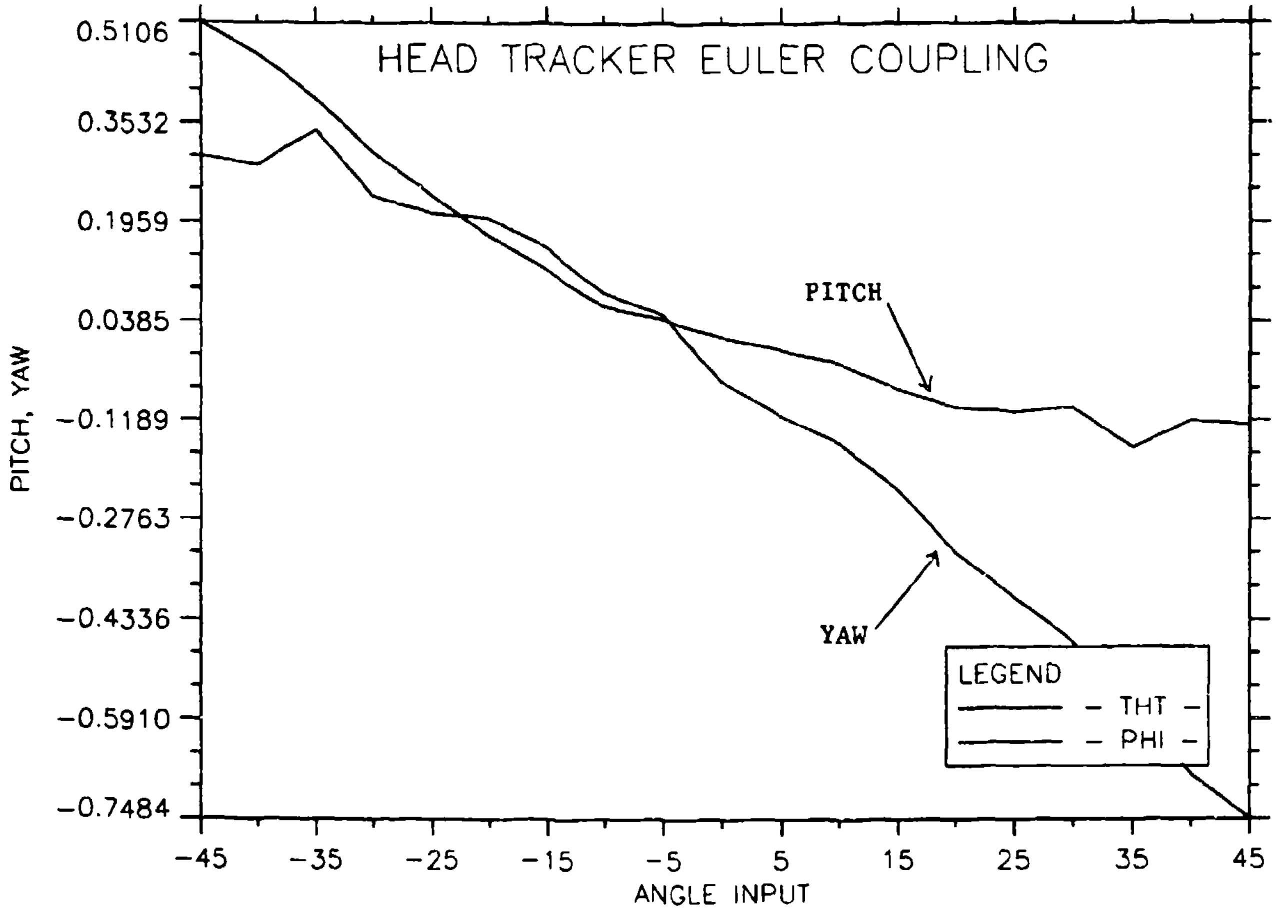


FIGURE A4: Roll calibration chart.

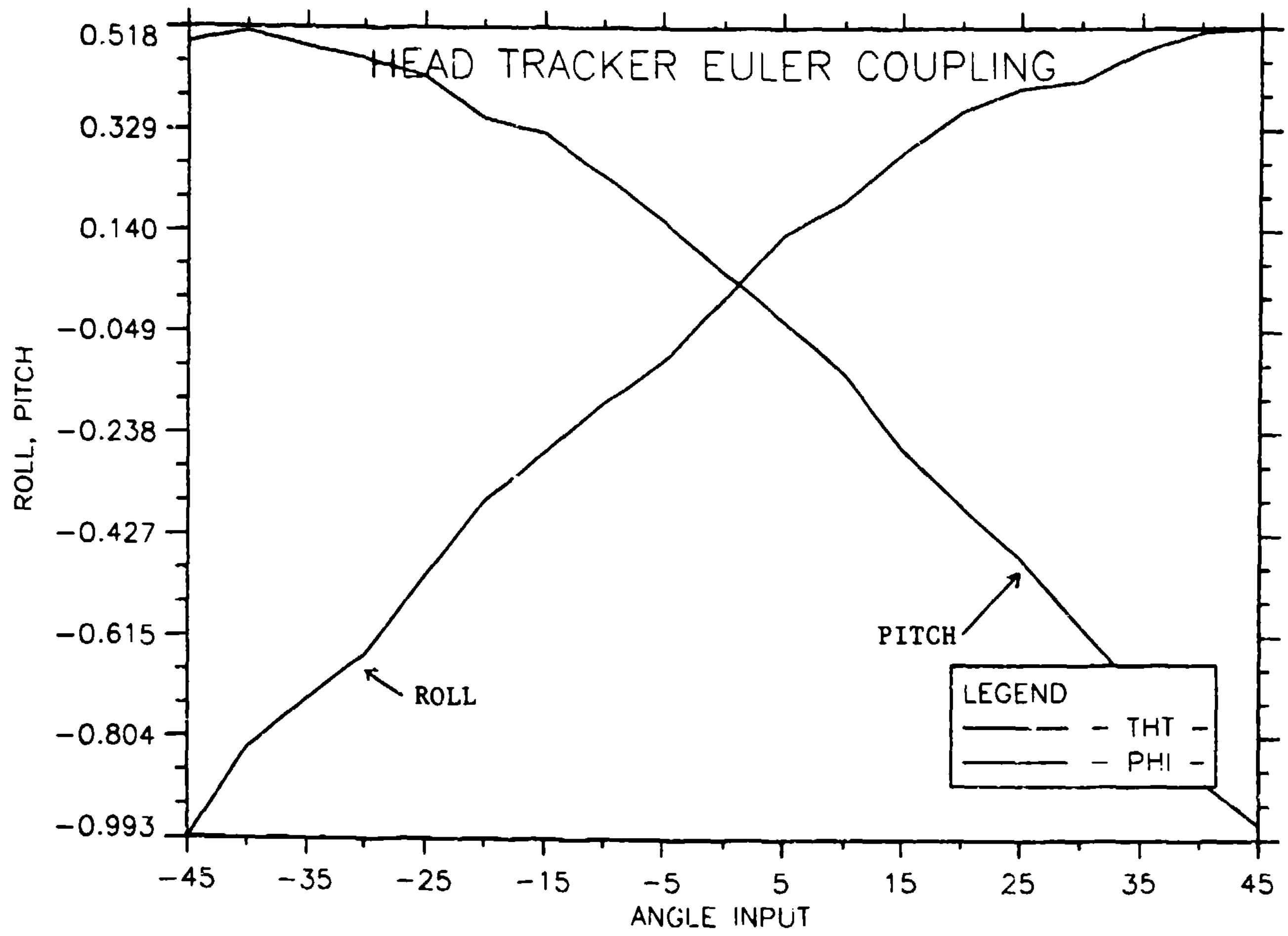


FIGURE A5: Yaw calibration chart.

THIS

PAGE

IS

MISSING

IN

ORIGINAL

DOCUMENT

APPENDIX

C. Raw Data

The raw data is presented below simply to give the reader a "feel" for the results of the experiment. It is emphasized that statistics were not run on the raw data for the purpose of drawing conclusions on the hypothesis or results of the experiment.

The raw data are plotted using the PV-WAVE P&C version 2.0 program. This program is produced by Visual Numerics Precision Visuals Wave (PV-WAVE). The three figures depicted below are plots of the raw data or are derived from those plots. Figure C.1 depicts the raw data of all sixteen subjects flying the ACTIVE. Each black cross represents one sample of one head tilt of a particular subject. All sixteen subjects are then combined into the same graph.

The gray line running through the data was fit using the POLY_FIT function. This function uses the least squares method to minimize error at each point of the curve. This function is useful for showing the relationship between two variables, in this case, pilot head tilt and aircraft roll. Figure C.2 depicts the raw data of the sixteen subjects in the PASSIVE condition. Figure C.3 is simply an overlay of the two fitted lines.

Each of the fitted lines is a 4th order polynomial. The lines can be described mathematically by the equations below.

ACTIVE $f(X) = 4.756 * 10^{-8}X^4 + 1.483 * 10^{-5}X^3 - 3.718 * 10^{-4}X^2 - .277X + .3943$

PASSIVE $f(X) = -8.192 * 10^{-8}X^4 + 3.822 * 10^{-5}X^3 + 4.682 * 10^{-4}X^2 - .4271X - .1039$

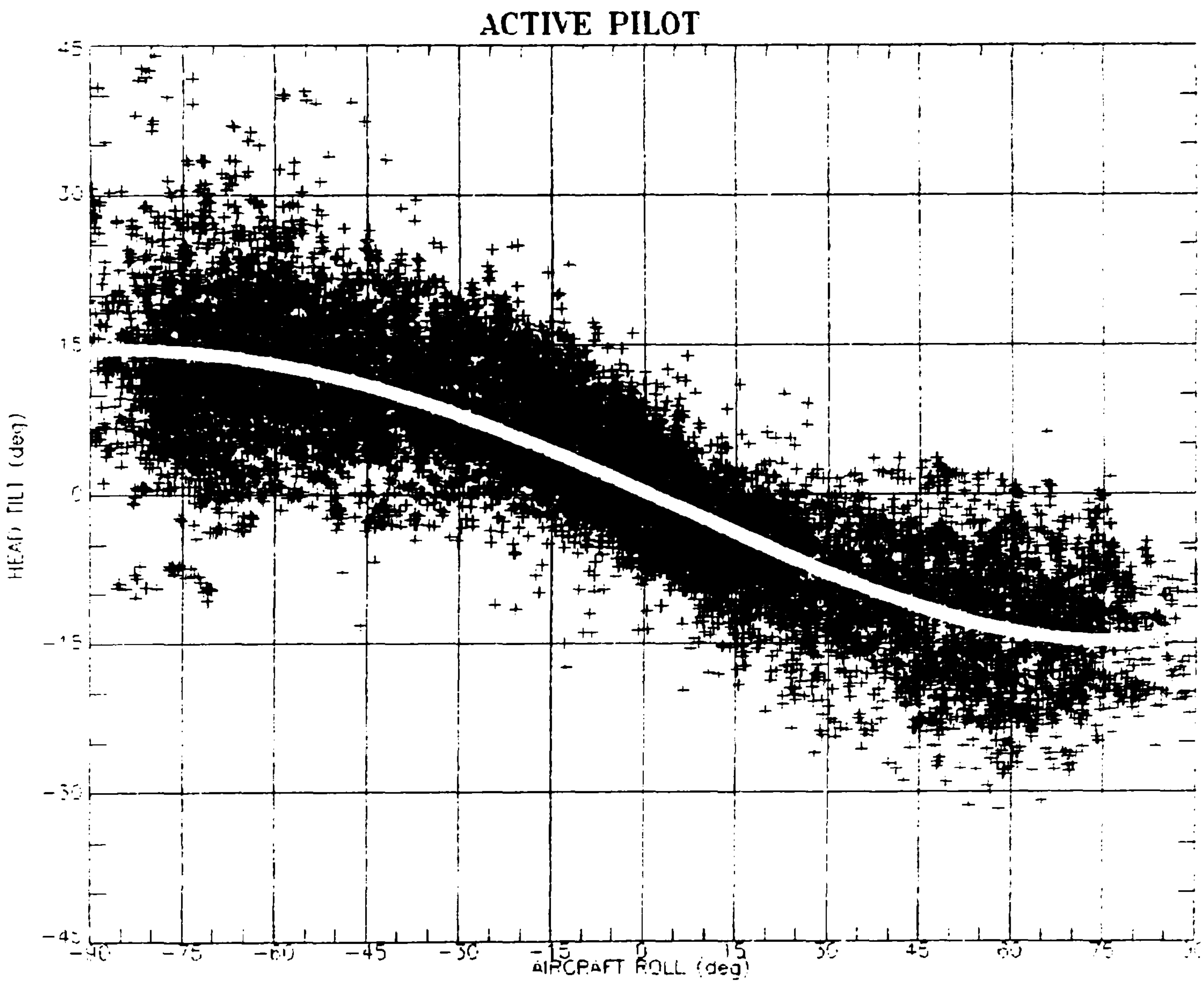


FIGURE C1: Raw data in active condition.

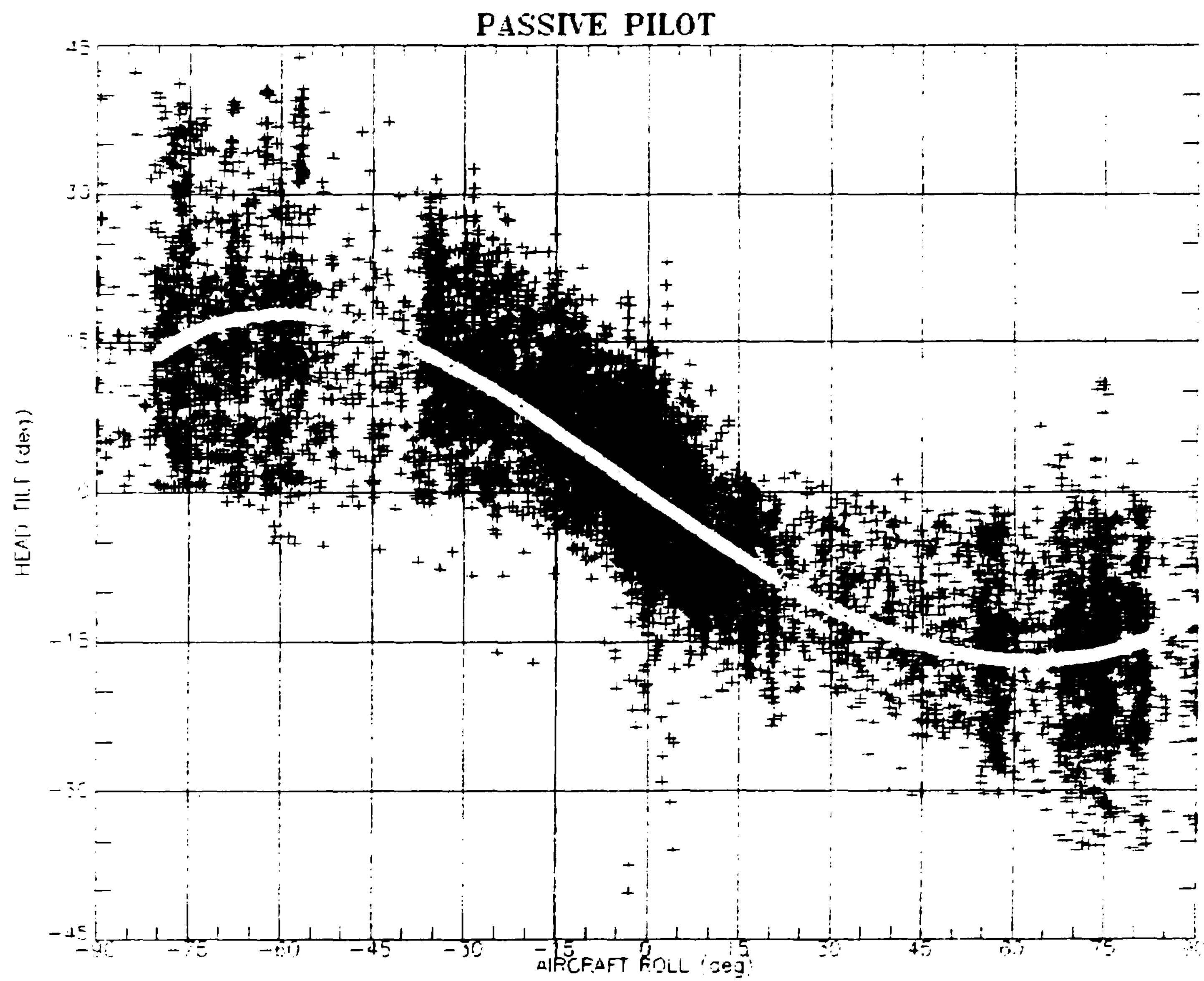


FIGURE C2: Raw data in passive condition.

OVERLAY OF ACTIVE AND PASSIVE FITTED LINES

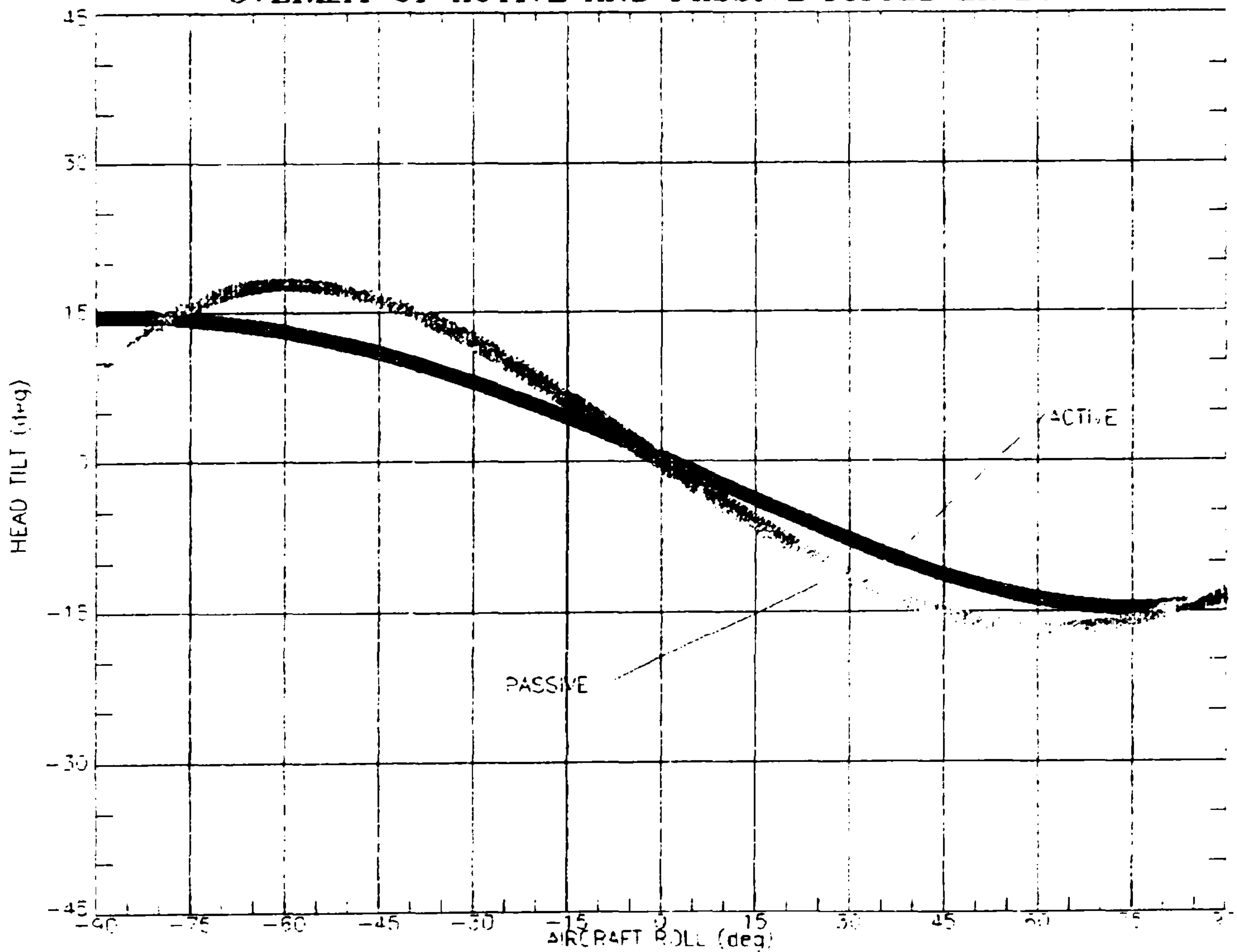


FIGURE C2: Overlay of two fitted lines of raw data

REFERENCES

Adams, J.A. (1989). *Human Factors Engineering.* New York NY: Macmillan Publishing.

Air Force Manual 51-37 (1984) p. 8.

Air Service Medical book (1918)

Barnum, F. and Bonner, R.H. (1971). Epidemiology of USAF spatial disorientation aircraft accidents, 1 Jan 1958-31 Dec 1968. *Aviation, Space, and Environmental Medicine,* 42(8), 896-898.

Beringer, D.B., Williges, R.C. and Roscoe, S.N. (1975). The transition of experienced pilots to a frequency-separated aircraft attitude display. *Human Factors,* 17(4), 401-414.

Brandt, T., Dichgans, J. and Koenig E. (1972). Differential effects of central versus peripheral vision on egocentric and exocentric motion perception. *Experimental Brain Research,* 16, 476-491.

Browne, R.C. (1945). Trial of two attitude indicators. In Johnson, S.L. and Roscoe, S.N. (1972). What moves, the airplane or the world? *Human Factors,* 14(2), 107-129.

Dichgans, J. (1974). Spinal afferents to the oculomotor system. In Howard, I.P. (1982). *Human Visual Orientation.* New York, NY: John Wiley & Sons.

Dorland (1988). *Dorland's Medical Dictionary* (27th ed.). Philadelphia, PA: W.B. Saunders.

Dunlap and Associates, Inc. (1955). Pilot performance with two different attitude displays. In Johnson, S.L. and Roscoe, S.N. (1972). What moves, the airplane or the world? *Human Factors,* 14(2), 107-129.

Fitts, P.M. and Jones R.E. (1947). Psychological aspects of instrument display. I: Analysis of 270 "Pilot-Error" experiences in reading and interpreting aircraft instruments (*Mem. Rep. TSEAA-694-12A*). Wright-Patterson Air Force Base, Ohio: Air Materiel Command, Aero Medical Laboratory.

Fogel, L.J. (1959). A new concept: The kinalog display system. *Human Factors,* 1(2), 30-37.

Friederici, A.D. and Levelt, W.J.M. (1987). Resolving perceptual conflicts: The cognitive mechanism of spatial orientation. *Aviation, Space, and Environmental Medicine,* 58(9, Suppl.), A164-9.

Gardner, J.F. (1954). Speed and accuracy of response to five dive different attitude indicators. In Johnson, S.L. and Roscoe, S.N. (1972). What moves, the airplane or the world? *Human Factors*, 14(2), 107-129.

Gardner, J.F. and Lacey, R.J. (1954). An experimental comparison of five different attitude indicators (*WADC Technical Report 54-32*). Wright-Patterson Air Force Base, Ohio: Wright Air Development Center.

Gillingham, K.K. (1992). The spatial disorientation problem in the United States Air Force. *Journal of Vestibular Research*, 2, 297-306.

Gillingham, K.K. and Wolfe, J.W. (1986). Spatial orientation in flight (*USAFSAM-TR-85-31*). USAF School of Aerospace Medicine, Aerospace Medical Division (AFSC), Brooks Air Force Base, TX.

Gilson, R.D., Guedry, F.E., Hixson, W. and Niven, J.I. (1973). Observation on perceived changes in aircraft attitude attending head movements made in a 2-g bank and turn. *Aerospace Medicine*, 44(1), 90-92.

Graybiel, A. (1974). Measurement of otolith function. In Young, L.R., Shelhammer, M. and Modestino, S. (1986). M.I.T./Canadian vestibular experiments on the Spacelab-1 mission: 2. Visual vestibular tilt interaction in weightlessness. *Experimental Brain Research*, 64, 300.

Howard, I.P. (1982). *Human Visual Orientation*. New York, NY: John Wiley & Sons.

Ince, F., Williges, R.C. and Roscoe, S.N. (1975). Aircraft simulator motion and the order of merit of flight attitude and steering guidance displays. *Human Factors*, 17, 388-400.

Johnson, S.L. and Roscoe, S.N. (1972). What moves, the airplane or the world? *Human Factors*, 14(2), 107-129.

Jones, G.M. (1965). Disturbance of oculomotor control in flight. *Aerospace Medicine*, 36(5), 461-465.

Kirkham, W.R., Collins, W.E., Grape P.M., Simpson, J.M. and Wallace, T.F. (1978). Spatial disorientation in general aviation accidents. *Aviation, Space, and Environmental Medicine*, 49(9), 1080-1086.

Knight, J.L. (1987). Manual control and tracking. In G.I. Salvendy (Ed.), *Handbook of Human Factors*, 184. New York NY: John Wiley & Sons.

Kuipers, A., Kappers, A., van Holten, C.R., van Bergen, J.H.W. and Oosterveld, W.J. (1990). Spatial disorientation incidents in the R.N.L.A.F. F16 and F5 aircraft and suggestions for prevention. *AGARD Conference Proceedings No.478*, OV-E-1-OV-E-16.

Loucks, R.B. (1947). An experimental evaluation of the interpretability of various types of aircraft attitude indicators. In Johnson, S.L. and Roscoe, S.N. (1972). What moves, the airplane or the world? *Human Factors,* 14(2), 107-129.

Lyons, T.J., Ercoline, W.R., Freeman, J.E. and Gillingham, K.K. (1994). Classification problems of U.S. Air Force spatial disorientation accidents, 1989-91. *Aviation, Space, and Environmental Medicine,* 65, 147-152.

Matheny, W.G., Dougherty, D.J. and Willis, J.M. (1963). Relative motion of elements in instrument displays. In Johnson, S.L. and Roscoe, S.N. (1972). What moves, the airplane or the world? *Human Factors,* 14(2), 107-129.

North, D.M. (1990). Aviation Week editor flies Soviet-based Mig-29 fighter. *Aviation Week & Space Technology,* Feb. 26, 36-48.

Nygaard, J.E. and Roscoe, S.N. (1953). Manual steering display studies: 1. Display-control relationships and the configuration of the steering symbol. In Johnson, S.L. and Roscoe, S.N. (1972). What moves, the airplane or the world? *Human Factors,* 14(2), 107-129.

Outerbridge, J.S. and Jones, G.M. (1971). Reflex vestibular control of head movement in man. In Howard, I.P. (1982). *Human Visual Orientation.* New York, NY: John Wiley & Sons.

Patterson, F.R. (1994). *Aviation Spatial Orientation in Relationship to Head Position and Attitude Interpretation.* Unpublished Dissertation, Dayton, OH: Wright State University.

Patterson, F.R. (1994). Personal interview, March 1994.

Pew, R.W. (1974). Human perceptual-motor performance. In B. Kantowitz (Ed), *Human information processing.* Hillsdale, NJ: Erlbaum.

Poppen, J.R. (1936). Equilibratory functions in instrument flying. *The Journal of Aviation Medicine,* 7(4), 148-160.

Poulton, E. (1974). Tracking skill and manual control. In Sanders M.S. and McCormick, E.J. (1993). *Human Factors in Engineering and Design* (7th ed.). New York NY: McGraw-Hill.

Roscoe, S.N. (1989). The eyes prefer real images. In R.S. Jensen (Ed), *Aviation Psychology,* 232. Triptree, Great Britain: Anchor Press Ltd.

Roscoe, S.N., Corl, L. and Jensen, R.S. (1981). Flight display dynamics revisited. *Human Factors*, 23(3), 341-353.

Roscoe, S.N., Johnson, S.L. and Williges, R.C. (1980). Display motion relationships. In S.N. Roscoe (Ed), *Aviation Psychology*. Ames IA: Iowa State University Press.

Roscoe, S.N. and Williges, R.C. (1975). Motion relationships in aircraft attitude and guidance displays: A flight experiment. *Human Factors*, 17(4), 374-387.

Roscoe, S.N., Hopkins, C.O. and McCurley, E.A. (1955). Manual steering display studies: III. The transition of interceptor pilots to the moving-airplane display in the F-86D aircraft. In Johnson, S.L. and Roscoe, S.N. (1972). What moves, the airplane or the world? *Human Factors*, 14(2), 107-129.

Roscoe, S.N., Wilson, K.V. and Deming, H.D. (1954). Manual steering display studies: II. The transition of skilled interceptor pilots from the E-series display to the moving airplane display. In Johnson, S.L. and Roscoe, S.N. (1972). What moves, the airplane or the world? *Human Factors*, 14(2), 107-129.

Sanders M.S. and McCormick, E.J. (1993). *Human Factors in Engineering and Design* (7th ed.). New York NY: McGraw-Hill.

Weisz, A.Z., Elkind, J.I., Pierstorff, B.C. and Sprague, L.T. (1960). Evaluation of aircraft steering displays. In Johnson, S.L. and Roscoe, S.N. (1972). What moves, the airplane or the world? *Human Factors*, 14(2), 107-129.

Wickens, C.D. (1992). *Engineering Psychology and Human Performance* (2nd ed.). New York NY: HarperCollins Publishers.

Young, L.R., Shelhammer, M. and Modestino, S. (1986). M.I.T./Canadian vestibular experiments on the Spacelab-1 mission: 2. Visual vestibular tilt interaction in weightlessness. *Experimental Brain Research*, 64, 299-307.

Young, L.R. and Oman, C.M. (1984). Spatial Orientation in weightlessness and readaptation to earth's gravity. *Life Sciences*, 225, 205-208.

Young, L.R., Oman, C.M. and Dichgans, J.M. (1975). Influence of head orientation on visually induced pitch and roll sensation. *Aviation, Space, and Environmental Medicine*, 46(3), 264-268.