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The Effects of Angle-of-Attack Indication on Aircraft Control in the Event of an Airspeed Indicator Malfunction

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M.S., Embry-Riddle Aeronautical University Worldwide, 2011

A Thesis Submitted to the College of Arts and Sciences
in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Human Factors and Systems

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ABSTRACT

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Analysis of accident data by the Federal Aviation Administration, the National Transportation Safety Board, and other sources show that loss of control is the leading cause of aircraft accidents. Further evaluation of the data indicates that the majority of loss of control accidents are caused by the aircraft stalling. In response to these data, the Federal Aviation Administration and the General Aviation Joint Steering Committee emphasize the importance of stall and angle-of-attack awareness during flight. The high-profile crash of Air France Flight 447, in which pilots failed to recover from a self-induced stall, reinforced concerns over the need for improved stall and angle-of-attack awareness and reinvigorated interest in the debate over the effectiveness of angle-of-attack information displays. Further support for aerodynamic information in the form of an angle-of-attack indicator comes from core cognitive engineering principles. These principles argue for the provision of information about system functioning and dynamics as a means to ensure a human is always in position to recover a system when technology is unable. The purpose of this research was to empirically evaluate the importance of providing pilots with feedback about fundamental aircraft aerodynamics, especially during non-standard situations and unexpected disturbances. An experiment was conducted using a flight simulator to test the effects of in-cockpit angle-of-attack indication on aircraft control following an airspeed indicator malfunction on final approach. Participants flew a final approach with a target airspeed range of 60 to 65 knots. Once participants slowed the aircraft for final approach, the airspeed indicator needle would be stuck at an indication of 70 knots. One group of participants flew the final approach with an angle-of-attack indicator while the other group lacked such an instrument. Examination of aircraft performance data along the final approach showed that, when confronted with a frozen airspeed indicator, pilots flying with an angle-of-attack indicator were producing less airspeed and glideslope deviation than pilots who were flying without an angle-of-attack indicator. Furthermore, in the absence of airspeed information, pilots with an angle-of-attack indicator were less prone to slow the aircraft to an airspeed at which the aural stall-warning activated. Overall, the results of this experiment provide support for making aerodynamic information available to the pilot, thus contributing empirical results to the aviation-safety debate over the effectiveness of angle-of-attack information displays.

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CHAPTER I

INTRODUCTION

Human Error and Loss of Control Accidents

With an increase in mechanical reliability of modern aircraft, human error is progressively more often at the center of attention in both the prevention and analysis stages of aviation accidents (Wiegmann & Shappell, 2003). Thus, in an effort to better support human operators performing their tasks, a considerable amount of research has been conducted addressing areas such as display design, pilot information requirements, pilot situation awareness (SA) requirements, and pilot-aircraft interaction (e.g., Endsley, 1993, 2001; Flach et al., 2003; Hameed & Sarter, 2009; Williams, 2002). Despite these continuous efforts, some of the worst accidents in aviation history involve perfectly flyable airplanes (with minor, recoverable mechanical problems; or no mechanical problems at all) crashing due to loss of control in flight, often caused by human error, or more specifically, improper flight control inputs by the pilot (e.g., Bureau de l'Enquêtes et d'Analyses pour la sécurité de l'aviation civile [BEA], 2012; National Transportation Safety Board [NTSB], 2010; NTSB, 1975).

In fact, loss of control in flight, either in the presence or the absence of a system/component failure or malfunction, is identified as the number one cause of fatal commercial jet fleet accidents from 2002 through 2011 (Boeing, 2012), as can be seen in Figure 1. This trend is also evident in general aviation (GA). When the Federal Aviation Administration (FAA) conducted a review of fatal general aviation accidents from 2001 to 2010, the majority of these were identified as loss of control accidents (GAJSC, 2012).

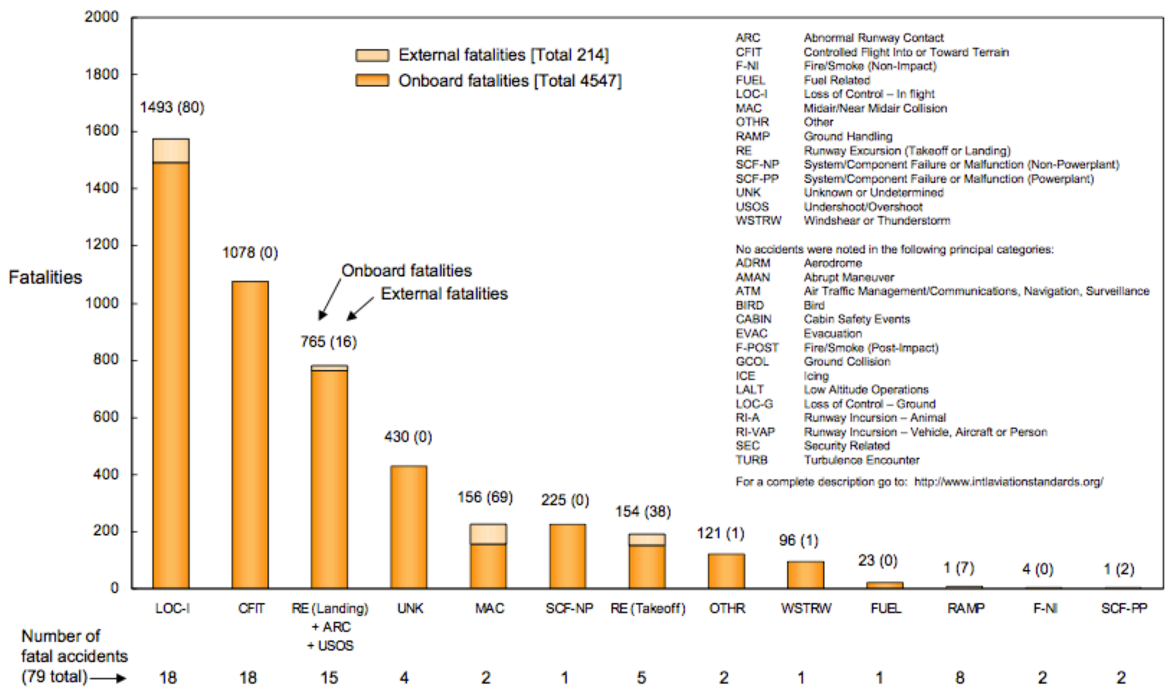

Figure 1. Worldwide commercial jet fleet fatalities from 2001 through 2010. Classified by type of event. Adapted from "*Statistical Summary of Commercial Jet Airplane Accidents: Worldwide Operations 1959-2011*" by Boeing, 2012, p. 22.

Stall as the Leading Cause of Loss of Control

Detailed analyses of loss of control accidents identified aerodynamic stall as the leading cause of such accidents. For example, an analysis performed by the NTSB of 20 transport-category loss of control accidents from 1986 to 1996 revealed that the majority of those accidents were caused by the aircraft stalling (FAA, 2008). More recently, Lambregts, Nesemeier, Wilborn, and Newman (2008) analyzed 75 aircraft upset and loss of control accidents in airline operations from 1993 to 2007. They found aerodynamic stall to be the number one cause of these accidents and incidents. A summary of their data can be found in Table 1.

Table 1

Summary of Upset and Loss of Control Events to Transport Airplanes

Cause	Number	Fatalities
Aerodynamic Stall	27	848
Flight Control System	16	604
Spatial Disorientation	8	630
Contaminated Airfoil	8	200
Atmospheric Disturbance	6	477
Other	6	122
Undetermined	4	380
Total	75	3261

Note. The data presents findings from Lambregts et al. (2008).

Three examples of commercial airplane accidents in which the aircraft inadvertently entered a stalled condition and the aircrew failed to subsequently recover the aircraft from the self-induced stall are the crashes of Colgan Air Flight 3407 on approach to Buffalo Niagara International Airport on February 12, 2009 (NTSB, 2010); Northwest Airlines Flight 6231 (NWA6231) while on a flight without passengers to move the aircraft to Buffalo, New York on December 1, 1974 (NTSB, 1975); and the crash of Air France (AF) Flight 447 over the Atlantic Ocean on June 1, 2009 (BAE, 2012).

While detailed causes of the stalls often vary, it is assumed by the GAJSC (2012) that a significant contributing factor to a number of stall accidents may be a deficit in the pilot's aerodynamic state awareness caused by limitations or gaps in aircraft instrumentation.

Air France Flight 447

Past discussions about the possible benefits of angle-of-attack (AOA) information made accessible to the pilots (e.g., Forrest, 1969; Gee, Guidsick, & Enevoldson, 1971) have been renewed after the accident of AF Flight 447 in 2009 (i.e., BAE, 2012; FAA, 2012; GAJSC, 2012). The following is a quick synopsis of the accident of AF Flight 447 according to the final accident report published by the BAE (2012). The synopsis is not a complete summary of the report and does not touch on all aspects of the mishap, but rather focuses on the key points of the accident that are important for the purpose of this study.

AF Flight 447 was scheduled as a flight from Rio de Janeiro Galeao to Paris Charles de Gaulle airport on June 1, 2009. Over the Atlantic, about two hours into the flight, the airspeed indications became erroneous which led to the disconnection of the automatic systems including the autopilot and autothrottle. This was most likely caused by the obstruction of the airspeed sensors in an ice crystal environment because the airplane was passing through an area of bad weather. Numerous other failure indications began to develop as a result of faulty data input from the airspeed sensors to the air data computer of the aircraft.

At the time of the accident, two copilots occupied the cockpit while the experienced captain was taking a rest. Upon being confronted with the disconnection of the automatic systems, combined with intermittent airspeed indications and other resulting failure indications, the two copilots could not bring the aircraft under control. Various inputs to the controls led to the aircraft exiting normal aerodynamic flight conditions in less than one minute after autopilot disconnection and the aircraft was subsequently allowed to enter a stall as a result of failed attempts to regain control. During this time, the captain was called back to the cockpit. The copilots were not successful in recovering the stall situation that the aircraft was in and could not give enough information to the captain concerning the state of the aircraft. Neither the copilots nor the captain subsequently seemed to be able to determine which information about the various aircraft systems could be relied on. The stall warning was also unreliable, in part due to unreliable airspeed data that was being fed to the onboard computers.

For the remainder of the flight, the aircraft was held in a fully stalled condition, descending towards the water from about 35,000 feet. Throughout the mishap sequence, the engines were fully functional as were the controls of the aircraft. The aircraft impacted the water with last recorded values of a vertical speed of -10,912 feet per minute, a ground speed of 107 kts, and a pitch attitude of 16.2 degrees nose-up. All persons on board the flight were killed in the accident.

Increase Aerodynamic Awareness by Displaying AOA to the Pilot?

Failure to recover from a self-induced stall, especially in the presence of aircraft malfunctions or other disturbances, has been the leading cause for two recent major accidents in commercial aviation (BEA, 2012; NTSB, 2010). In addition, stall accidents have historically been a leading cause of GA fatalities (e.g., Aircraft Owners and Pilots Association [AOPA], n.d; GAJSC, 2012; Lambregts et al., 2008; NTSB, 1996; NTSB, 2011), and the FAA (2012) and GAJSC (2012) leave no doubt that stall awareness is currently one of the highest interest items when it comes to flight safety. Along the same lines, the FAA acknowledges the possible benefits of AOA indication in the cockpit and recently declared the installation of certain AOA systems in GA aircraft as *minor alterations* requiring only a logbook entry instead of a full-up installation approval process, thus facilitating the installation of such systems (Hirschman, 2012).

Traditional stall warnings in GA aircraft, as well as instrumentation, generally lack the ability to show the influence of AOA on aerodynamics and only provide a warning when the aircraft is already very close to a stall. As noted earlier, improving aircraft instrumentation might reduce the number of stall accidents by enhancing a pilot's aerodynamic awareness (GAJSC, 2012).

Research Objectives

Limited research has evaluated the overall effectiveness of in-cockpit AOA indication in GA. Forrest (1969) surveyed pilots with qualitative measures of effectiveness and did not find a difference in pilot performance of pilots flying with in-cockpit AOA indication versus pilots flying without in-cockpit AOA indication during normal flight operations. However, he acknowledges that the design of the study might have precluded discovering an effect. Gee et al. (1971) evaluated airspeed indication and AOA indication as aircraft control parameters and found that AOA indication is not necessarily superior to airspeed indication in all phases of flight. Furthermore, a cognitive task analysis (CTA) of the approach-to-landing phase performed by Flach et al. (2003) led them to the conclusion that it might be more effective to focus on better integration of information displayed to pilots than to present AOA information in the cockpit as a separate critical variable. While they suggest that new displays should aim at better integration of aerodynamic information, no concrete examples of such displays are presented (Flach et al., 2003). Interestingly, neither of these studies specifically examined areas of flight in which AOA indication is assumed to be most advantageous, namely non-standard situations and disturbance management.

The purpose of the research described herein was to evaluate the importance of providing pilots with feedback about fundamental aircraft aerodynamics during non-standard situations and unexpected disturbances. Specifically, the purpose was to evaluate a pilot's ability to fly a more stable approach with the usage of an AOA indicator than without in the event of an airspeed indicator malfunction. It was not the researcher's intent to blame available display technology for deficits in pilot aerodynamic awareness associated with stall; rather, the intent of the study was to evaluate how to support aerodynamic awareness. A secondary goal was to test a principle of cognitive systems engineering, according to which system dynamics and status must be communicated to the humans in the system if the humans are to help the system adapt, or be resilient in the face of challenging circumstances.

Hypotheses

In order to test the importance of providing pilots with feedback about AOA, pilots were confronted with an airspeed indicator malfunction while flying a final approach. One group of pilots was flying with AOA information, whereas the other group lacked information about AOA.

The overarching hypothesis was that pilots flying with in-cockpit AOA indication would be able to better keep the aircraft within a prescribed flight envelope when confronted with an airspeed indicator malfunctions than pilots flying without in-cockpit AOA indication. The derived hypotheses are as follows:

H1: Pilots flying with in-cockpit AOA indication are able to fly an overall more stable approach after being confronted with an airspeed indicator malfunction than pilots without in-cockpit AOA indication.

H2: Pilots flying a final approach with in-cockpit AOA indication are able to notice a frozen airspeed indication earlier than pilots flying without AOA indication.

Additionally examined was the frequency with which pilots in each condition allowed the aircraft to come close to a stall.

Limitations and Assumptions

This study focused on GA pilots. For generalizability of the findings to the population of all GA pilots, it would have been desirable to draw a sample from a pool of all GA pilots. The fact that most of the participants received their flight training from Embry-Riddle Aeronautical University (ERAU) might have been a limitation of the study; however, considering that the required piloting abilities for receiving a pilot's license are the same for all FAA licenses, this limitation was considered negligible by the researcher.

Another limitation was the usage of a flight simulator on a personal computer. The control yoke used for flight simulation on a personal computer does not adequately represent the forces that are acting on a control yoke in a real aircraft. In addition, other controls such as trim had to be operated by buttons on the control yoke in the absence of more realistic controls. Furthermore, a decision had to be made about which aircraft to use for simulation. It was decided to use a Cessna 172 aircraft because this aircraft is commonly used for flight training. The Cessna was equipped with standard instrumentation although, in recent years, more and more pilots are primarily trained in aircraft with technologically advanced instrumentation, or glass-cockpits. Pilots primarily trained in glass-cockpits might have had difficulty adjusting to older forms of cockpit instrumentation, such as the round-dial analogue instruments used in the simulator.

Due to time limitations, pilots were not trained to proficiency in flying with an AOA indicator. This has two implications for the study. One implication is that using pilots novice to AOA indicators for the study can provide information about how effectively an AOA indicator can be used as a backup instrument in case of airspeed indicator malfunctions even after only a short training period. The other implication is that the findings of this study, if supportive of AOA information made accessible to the pilots, would be conservative.

This experiment set out to use quantitative measures in order to assess effectiveness of in-cockpit AOA indications. It was assumed that airspeed and glideslope deviations would provide the best insight into a pilot's ability of flying a stable final approach. More specifically, airspeed and glideslope deviations were expected to be sensitive to a general decline in aircraft control on final approach. While other parameters such as lateral deviations on final approach, actual AOA, pitch angle, and various other measures can provide additional information, none of those were considered to be of the same level of importance as airspeed and glideslope deviations for measuring final approach control.

Definitions of Terms

Angle of Attack	The measured angle between the chord line of an airfoil and the relative wind (FAA, 2007b).
Chord Line	The chord line of an airfoil is “a straight line drawn through the profile of the wing connecting the extremities of the leading edge and trailing edge” (FAA, 2007b, p. 1).
Pilot’s Operating Handbook	Operations manual for an aircraft, containing checklist, procedures, limitations, amongst other information. Usually published by the manufacturer of the aircraft. The military calls the operations manual for an aircraft the “Dash One”, referring to the numerical designation of the manual: “-1”. In this publication the term “Pilot’s Operating Handbook” is used to encompass all operating handbooks.
Stall	A loss of lift of an airfoil and an increase in drag occurring when an aircraft is allowed to exceed an angle of attack greater than the angle for maximum lift (FAA, 2007b).

List of Acronyms

AF	Air France
AGL	Above Ground Level
ANOVA	Analysis of Variance
AOA	Angle of Attack
AOPA	Aircraft Owners and Pilots Association
ATC	Air Traffic Control
BEA	Bureau de l'Enquêtes et d'Analyses pour la sécurité de l'aviation civile
C_L	Coefficient of Lift
COCOM	Contextual Control Model
CSE	Cognitive Systems Engineering
CTA	Cognitive Task Analysis
ECOM	Extended Control Model
EID	Ecological Interface Design
ERAU	Embry-Riddle Aeronautical University
FAA	Federal Aviation Administration
G	Units of Gravity
Gz	Vertical Component (Units of Gravity)
GA	General Aviation
GAJSC	General Aviation Joint Steering Committee
GPS	Global Positioning System
JCS	Joint Cognitive System

KDAB	Daytona Beach International Airport
MANOVA	Multivariate Analysis of Variance
MSL	Mean Sea Level
NTSB	National Transportation Safety Board
NWA	Northwest Airlines
PAPI	Precision Approach Path Indicator
POH	Pilot’s Operating Handbook
RMSE	Root-Mean-Square-Error
SA	Situation Awareness

CHAPTER II

REVIEW OF THE RELEVANT LITERATURE

In modern aviation, the tasks the pilot has to perform can be categorized as aviating, navigating, communicating, and managing systems. The hierarchy in which those tasks are performed in has some flexibility, but usually those tasks are prioritized in the order in which they were just listed (Wickens, 2002). Nowadays, in most commercial aircraft cockpits, automation has taken over most of the aviating processes. As a result, it seems that the basic task of aviating, more specifically, keeping the aircraft in an aerodynamically stable condition, can pose a challenge when the aircrew is confronted with automation or other system failures and unexpected events (e.g., BEA, 2012; NTSB, 2010). Once the aircraft departs from an aerodynamically stable condition, previous accidents show that the aircrew might be unsuccessful at recovering the aircraft back into a stable flight envelope (e.g., BAE, 2012; NTSB, 1975; NTSB, 2010). While arguably a multitude of factors can be identified as eventually leading to the failure to recover from a self-induced stall, one possibility is that aircraft instrumentation might be deficient in supplying the pilot with enough aerodynamic state awareness which, in turn, might lead to deficits in the pilots' mental models about the interactions of aerodynamic forces, which sets the stage for improper recovery attempts from aerodynamic stalls.

Background to Aerodynamics

> If you push the stick forward, the houses get bigger. If you pull the stick back, they get smaller. That is, unless you keep pulling the stick all the way back, then they get bigger again (Author unknown).

An explanation of the basic principles of aerodynamics relating to this research will help the reader understand the importance of aerodynamic state awareness and proposed display requirements that follow in later chapters. By no means is the following explanation of basic aerodynamic concepts meant to be comprehensive. The interested reader is encouraged to refer to the source documents (e.g., Langewiesche, 1972; see also FAA, 2004, 2007b, 2008) for a more complete explanation of aerodynamics. Definitions for the technical terms discussed in this section can be found in the *Definitions of Terms* section.

The lift equation. An introduction to aerodynamics usually begins with introducing the general equation of lift for any wing:

$$Lift = C_L \times \frac{\rho \times V^2}{2} \times A \,. \tag{1}$$

where C_L is the coefficient of lift, ρ the density of the surrounding air, V the velocity of the wing, and A the wing area. For the purpose of this research, the coefficient of lift (C_L) is certainly the most salient factor in the equation, and plays a central role in how much lift a wing creates at any time. While the other variables are certainly equally important, C_L is mainly controlled by AOA, which is the focus of this research. Thus, understanding how C_L influences overall lift is important. Note that the higher the C_L, the more lift can be created at a certain velocity and a certain altitude (the wing area is regarded as a constant here). Also note that with a C_L of zero, it would be impossible to create lift. This short overview of the lift equation should help to understand the relationships between AOA, C_L and overall lift, forming the basis for the following discussions.

Angle of attack. In his book *Stick and rudder: An explanation of the art of flying*, Langewiesche (1972) focuses his introduction on a concept that is very basic to the art of flying: AOA. He argues that while the concept of how lift is created, namely Bernouilli's Theorem, is often the main focus in the theory of flight and explanation of aerodynamics, the focus should be on AOA instead. In his words:

> It is the plane part of the airplane we have to understand. This plane is inclined so that as it moves through the air, it will meet the air at an angle and thus shove it downward, in somewhat the same way that the inclined plane of a snowplow, in moving forward against the snow, shoves the snow to the side. And the angle by which it is inclined, the angle at which it meets the air, is for every pilot the most important thing in flight: for *that* is the Angle of Attack. (Langewiesche, 1972, p. 10)

Another fundamental point to understand is that the AOA is *not* the pitch angle of the aircraft measured from the horizon. In the easiest terms available, "the Angle of Attack is the angle at which the wing meets the air" (Langewiesche, 1972, p. 7). This air is often referred to as the relative wind. For a more precise definition, please refer to the *Definitions of Terms* section. The FAA's (2004) *Airplane Flying Handbook*, designed as "a technical manual to introduce basic pilot skills and knowledge that are essential for piloting airplanes" (p. iii), provides a figure to explain AOA and its implications for overall lift (see Figure 2).

As AOA increases, the C_L produced by the airfoil usually increases linearly all the way up to a certain point. This point is called the "critical AOA". At the critical AOA, the wing produces maximum lift (for a certain velocity, density, and wing area; refer back to Equation 1), but at the same time the airflow over the wing begins to separate from the upper surface. If the AOA is increased beyond the critical AOA, lift decreases and the wing is considered stalled. Eventually the airflow will completely detach from the upper surface of the wing, resulting in complete loss of lift.

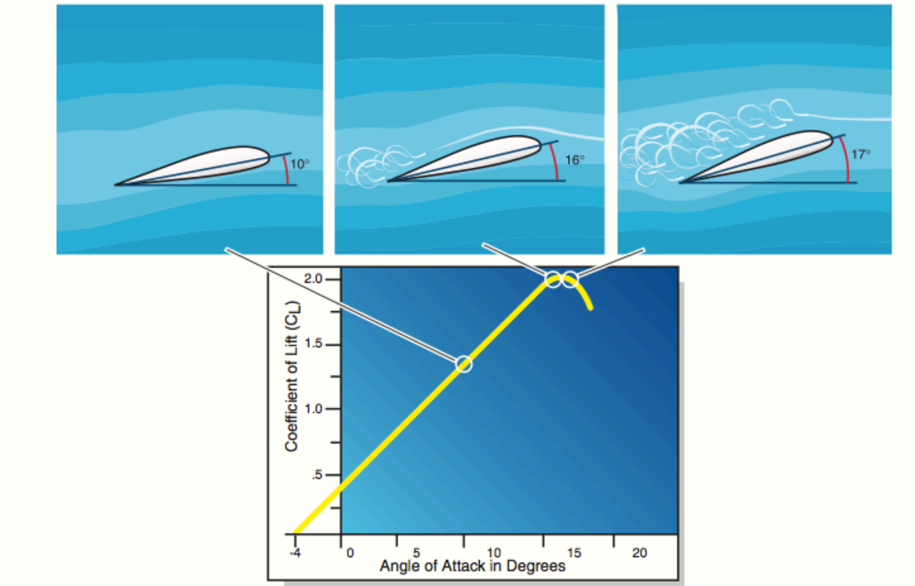

Figure 2. Critical angle of attack and stall. Note: The degrees of AOA and coefficient of lift values specified in the picture are examples only. Adapted from "*The Airplane Flying Handbook*" by the Federal Aviation Administration, 2004, p. 4-3.

In summary, when the critical AOA of a wing is exceeded, lift will decrease (due to a decrease in C_L; see Equation 1), drag will increase, and the wing will stall *regardless of airplane speed or attitude* (FAA, 2008). Pictures used to explain this phenomenon often use a horizontal line to depict the relative wind. While this depiction at first may not seem problematic, it often causes the reader to confuse the relative wind with the horizon line and AOA with pitch attitude. A clearer approach to showing the dynamics of AOA and the interactions is used by Flach et al. (2003), depicted in Figure 3.

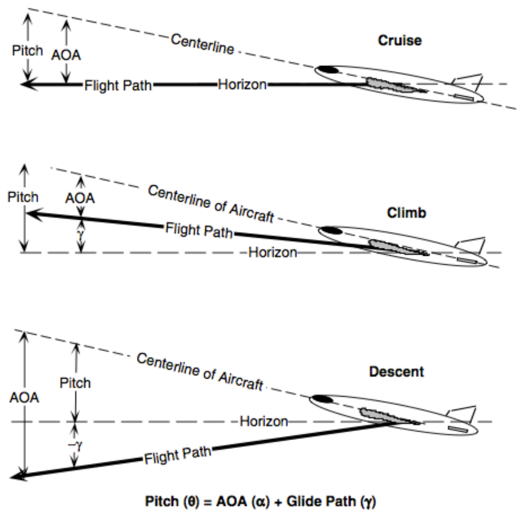

Figure 3. Relationships between AOA, centerline of the aircraft, and actual flight path. Adapted from "*A Search for Meaning: A Case Study of the Approach-to-Landing*" by Flach et al., 2003.

Another way to look at the concept of AOA is that it is the "difference between where the airplane points and where (in the up-and-down sense) it goes" (Langewiesche, 1972, p. 11), depicted by the flight path and centerline of the aircraft in Figure 3.

The connection between load factor and AOA. It is essential, for an aerodynamic discussion of AOA, to mention the role of load factor. Load factor is a measure of the amount of acceleration being experienced by an airplane (or any object for that matter), which is usually quantified by comparing it to the acceleration due to gravity and expressed as units of gravity along the z-axis (Gz) when addressing the vertical component (FAA, 2008). This discussion will focus on a simple explanation of vertical load factor only (perpendicular to the floor of the airplane), because it operationally seems to be the most important factor when examining the dynamics of AOA. For a more detailed description, refer to FAA (2008). For a less technical description, see Langewiesche (1972).

An aircraft in level flight has a vertical load factor of 1.0 Gz (one times the acceleration due to gravity), which equates to the lift produced by the aircraft being equal to 1.0 times the weight of the aircraft. An increase in lift, achieved by pulling back on the yoke/stick of the aircraft, increases the load factor because essentially centrifugal forces are now acting on the aircraft. If one would increase the load factor to 2.0 Gz, the force created by the airplane would be twice the force of gravity and the aircraft's flight path would become curved (FAA, 2008). An increase in load factor essentially is also an increase in weight of the aircraft. An aircraft at 2.0 Gz, for example, weighs twice as much as an aircraft at 1.0 Gz.

In a turn, lift has a vertical and a horizontal component because it is created perpendicular to an aircraft's wings. To make up for the decrease in the vertical component due to the aircraft turning, an increase in overall lift (by increasing any of the variables of Equation 1 – usually the C_L) is required to keep the vertical component of lift constant, thus maintaining level flight. During this maneuver, centrifugal forces act on the aircraft and the combined result is an increase in load factor. In a 60-degree bank turn, for example, 2.0 Gz are acting on the aircraft when maintaining level flight. An increase in AOA is necessary to generate the lift to support this load when trying to remain level.

This relationship has major implications for flight. For instance, if a pilot is flying a turn to lineup with the runway for landing from a perpendicular position to the runway (called base-turn-to-final; see Figure 4 for a graphical description of the maneuver), and initiates this turn too late, more than the usual amount of bank might be required to prevent the aircraft from overshooting the runway.

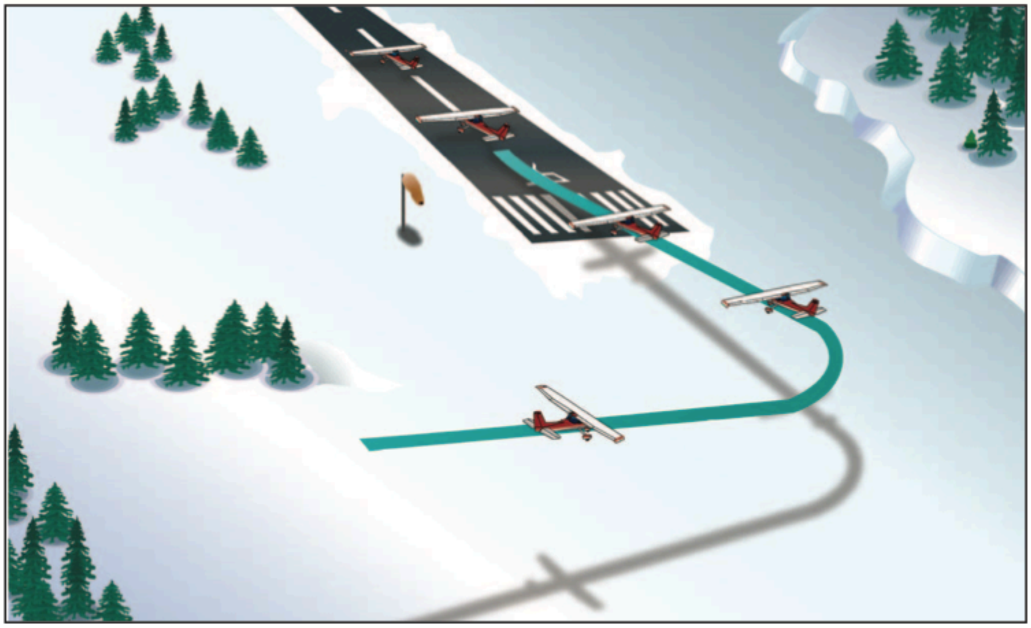

Figure 4. Turning from base leg to final. A maneuver often used by GA pilots to line up with the landing runway when flying in the traffic pattern. Adapted from "*The Airplane Flying Handbook*" by the Federal Aviation Administration, 2004, p. 8-1.

If the pilot were to use an excessive amount of bank (while still trying to maintain level flight or a standard descent to the runway), the load factor increases. Worst case, the AOA required to generate the lift to support this greater load factor might be beyond the critical AOA and the aircraft might stall. Frequently, pilots feel safe because they are at a relatively high airspeed but do not account for the increase in load factor and its impact on the AOA in such a situation. The FAA (2004), especially, warns about the risks of using extremely steep banks in final turns. In a worst-case scenario, if the aircraft is allowed to enter a stall close to the ground, altitude might be insufficient for recovery and the aircraft will crash. The list of crashes due to inadvertent stalls in final turns in GA is long. For examples of stalls in the final turn due to excessive bank and/or insufficient airspeed, see for instance: AOPA (n.d.), NTSB (1996), and

NTSB (2011). Factors such as becoming too fixated on the runway can also play a role by causing the cues for an impending stall to be missed. Especially when close to the ground, it is very important to recognize the conditions that might lead to a high AOA condition and thus, worst case, to a stall, so that such situations can be avoided.

The role of airspeed. To elaborate on the role of airspeed, a scenario will be presented to improve understanding. Assume that an aircraft is flying level at cruise airspeed and subsequently slows down. Any airspeed above the stall airspeed described in the Pilot's Operating Handbook (POH) will work for this example (for details about the POH see the *Definitions of Terms*). When reducing the power and slowing the aircraft down, velocity of the wing decreases, which would lead to a decrease in overall lift (see Equation 1). In order to continue to maintain adequate lift to keep the aircraft flying level, the pilot can increase the C_L by increasing the AOA (usually by pulling back on the stick/yoke), thus keeping the overall lift constant even though the velocity is decreased. If the aircraft is slowed further, the AOA needed to keep overall lift constant might increase up to the critical AOA, eventually exceeding the critical AOA, and the aircraft will enter a stall.

The airspeed at which the aircraft exceeds the critical AOA varies by condition and configuration. For example, in the landing configuration, extending the flaps lowers the airspeed at which the aircraft will stall. At the most basic level, for single-engine GA aircraft, stall speeds listed in the POH for any particular aircraft are usually the stall speed in the clean configuration and the landing configuration. The landing configuration is often defined as a certain flap setting and landing gear extension, while the clean configuration is flaps and gear retracted (in aircraft with retractable landing gear). The main problem with relying on airspeeds is that airspeed does not account for bank angle, load factor, or air density, to name just a few of the factors that might contribute to an aircraft exceeding the critical AOA.

Aerodynamic Awareness Information Accessible to the Pilot

Despite the critical role of AOA in determining overall lift and the inherent danger of stalling the aircraft, AOA information is not directly available in many aircraft, including the Cessna 172, which is the most commonly used aircraft for primary flight training around the globe. The absence of AOA information in the cockpit, combined with the absence of AOA information in the POH of many training aircraft suggests that pilots may not adequately learn about AOA in primary flight training. Thus, other sources of aerodynamic state information have to be relied on and will now be discussed further. Because available information varies greatly between different aircraft, two of the most basic forms of aerodynamic information sources, found in numerous aircraft, will be discussed.

Natural stall warning: buffet. While stall characteristics of aircraft depend heavily on aircraft design and shape and form of the wings, amongst other factors, most aircraft will experience airframe buffeting, caused by turbulent airflow over the wings as the air begins to separate from the wing. In some aircraft, this turbulent air will also reach the horizontal stabilizer of the aircraft, leading to amplified buffeting of the aircraft. One problem with this kind of "natural" stall warning is that it gives little or no indication of the situation developing prior to the airflow becoming turbulent. Another problem is that the amplitude of the buffet might vary tremendously from aircraft to aircraft, potentially resulting in failure to recognize the cue. And finally, during high-altitude operations, another form of airframe buffeting may occur, known as *Mach tuck* or *Mach buffet* (FAA, 2008). Mach buffet occurs when an aircraft is flown at or beyond its critical Mach number, which means a speed at which any part of a wing exceeds

Mach 1.0. In this case, a shock wave will begin to form on the wing and buffeting will occur. Under normal circumstances this speed is never reached, but in the case of pilot-induced loss of control at high-altitude, such an event might occur. On the other hand, because Mach buffet occurs at high airspeeds, an excessive airspeed or Mach number reading usually separates it easily from buffeting due to a stalled condition. In case of AF447, airspeed information was unreliable and was surrounded by other non-standard indications, so the aircrew might have initially suspected an overspeed condition and possible buffet due to Mach buffet at high-altitude early in the accident sequence (BEA, 2012). In case of Northwest Airlines (NWA) flight 6231, the airspeed indicator was falsely indicating a much higher airspeed than the aircraft was actually at. The crew initially did not recognize the stalled condition of the aircraft, misinterpreting the airframe buffet as Mach buffet. When they finally recognized that the aircraft was in a stall, they did not apply the correct recovery procedures (NTSB, 1975).

Artificial stall warning and stick shaker/pusher. Aircraft used in initial pilot training and GA, such as the Cessna 172 series, are usually fitted with stall warning systems that provide an aural warning to the pilot at 5-10 kts above stall speed in all configurations (Cessna, n.d.). In some cases, these warnings are augmented by a visual indication in the form of a warning light. The Cessna 172 series aircraft, for example, never display AOA information in the cockpit, unless they are retrofitted with an off-the-shelf system.

Due to the fact that more sophisticated stall warning devices usually require input from multiple sensors of the aircraft, with those signals being processed by onboard computers, they have more parts within the system that can fail. This, in turn, might render the stall warning (or that particular stall warning system) inoperable, or it may become unreliable.

Toward Aerodynamic Awareness

Following the above review of real-world practicalities and evidence pointing to the potential value of AOA information, this discussion will now present pertinent areas of systems engineering and evaluate potential benefits of in-cockpit AOA indication as a means of providing fundamental information about system state and dynamics based on relevant research literature and theory. Initially, the focus will be on areas of systems engineering that acknowledge the relevance of human factors to their discipline in order to evaluate presentation of aerodynamic information to the pilot from a human factors perspective within the framework of engineering. In addition to information being presented, the operator has to be aware of the information, be able to understand it, and project its meaning and implications into the future. A discussion about SA and an evaluation of how to support awareness with design, within the context of providing fundamental aerodynamic information to the pilot, concludes this chapter.

Cognitive systems engineering. At the heart of supporting human performance within a system is an approach called *cognitive systems engineering* (CSE). This interdisciplinary approach is specifically concerned with cognitive functions such as “problem solving, judgment, decision making, attention, perception, and memory” (Roth, Patterson, & Mumaw, 2002, p. 2). Drawing from disciplines such as cognitive psychology, cognitive science, and computer science, the goal is to support human performance within a system (Roth et al., 2002). This is achieved by applying techniques and knowledge bases of cognitive psychology to the engineering process, an approach that takes systems engineering of the human-technology interface further than when just considering the human’s physical limitations (Hollnagel & Woods, 1983). CSE acknowledges the fact that the human is more than just an information-processing system and that the strengths of human cognition, as well as limitations, have to be taken into account (Hollnagel & Woods, 2005). Furthermore, CSE is a shift in paradigm from looking at the individual parts of a system as a decomposition of human and machine, to an approach that is interested in joint system performance (Hollnagel & Woods, 2005).

The joint cognitive system. A Joint Cognitive System (JCS) approach to CSE considers the communication between the parts of a system and their interaction, but the main focus is on "understanding how the joint system performs and how it can achieve its goals and functions" (Hollnagel & Woods, 2005, p. 18). Figure 5 illustrates how a JCS maintains control over its processes by showing a cyclical model of steps necessary for controlled performance.

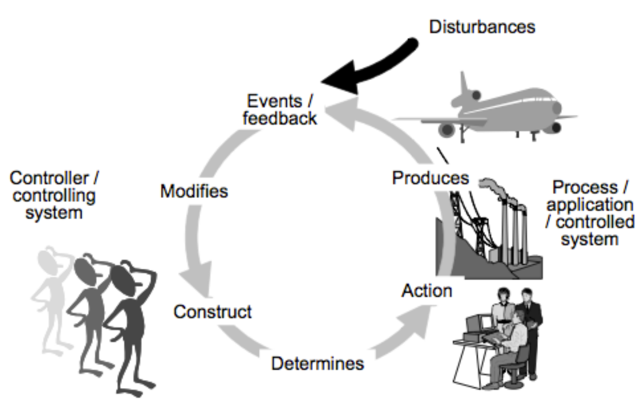

Figure 5. Model of a JCS emphasizing the interdependency of different parts of a system. Adapted from "*Joint Cognitive Systems: Foundations of Cognitive Systems Engineering*" by Hollnagel, E. & Woods, D.D, 2005.

Control theory in human performance. The JCS approach describes human system interaction in terms that matter in systems engineering – for example, feedback and control. The cyclical model, combining a feedback and feedforward loop, affects anticipation, as well as response (Hollnagel & Woods, 2005). To conceptualize control and associated cognition within a

JCS, Hollnagel and Woods (2005) propose the contextual control model (COCOM). A COCOM differs from other models of control in that “actions are determined by the context rather than by an inherent sequential relation between them” (p. 144). Its primary features are four different control modes corresponding to characteristic differences in the orderliness or regularity of the context (Hollnagel & Woods, 2005). According to Hollnagel and Woods (2005), those control modes are as follows:

- Scrambled control:

  The choice of the next action is random, based on blind trial-and-error performance. A reason for scrambled control might be that the situation assessment is deficient or paralyzed. For example, if critical information pertaining to a situation is not being received, this might result in scrambled control.

- Opportunistic control:

  The situation is not clearly understood or time is limited. Causes of such limited understanding can be “lack of competence, an unusual state of the environment, or detrimental working conditions” (p. 147). This leads to planning and anticipation being limited. Especially when the description of the situation used by the system to evaluate events and select actions is inadequate, choice of actions is often inefficient because delayed effects of such actions are not being considered.

- Tactical control:

  Performance more or less follows a known procedure or rule. In this mode, “the time horizon goes beyond the dominant needs of the present, but planning is of limited scope or range…. The determination of whether an action was successful will take delayed effects into account” (p. 147).

- Strategic control:

  The time horizon goes beyond that of tactical control. The dominant features of the current situation have less influence on the choice of action and the JCS can look ahead at higher-level goals.

Part of control is essentially the ability to compensate for disturbances and disruptions in a timely and effective manner (Hollnagel & Woods, 2005). Hollnagel and Woods (2005) state that the scrambled control mode is clearly the least efficient, and that normal human performance usually is likely to be a mixture of the opportunistic and tactical control modes, with the strategic control mode requiring so much effort that it cannot be continually sustained.

Because of the fact that performance in a JCS takes effect on several layers of JCS control simultaneously, the Extended Control Model (ECOM) complements the COCOM. The ECOM accounts for the fact of simultaneous control of different types during different types of cognitive work (see Figure 6), where cognitive work within a system often consists of activities that can be described as tracking, regulating, monitoring, and targeting.

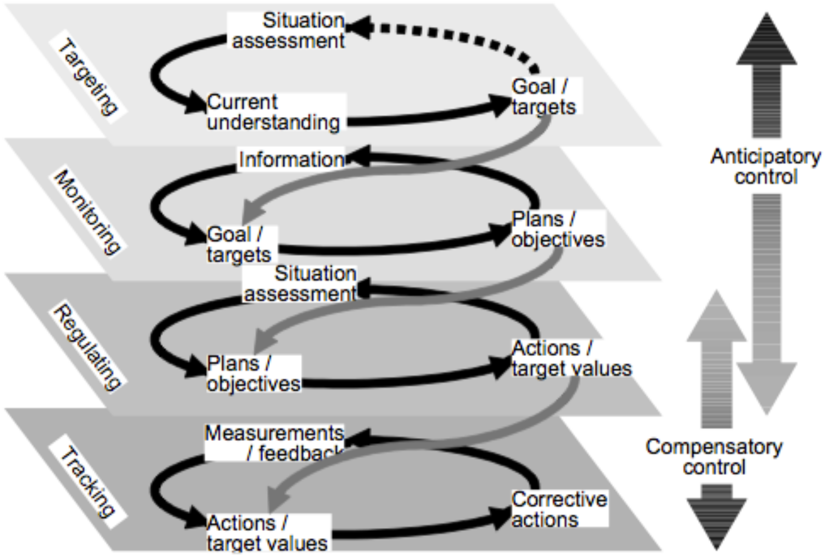

Figure 6. Different control loops and the interactions between them. Hollnagel and Woods (2005) acknowledge that these are proposed layers of performance and that the layers are changeable and extendable. Adapted from "*Joint Cognitive Systems: Foundations of Cognitive Systems Engineering*" by Hollnagel, E. & Woods, D.D, 2005.

Of special interest for this discussion is the ECOM's tracking loop because of its relevance to flight control. It is concerned with the control activities required to keep the system within predetermined boundaries or to return the system within boundaries should these have been exceeded. In addition, the monitoring layer is of particular interest because of an increase in automation on modern flight decks. Implications will now be further discussed.

Humans give the system resilience. In a JCS such as a modern airliner, the tracking loop is often taken over by automation for a considerable portion of the flight. It follows that the major work of the human operator in such complex systems is performed largely in the monitoring layer and concerned with detecting and dealing with the unexpected events that might occur (Reason, 1990), a view also shared by Endsley (1997). She describes the human role in complex systems as performing tasks that are not easily automated and concludes that the "human operator has usually remained to insure that the automated systems perform properly and to detect the occurrence of aberrant conditions" (Endsley, 1997, p. 200). In order to be considered resilient, a JCS has to be able to handle disruptions and variations that fall outside the normal adaptive capabilities of the system (Woods, 2006). Thus, if automation is not able to adapt to disruptions in the system; for example, due to sensor failure as was the case in the AF Flight 447 accident (BAE, 2012), or due to automation being unable to keep the system within predetermined boundaries (e.g., NTSB, 2010), the human can give the system resilience by detecting, reacting to and dealing with the unexpected events that might unfold, eventually returning the system to within boundaries.

The new role of the pilot as being primarily a supervisory role above the automation in modern aircraft demands a departure from classical approaches to system design. Flach et al. (2003) state that with complex systems, such as aircraft, classical approaches to work design will not be effective because most of the procedural work aspects of those systems are automated. Essentially, to design for these systems, the goal is to design for understanding of the process being controlled so that the "operators can assemble the appropriate actions as required by the situation encountered" (Flach et al., 2003, p. 173). This is achieved by providing the operator with the information required for a deep understanding of the processes being controlled.

Automation failure and the effects on the JCS. Whenever automation fails and the state that the system is in is not clearly understood by the operator, the system is likely to degrade to something close to opportunistic control. In this case, anticipation and planning will become limited. Even worse, if the operator is not able to assess the situation at all, control might be degraded to the scrambled control mode and actions taken by the operator will become random.

There will be a disparity between the actions taken in scrambled control mode, and the appropriate actions that are required to return the system to its predetermined boundaries.

Usually automation does not just fail without reason but might not be able to cope with non-standard situations (e.g., BAE, 2012; NTSB, 2010). A disengagement of automation devices operating the tracking loop of the aircraft (autopilot and autothrottle) will prevent further adjustments within the tracking loop by automation, transferring control back to the operator. In a dynamic flying environment, adjustments are constantly needed to keep the aircraft in the desired state. In addition, margins for safety are small if an aircraft is close to its aerodynamic performance boundaries at the time of control authority transfer. If the operator is unaware of the aerodynamic state at the time of automation failure, or cannot quickly enough achieve such awareness, a breakdown in the tracking loop might occur, and degradation in the control mode of the JCS might ensue. Only awareness about the situation will provide the operator with the necessary means to reestablish control in situations where predetermined boundaries were exited. Consequences of not being able to return the aircraft to the desired state can be disastrous (e.g., BAE, 2012; NTSB, 2010) and underline the importance of supporting the operator in providing resilience by improving awareness in the human operator within a JCS.

Situation awareness. In this section, definitions and concepts of SA will be presented. The most prominent definition is that of Endsley (1995), defining SA as “the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future” (p. 36). In Smith and Hancock (1995), the definition of SA revolves around “adaptive, externally directed consciousness” (p. 137). They use the term “externally directed” to specify that the “goal of the behavior that SA directs must reside in the task environment rather than in the agent’s head.” (p. 139). Products of

SA, according to Smith and Hancock, are knowledge about and directed action within the environment.

The concept and definitions of SA have sparked various debates. Flach (1995) suggests treating SA as a phenomenon description and specifically cautions against the concept possibly being considered a causal agent, as this might lead to circular reasoning and present an obstacle to productive research. As an example, he utilizes a statement that SA, or the loss thereof, is the leading cause of human error in military aviation mishaps and describes how it might be criticized as circular reasoning as follows: “How does one know that SA was lost? Because the human responded inappropriately. Why did the human respond inappropriately? Because SA was lost” (p. 151). On the other hand, considering SA as a phenomenon description would be to note that loss of SA is evident in many pilot errors. According to Flach, only when SA is considered a phenomenon description does it become very fruitful to research because it challenges researchers to go beyond simple standard laboratory paradigms in an attempt to recreate the dynamic, interactive complexity of natural task environments.

Along the lines of Flach, who doubts the falsifiability and thus the theoretical validity and strength of the SA concept, Dekker and Hollnagel (2004) additionally criticize the concept of SA as relying on overgeneralization in the sense that the concept is often applied to situations that it was never meant to speak about. Wickens (2008), on the other hand, defends SA as a “viable and important construct” while acknowledging that it “still possesses some controversy over measurement issues” (p. 397) and predicts that the interest in how SA may degrade or can be supported will continue to grow into the future. He also specifically supports Endsley’s (1995) definition of SA, stating that it has stood the test of time, albeit a matter of 13 years. The focus of the following discussion will be on Endsley’s model of SA.

Endsley (1995) recognizes three different levels of SA. At the most basic level, Level 1, is perception of the elements in the environment; more specifically the perception of the status, attributes, and dynamics of relevant elements in the environment.

Level 2 SA is achieved when the agent is able to form a holistic picture of the environment by incorporating the knowledge of level 1 SA elements into something meaningful, leading to a comprehension of the situation at hand.

Finally, Endsley defines the highest level of SA (Level 3) as being able to project the future actions of the elements, with projection extending to at least the very near term. As a matter of consistent terminology, she distinguishes the term "situation awareness" as a knowledge state from the processes used to achieve SA, which she combines under the term "situation assessment".

In addition, Wickens (2008) states that knowledge structures, such as scripts, schemas, and expectancies contribute to understanding and comprehending the current state, while selective attention works to direct the acquisition of information. These elements of cognition (selective attention and knowledge structures) directly influence Level 1 and Level 2 SA, according to Wickens (2008).

Decision making, goals, and performance. In a sense, decision making can be linked to SA but in Endsley's theory they should not be coupled as parts of one process (Endsley, 2000). According to Endsley (2000), pilots can have perfect SA and make bad decisions, or can have low-levels of SA and still make the correct decisions, if purely by luck. Along the same lines, Wickens (2008) states that good SA is not indicative of good performance and further notes that "an operator with excellent SA of a failing system may not possess the knowledge of procedures to remedy the failure or may not have the motor execution skills to implement that remedy" (p. 398).

While SA is seen as a construct separate from decision making and performance (Endsley, 1995), the goal of flight deck design should be to furnish the operator with information required for good SA in order to provide a solid basis for appropriate decisions. Figure 7 shows how Endsley (1995) links SA and decision making.

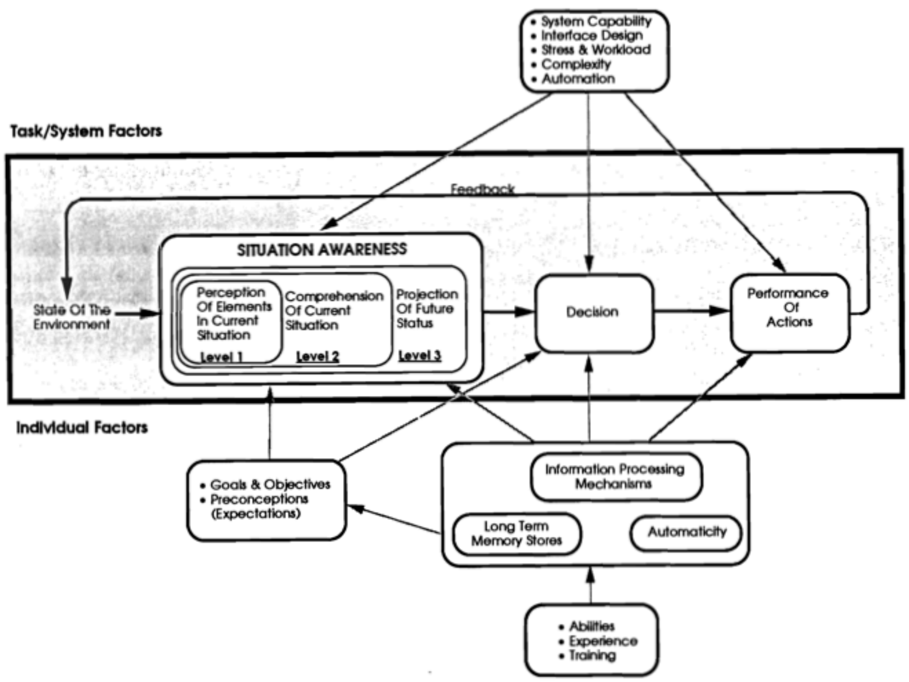

Figure 7. Model of SA in dynamic decision making. Adapted from "Towards a theory of situation awareness in dynamic systems" by Endsley, 1995, p. 35

Note in Figure 7 how individual factors, such as "abilities, experience, and training" contribute to the formation of SA and how "goals, objectives, and expectations" influence acquisition of SA, as well as the decision making process.

Smith and Hancock (1995) base their model of SA primarily on Neisser's (1976) model of perception, which emphasizes the perception-action cycle, that is, the importance of active perception on the part of the user to make sense of a situation that the user is acting in. Their approach, like Endsley's, also emphasizes the importance of goals. Smith and Hancock use the example of finding a car in a parking lot. For them, only if the goal is explicitly stated, can the quality of the performance be judged, and knowing what must be known in order to solve an information-processing problem constitutes the person's SA (Smith & Hancock, 1995).

Furthermore, Smith and Hancock define SA as "a generative process of knowledge creation" (p. 142), emphasizing that SA is more than merely a current snapshot of the agent's mental model; rather, SA guides the process of knowledge modification. In their model, the knowledge that is created is called the "big picture" of the situation. Experienced personnel are often self-aware of the process of losing the big picture, which can happen when their big picture becomes insufficient to support the task (Smith & Hancock, 1995). One of the great advantages of the approach taken by Smith and Hancock is that such self-awareness is explained by stating that SA is not the agent's big picture but rather it is the agent's SA that builds the big picture.

Regardless of the stance taken when defining the construct of SA, the discussed models have in common that external goals must exist, and eventually a decision (Endsley, 1995) or action (Smith and Hancock, 1995) will be taken, resulting in observable performance. The resulting performance can only be judged if the goals of the operator are known. To illustrate this point, if a person were observed walking around a parking lot, that person could be doing a number of things. For example, maybe the person is lost or maybe the person is looking for a car. Only if the goal (i.e. looking for a car) is known can the performance and SA at the task be judged. If a system has exited predetermined boundaries, and the operator is to return the system to a predetermined state, the operator needs to actively construct knowledge-comprehension of the unfolding situation. Information displays about the state of the system will support the operator in doing so.

How to support "knowing what's going on" using design. In general, it can be said that the desired state is for the operator to be in control of a system or process at all times. In most general terms, such a process could be flying the aircraft. Hollnagel and Woods (2005) identify a number of common conditions that can lead to loss of control. If the conditions that can cause loss of control are known, appropriate means to combat those conditions can be deduced. Figure 8 shows examples of loss of control causes and how control can be maintained or regained if lost.

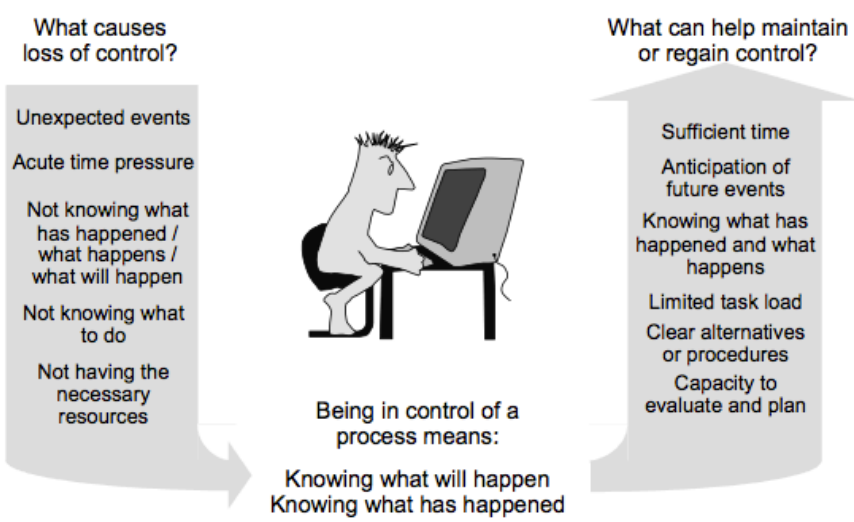

Figure 8. Determinants of control. Adapted from "*Joint Cognitive Systems: Foundations of Cognitive Systems Engineering*" by Hollnagel, E. & Woods, D.D, 2005.

At the center of being in control of a process is the knowledge of what will happen and what has happened (Hollnagel & Woods, 2005). In essence this constitutes good SA that can be supported with adequate interface design. While different approaches to interface design exist, this section will introduce a theoretical framework called *ecological interface design* (EID; Vincente & Rasmussen, 1992).

Ecological interface design. EID is aimed specifically at designing interfaces for complex human-machine systems, such as a JCS. One of the premises of EID is being able to provide a detailed symbolic description of an underlying process to the operator if needed for analytical problem solving, especially during unfamiliar events (Vincente & Rasmussen, 1992). According to Vincente and Rasmussen, unfamiliar events can either be anticipated or unanticipated. They further state that unfamiliar but anticipated events occur infrequently, thus operators might have limited experience to rely on, but designers have most likely built means of coping with such events into the system. Unfamiliar and unanticipated events pose the biggest challenge to operators because operators are most likely unfamiliar with these events given their low probability of occurrence, and designers of the system did not anticipate the event (Vincente & Rasmussen, 1992).

In unfamiliar and unanticipated events, for the human to be able to provide resilience, deep control of the system is needed. Operators cannot rely on a built in solution and have to improvise a solution themselves (Vincente & Rasmussen, 1992). Such deep control “is guided by the operator’s mental model of the underlying process” (p. 596). Vincente and Rasmussen further elaborate that research has shown that humans have a tendency to prefer cognitive strategies that are less versus more effortful. Humans prefer to use established cue-response patterns and other cognitive shortcuts when possible. Preference for lower levels of cognitive control makes it easy for operators to forget, and fail to consider, the underlying properties of the process that are not shown on the display (Vincente & Rasmussen, 1992).

Ecological interface design and situation awareness. Burns, Jamieson, Skraaning, Lau, and Kwok (2007) note that both the concepts of EID and SA "contribute to the development of information displays that improve operator insight into decision-making spaces" (p. 205). They go on to state that both concepts must, at practical levels, overlap. When considering the three levels of SA (Endsley, 1995), it becomes clear where those overlaps might be. Perception of the elements is the basis for Level 1 SA. A good EID will support Level 1 SA by providing the required information to control the process. In addition, Burns et al. (2007) point out that EID should support comprehension (Level 2 SA) by communicating the purposeful structure of the system; and conclude that it should support projection (Level 3 SA), by enabling operators to make assumptions on the future state of the system based on the mental model that is externalized by the ecological interface.

Burns et al. (2007) designed displays according to EID for two sections of a nuclear power plant. Using six nuclear control room-operating crews as participants, they compared three different interface types, namely EID-based, traditional, and advanced displays. The traditional display was representative of contemporary displays for nuclear power plants. Advanced displays added trends and configural graphics to the traditional display. On the other hand, the EID-based interface provided information that was deemed important to support anomaly detection, decision making, and action under abnormal events. The control room-operators were confronted with a total of six scenarios. Three of the scenarios were typical scenarios that the operators had faced before, and the other three were scenarios that the operators had never faced before. Burns et al. found that the ecological interface only provided advantages over the two other displays when the crews were facing atypical situations. Ecological interfaces did not provide an advantage on SA measures during scenarios that the crews were used to. This led Burns et al. to the conclusion that supporting visual information for anomaly detection, decision making, and action under abnormal events might not help operators perform strictly procedural tasks. The real advantages of ecological interfaces might be only seen in unfamiliar and unanticipated events.

Cognitive task analysis. In order to design for systems that support human performance in cognitive functions such as problem solving, decision making, and attention, up-front analyses of the demands of the domain and requirements for effective JCS performance need to be conducted (Roth et al., 2002). CTA methods are methods used to perform those analyses and assess complex cognitive work. CTA is used to understand the “cognitive activities required of the … [JCS] and to fashion those requirements into a state that matches both the technical demands of the application and the operator’s functional characteristics in the cognitive domain” (Hollnagel & Woods, 1983, p. 592). CTA data can be collected by observing behavior of operators (in a simulator, for example), studying work artifacts, and using semi-structured interviews, as examples. Using the data from these sources, processes can be mapped out in schematic or hierarchical representations to provide the basis for engineering that supports cognitive work in a given work domain.

Task analysis has been used to evaluate possible benefits of in-cockpit AOA indications. Flach et al. (2003) wondered if making the AOA explicit in the cockpit could not only lead to the prevention of stalls but also to a general enhancement of piloting capabilities. They observed pilot participants in a synthetic task environment flying a final approach to landing. When they broke down the task into a schematic diagram assessing the couplings between control inputs to the aircraft and performance indices, they noticed that the AOA was at a central position in the diagram. Consequently, they acknowledge the tight coupling of AOA to the piloting task.

Summary

In the previous sections, a mix of design philosophies, strategies for design, and strategies for assessing the work and determining what information and relationships need to be shown to operators, have been discussed. All of these philosophies, strategies, and methods center around the premise that system designs must effectively interface the human and technology components of a system. In a complex system, knowledge of system state is vital so that an operator can manage the system appropriately, detect problems early, take over at any given time if automation fails, and handle abnormal situations adequately. A well-designed interface will facilitate understanding the dynamics of flight and effectively communicate the state of the system.

By making AOA explicit to pilots, it can be used for problem solving and troubleshooting. Displaying AOA provides observability of the aerodynamic state and feedback that provides insight into the dynamic nature of how control inputs by the operator change this aerodynamic state, one of the support requirements for cognitive work listed by Woods (2005). In addition, Woods (2005) lists support for resilience as a requirement for cognitive work, with cross checks as possible means to avoid premature narrowing and related vulnerabilities in cognitive work. Overt AOA supports resilience by providing direct feedback to changes in aerodynamic state and also provide means for cross check, especially if the validity of another source of information (i.e. airspeed information) is questioned. Being able to assess AOA information directly facilitates assessing the aerodynamic state, rather than having to integrate information from various sources (i.e. airspeed indicator, vertical speed indicator, attitude indicator). There is no need to integrate individual elements in order to make a higher order assessment, or more precisely, in order to evaluate the aerodynamic state, thus facilitating situation awareness and aerodynamic awareness. As such, AOA can be seen as an overall aerodynamic state indicator providing a clear description of the underlying process. In addition, understanding the concepts of AOA might require AOA to be more than an abstract concept. If AOA information is made accessible to the pilot it will facilitate understanding and visualization of the "dynamics" in aerodynamics, which should positively influence the flexibility of response required in non-standard situations.

CHAPTER III

METHODS

Participants

Thirty-four pilots recruited from ERAU participated in the experiment. Two of the participants produced unusable data due to technical simulator difficulties and were replaced by two additional participants. Any previous experience flying with in-cockpit AOA indication was an exclusion criterion for the study. Pilots were required to hold at least a private pilot certificate and were required to have a minimum of 200 total flight hours to ensure familiarity with standard piloting procedures. They were equally split by random assignment into two groups, namely an AOA and No-AOA group. The average age of participants in the AOA condition was 24.44 years (SD = 4.59). In the No-AOA condition, the average age was 21.12 years (SD = 1.86). The average flight hours for participants in the AOA condition were 1114.69 hours (SD = 1528.6, Mdn = 285), and 368 hours (SD = 209.28, Mdn = 297.5) in the No-AOA condition. The relatively large discrepancy in flight hours between the two conditions is further addressed in the *Results* chapter.

Participants received an incentive of $20 after participating. The experiment consisted of a single session, which did not exceed one hour in duration. Participants were required to sign a consent form (see Appendix B) and informed that they could end their participation in the experiment at any time and would be paid for the time they have already completed. In addition, demographic information was collected from the participants. The collected information included age, total flight hours, and certificates held. See Appendix C for a complete listing of demographic information requested. All data collected during the experiment is kept confidential.

Apparatus

The experiment was conducted with the use of X-Plane 9 flight simulation software created by Laminar Research. The software ran on a Windows desktop computer with a 22-in computer screen providing a full-screen view of the aircraft instrument panel and a forward view from the pilot's perspective. A yoke and throttle were used as flight controls allowing participants to interface with the flight simulator. The flight simulation software was used to simulate a Cessna 172 aircraft, a common initial flight training aircraft that the participants should have been familiar with. The Cessna 172 was equipped with analogue instrumentation and lacked a GPS so as to not provide redundant airspeed information. On trials featuring AOA information, an AOA indicator was displayed on top of the aircraft's dashboard, to the left and within the pilot's outside field of view, a standard position for popular off-the-shelf GA aircraft AOA indexers (Hirschman, 2012; see also Figure 9). Participants were given the opportunity to familiarize themselves with the aircraft and instrumentation during practice trials before the beginning of the experiment.

The AOA indexer used in this experiment was a cue-based AOA indexer (see Figure 9) and consisted of three symbols calibrated to show optimum AOA for the approach-to-landing phase and deviations from optimum AOA. For a no-flap final approach, the optimum AOA was achieved when the aircraft was flown between 60 to 65 kts.

Figure 9. A cue-based AOA indicator or indexer. The indicator is situated on top of the aircraft's dashboard, slightly to the left off-center and within the pilot's outside field of view. Note that in this picture the AOA is slightly lower than optimum AOA. Screenshot taken from *X-Plane* by Laminar Research.

The three cues used to show AOA were a green donut, a yellow upward pointing chevron, and a red downward pointing chevron. The green donut in the middle of the instrument illuminates if the aircraft is flying at optimum AOA for the approach. The yellow upward pointing chevron on the bottom of the indexer illuminates if the AOA is lower than the optimum approach AOA. A red downward pointing chevron on the top of the indexer (not illuminated in Figure 9) illuminates if the AOA is higher than the optimum approach AOA. Combinations of on-speed and either the upward or downward pointing chevron are possible to show smooth transitions between optimum AOA and either lower than optimum or higher than optimum AOA.

The flight simulator used for this study was located in a dedicated research facility and flanked on either side by cloth dividers. No other activity took place in the facility during the conduct of this experiment.

A software plugin developed by a software engineering student, Matthew Grasso, from ERAU was used to record research-critical flight parameters throughout the experiment. Specifically, the software plugin recorded, among other values, the indicated airspeed of the aircraft, glideslope deviations, the activation of the stall warning during flight, and whether a button on the yoke was pressed. The flight data was recorded at a rate of 5 times per second and automatically saved to an Excel file. An excerpt of such a data-file can be found in Appendix G. In addition, the plugin automatically failed the airspeed indicator to a frozen position once the airspeed decreased to 70 kts.

Experimental Design

The experiment was a two-level between subjects design (No-AOA versus AOA). The dependent variables were: approach speed deviation, glideslope deviation, time until airspeed indicator malfunction was noticed, whether and how often the stall warning horn activated during flight, and correct identification of the malfunction.

Participants in the No-AOA condition flew practice and experimental trials without the addition of an AOA indicator, whereas pilots in the AOA condition flew practice and experimental trials with an AOA indicator added to the instrumentation. The required sample size of 32 participants for such a design with two outcome variables was calculated a priori using a statistical power analysis program called G*Power Version 3.1.6 from the Heinrich Heine Institute for Experimental Psychology at the University of Duesseldorf, Germany (Faul, Erdfelder, Lang, & Buchner, 2007). Specifically, the required sample size was calculated for an

F-Test Multivariate Analysis of Variance (MANOVA) using $\alpha = .05$, power $(1-\beta) = .8$, and an effect size of $f^2 = 0.35$. It was assumed that the experimental interventions in this study would produce a large effect which Cohen (1988) assumes to be $f^2 = 0.35$. The statistical power of .8 was chosen as a trade-off between feasible sample-size and statistical power.

Pilot Testing

Pilot testing was performed with two volunteer pilots from ERAU to optimize the flow of the experiment and to determine how many practice and experimental trials should be flown to provide a balance between adequate training and possible boredom effects. Furthermore, it was necessary to evaluate the airspeed indicator malfunction in terms of its detectability, and dependent variable sensitivity. In addition, the software plugin was tested and validated.

Initially, it was planned to have participants fly 10 practice approaches and four experimental trials. During pilot testing it was determined that the 14 planned approaches were too many as sloppiness was observed due to boredom and complacency effects. The total number of approaches was cut down to a total of eight approaches, namely six practice and two experimental trials. The pilot tests were used to evaluate the initial approach parameters for setting up the aircraft along the approach path. The resulting setup that was deemed adequate for the experiment is described in the next paragraph.

Procedure

The researcher followed an experiment script (shown in Appendix E) to standardize the conduct of the experiment. Participants were welcomed to the study and asked to read and sign the consent form (see Appendix B). Demographic information was collected using the questionnaire in Appendix C. They were informed that this experiment is “concerned with examining possible advantageous effects of in-cockpit angle-of-attack indications during flight”.

In addition, they were told that it is of utmost importance that they do not talk to their friends or colleagues about the events experienced during the experiment. This was done to prevent incoming participants from being prepared for an airspeed indicator malfunction. Incoming participants were asked if they had heard anything about the exact nature of the experiment.

The task. The pilots' task was to conduct final approaches to Runway 34 at Daytona Beach International Airport (KDAB). All approaches were set up on a 3 nm final, along the runway centerline, on glideslope, corresponding to at an altitude of 1000 ft MSL. The initial airspeed for the setup was 90 kts.

Participants were instructed to maintain a 3° glideslope during the descent towards the runway. Furthermore, participants were instructed to slowdown to between 60-65 kts as quickly as possible and to fly a no-flap final approach. An aid to visualization of the proper glideslope was provided in form of a precision approach path indicator (PAPI; an array of four lights usually situated to the side of a runway showing glideslope deviations to the pilot) situated to the left of the runway and calibrated for a 3° glideslope. Participants were required to aim for a touchdown 1000 ft beyond the runway threshold because this aiming point is consistent with the alignment of the PAPI. They were informed that transition to landing was neither required nor desired. This was done in an effort to produce usable data for the entire approach and to not skew the results. Any early transition to landing would have impacted the glideslope and airspeed deviation data. The simulation froze prior to the aircraft touching down. Upon simulation freeze, the aircraft was reset to the starting point of the approach.

Training. Before the experiment began, participants in the AOA group were instructed on the usage of an AOA indicator for flight. This training session lasted about 15 minutes. PowerPoint slides from this introduction are provided in Appendix F. Specifically the concept of

AOA was reiterated and the symbology of the AOA indicator explained. Some participants had misconceptions about AOA that had to be corrected during training. These misconceptions are further discussed in the *Discussions, Conclusions, and Recommendations* chapter.

Practice trials. In the first six trials, pilots flew practice approaches, one per trial, to familiarize participants with the aircraft, the controls of the aircraft, and the general task. They featured a 10-kt headwind and clear skies. There were no malfunctions or wind speed changes during these approaches.

Pilots in the AOA condition were instructed on the correct usage of the AOA indexer as a means of crosschecking final approach speeds. For the first three approaches, participants in the AOA group were further instructed to induce airspeed deviations to develop an understanding of how the AOA indexer works and how it can be useful in detecting anomalies during final approach. In order to provide consistency for pilots in both conditions, during the first three approaches, the No-AOA group was also instructed to explore a range of airspeeds on final.

Following the first three approaches, participants flew three additional approaches. For those additional approaches, they were told to focus on flying stable approaches and to minimize glideslope, horizontal, and airspeed deviations. After the practice approaches, experimental trials began.

Experimental trials. At the beginning of the experiment trials, participants were told that they would encounter different initial headwind conditions and a possible aircraft malfunction over the next set of trials. Before each experimental trial, the participant was asked to identify any suspected aircraft malfunction as soon as he or she detected it by pressing a button on the control yoke. The time at which the pilot pressed the button to indicate a suspected malfunction was recorded. Participants were instructed that their task would be to deal with the different headwind situations and the possible malfunction while still striving to accomplish a stabilized approach. Pilots were informed that discontinuing the approach, although certainly an option in a real-life scenario, would not be a valid option for the purpose of this experiment.

Participants were not told during which trial the malfunction would occur, nor did they know how many experimental trials they were facing. A total of two experimental trials were performed. The first trial included a steady headwind of 30 kts, whereas the second trial included a headwind at 25 kts and an airspeed indicator malfunction. While the participant slowed to final approach speed, the airspeed indicator failed automatically when the aircraft's airspeed passed through 70 kts. Failure of the airspeed indicator was simulated by a frozen indication of airspeed.

During all trials, if the aircraft would get too close to a stall, the sound off a stall warning horn would activate. The times at which the stall warning horn activated during flight were recorded. Furthermore, at the end of each experimental trial, the participant was asked if any malfunction was present during final approach. Answers from the experimental trial that included the airspeed indicator malfunction were scored as "1" if the participant correctly identified the airspeed indicator malfunction and as "0" if the participant did not suspect any malfunction or identified the malfunction as being of a different kind.

Data Processing

Data collected from the second trial were used in the data analysis. Deviations from glideslope and airspeed indications were measured at 5-second intervals throughout the approach. The data used for glideslope and airspeed analysis in this study were taken from the point along the approach at which the aircraft passed through 500 ft above ground level (AGL) to the point at which the aircraft passed through 100 ft AGL. The main underlying reason for using the described range of data is that the FAA (2007a) states that an aircraft should be stabilized on a final approach before descending through an altitude of 500 ft AGL in visual meteorological conditions (i.e., simplified, conditions that allow for being able to see the runway during the entire approach). Descending through the last 100 ft AGL of the approach, the participant might already have started a transition to landing, although told not to do so. This was observed in trials and most likely occurred due to personal habits that the participant might have acquired during their flying career. The resulting data range will be referred to as "final approach data" for the remainder of this document and measures taken during the experiment will now be discussed in more detail.

Airspeed and glideslope deviation. Airspeed deviation was calculated as the root-mean-square-error (RMSE) of all airspeeds that fell outside the prescribed range of 60 to 65 kts. In addition, glideslope deviation was calculated as the RMSE of deviations that fell outside of the PAPI on-glideslope indication. More specifically, PAPIs have an allowable range for which they show an "on 3° glideslope" indication. This is indicated by the PAPI showing two white and two red lights. Thus, the actual glideslope will be between an upper-boundary of 3.21° and a lower-boundary of 2.81° while the PAPI shows an on-glideslope indication. Upper and lower boundaries were calculated by Lloyd (2012) for a PAPI system modeled in X-Plane and might differ outside of the simulation. Refer to Figure 10 for a graphical representation. Deviations (in feet) outside of the upper and lower limit of the on-glideslope indication were recorded and the RMSE of such deviations calculated for each participant.

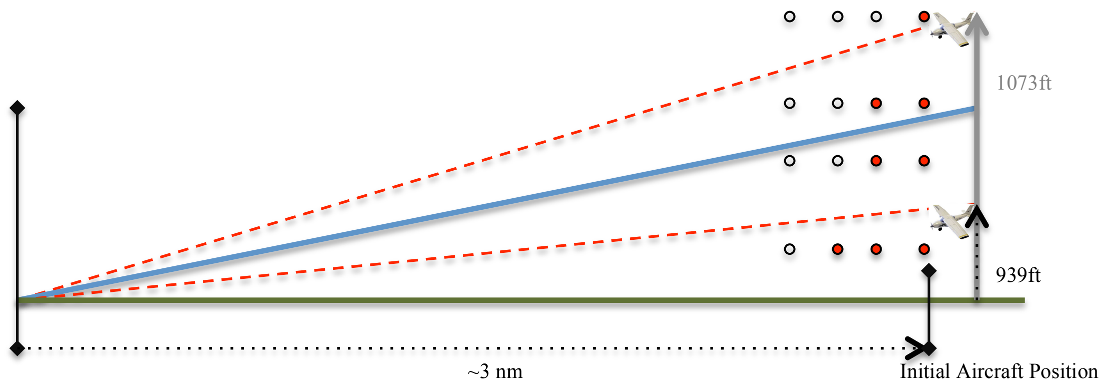

Figure 10. Upper and lower PAPI boundaries with respective PAPI indications. Adapted from "*The Effect of System lag on Unmanned Air System Internal Pilot Manual Landing Performance*" by Lloyd, M. E., 2012.

CHAPTER IV

RESULTS

Descriptive Statistics

Approach control was operationalized as airspeed and glideslope control on final approach. It was hypothesized that participants flying with in-cockpit AOA indication would be able to fly a more stable final approach than participants without in-cockpit AOA indication after failure of the airspeed indicator. The RMSE of airspeed and glideslope deviations for the final approach data was calculated for each participant and will initially be discussed separately in the descriptive analysis. Table 2 shows descriptive statistics for the RMSE of airspeed deviations of the two groups (AOA versus No-AOA).

Table 2

RMSE Descriptive Statistics for Airspeed Deviations (kts)

Condition	*n*	$\overline{X}$	*SD*	Min.	Max.
AOA	16	1.32	1.10	0.26	3.46
No-AOA	16	3.98	3.87	0	14.8

As shown in Table 2, the minimum value for RMSE in the No-AOA conditions is 0. This is because an airspeed range was given for participants to fly and one of the participants in the No-AOA group was able to fly the final approach exactly within those prescribed values. It can also be seen that the range of airspeed deviations was larger in the No-AOA group (14.8 kts) as opposed to the AOA group (3.2 kts). The maximum value of 3.46 kts for the AOA group, and 14.8 kts for the No-AOA group, when compared to their respective means, suggests that the data might be positively skewed. The boxplot shown in Figure 11 also supports the assumption that the data might be positively skewed.

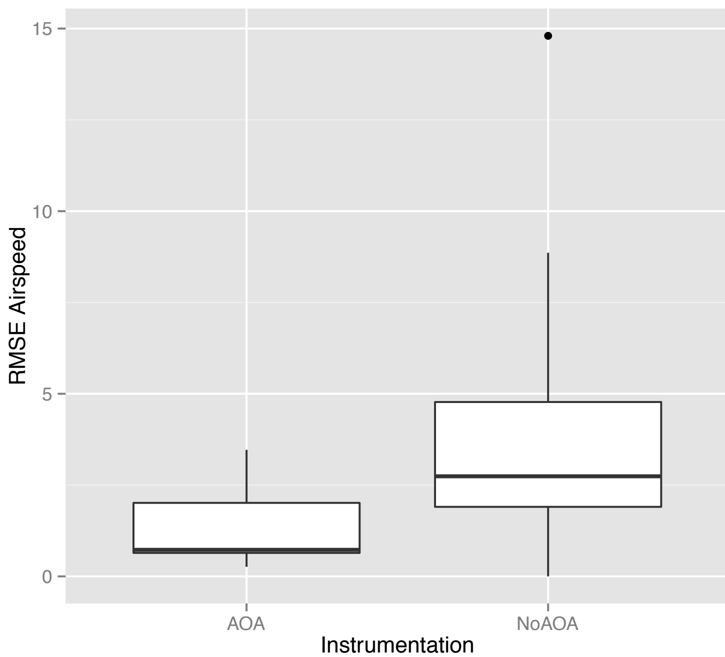

Figure 11. Boxplot of RMSE airspeed.

Skewness values were calculated using MINITAB's b_1 formula (Joanes & Gill, 1998). MINITAB's b_1 formula has been shown to generate the smallest mean-squared error in small samples that are normally distributed, when compared to other methods of calculating skewness (Joanes & Gill, 1998). Skewness values were found to be 0.88 in the AOA condition and 1.4 in the No-AOA condition respectively. Figure 11 shows the presence of an extreme score in the No-AOA group. A Q-Q plot of RMSE airspeed suggests that the data for both groups are not following a normal distribution (see Figure 12).

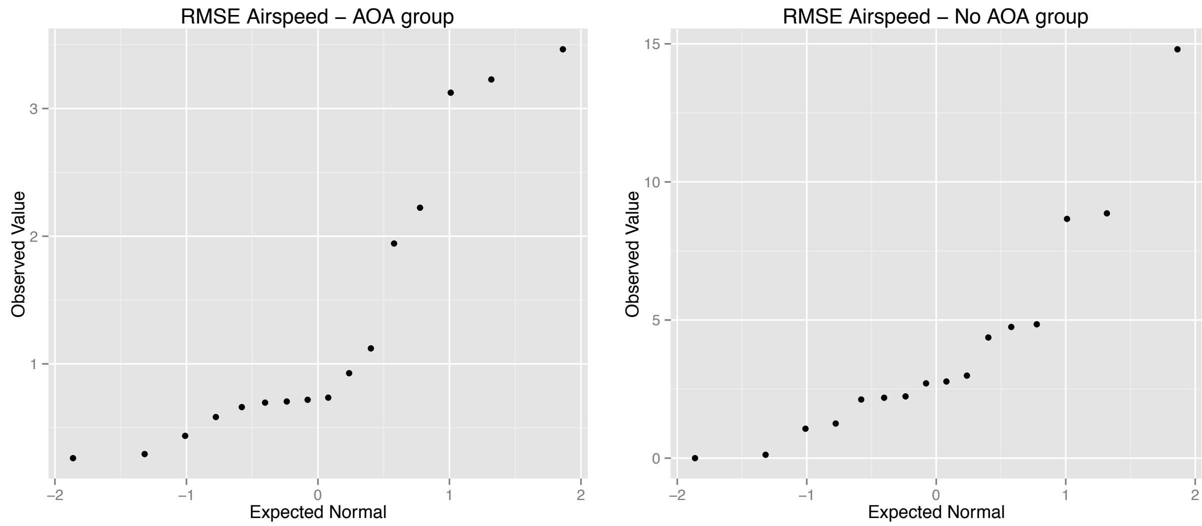

Figure 12. Q-Q plot of RMSE airspeed. Data for the AOA group is presented in the left plot and data for the No-AOA group in the right plot.

To quantify departure from normality, a Shapiro-Wilk test was performed for both the AOA and No-AOA groups. The RMSE airspeed data in the AOA group were non-normal (W = 0.798, p = .003), as were the RMSE airspeed data in the No-AOA group (W = 0.825, p = .006).

In order to reduce skewness of the data and attempt to normalize the datasets, a logarithmic transformation was applied (Field, Miles, & Field, 2012; Howell, 2012). Because the data included a value that was 0, a constant of +1 was added to all airspeed RMSE data before performing the logarithmic transformation (Field et al., 2012; Howell, 2012). After transformation, the data were visually assessed again using Q-Q plots (see Figure 13).

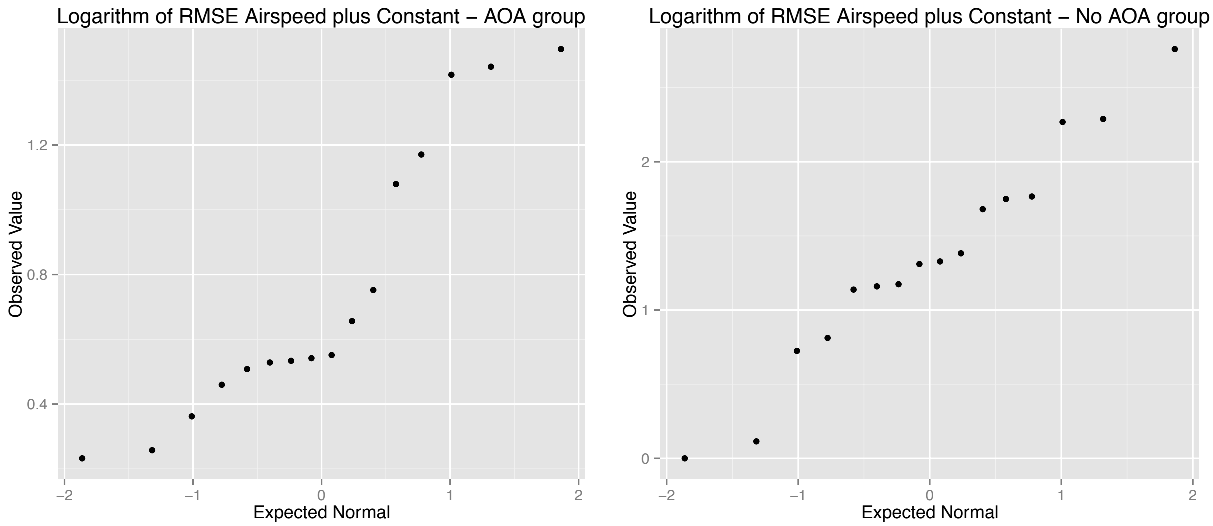

Figure 13. Q-Q plot of RMSE airspeed (transformed data). Data for the AOA group is presented in the left plot and data for the No-AOA group in the right plot.

The resulting boxplot of the transformed RMSE airspeed data can be seen in Figure 14.

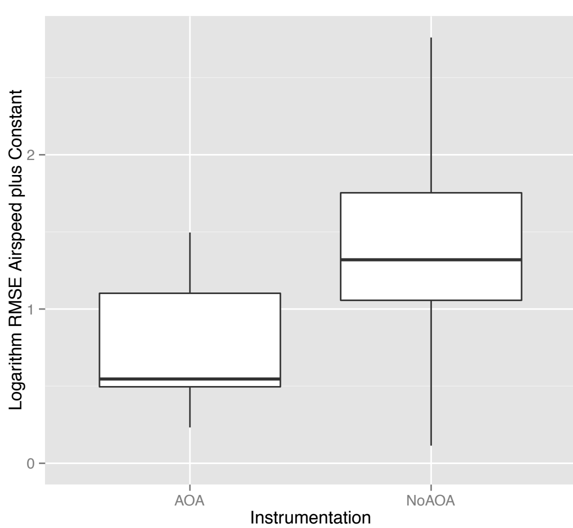

Figure 14. Boxplot of RMSE airspeed (transformed data). Data for the AOA group is presented in the left plot and data for the No-AOA group in the right plot.

By visual inspection of Figures 13 and 14, it can be deducted that skewness has been reduced and extreme scores have been eliminated. The calculated skewness values are reduced to 0.61 for the AOA group, and -0.04 for the No-AOA group respectively. Results from the Shapiro-Wilk test performed on the transformed data suggest data from the No-AOA group to be normally distributed ($W = 0.971$, $p = .853$). The Shapiro-Wilk test still indicates non-normality for the data from the AOA group ($W = 0.866$, $p = .023$). However, when comparing Q-Q plots (Figures 12 and 13) it can be seen that the distribution of data in the AOA group improved after transformation in terms of approaching normality.

An additional measure used to assess the overall stability of the final approach was the RMSE of glideslope deviations. The descriptive statistics can be found in Table 3.

Table 3

RMSE Descriptive Statistics for Glideslope Deviations (ft)

Condition	*n*	$\overline{X}$	*SD*	Min.	Max.
AOA	16	17.04	17.86	0.64	58.73
No-AOA	16	24.39	17.59	3.95	65.46

In contrast to the RMSE of airspeed deviations, the RMSE of glideslope deviations does not show a floor effect. The lowest value is 0.64 ft, indicating that none of the participants were able to fly along the glideslope exactly within prescribed PAPI limits at all times. Again, the maximum values, when compared to their respective means, suggest a possible positive skew to the data. A boxplot for the data had been generated (see Figure 15).

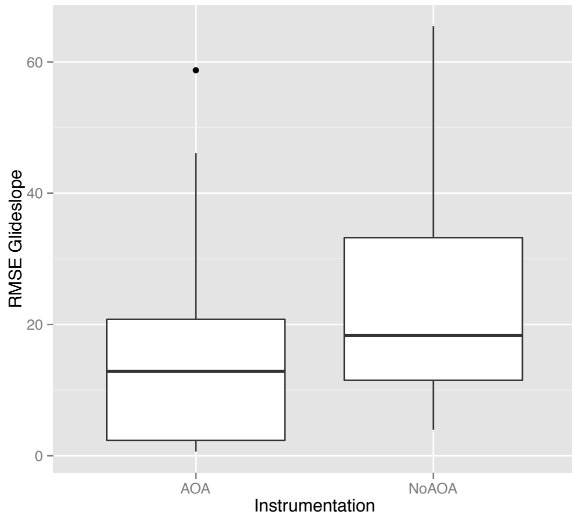

Figure 15. Boxplot of RMSE glideslope.

Figure 16 supports the existence of a positive skew to the data and shows the presence of an extreme score. Skewness values were found to be 1.00 in the AOA, and 0.93 in the No-AOA condition. Q-Q plots were generated for the data (see Figure 16).

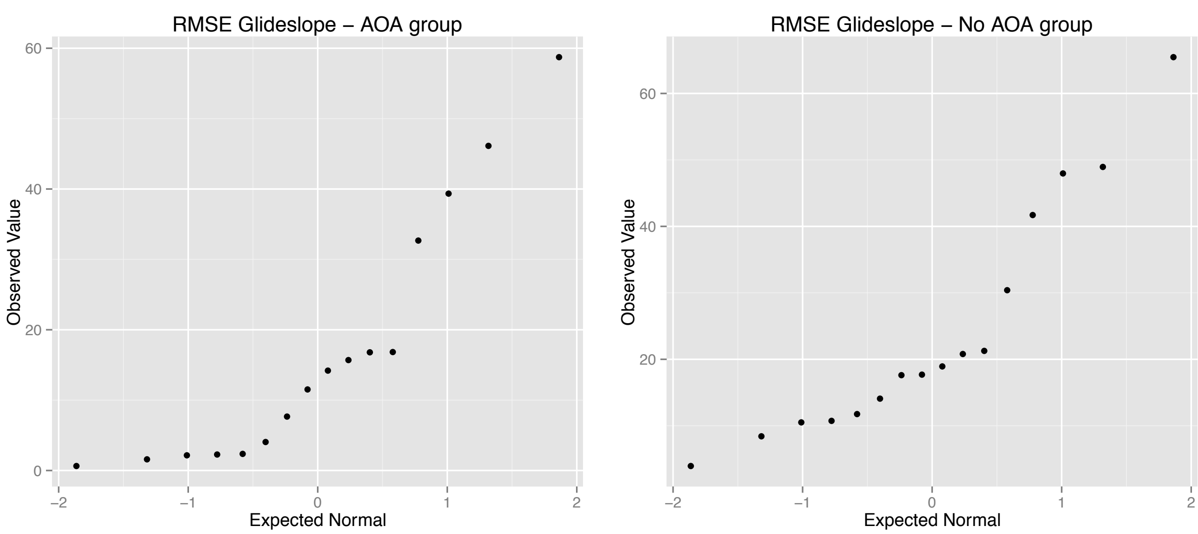

Figure 16. Q-Q plot of RMSE glideslope. Data for the AOA group is presented in the left plot and data for the No-AOA group in the right plot.

A Shapiro-Wilk test performed on the RMSE glideslope data indicated non-normality for both datasets (AOA group: $W = 0.834$, $p = .008$; No-AOA group: $W = 0.869$, $p = .026$). Thus, a logarithmic transformation was applied to the glideslope data as well. This time, no constant was added because the smallest value was greater than 0 in both datasets (RMSE AOA and RMSE No-AOA). After transformation, the data were again inspected for normality (Figure 17).

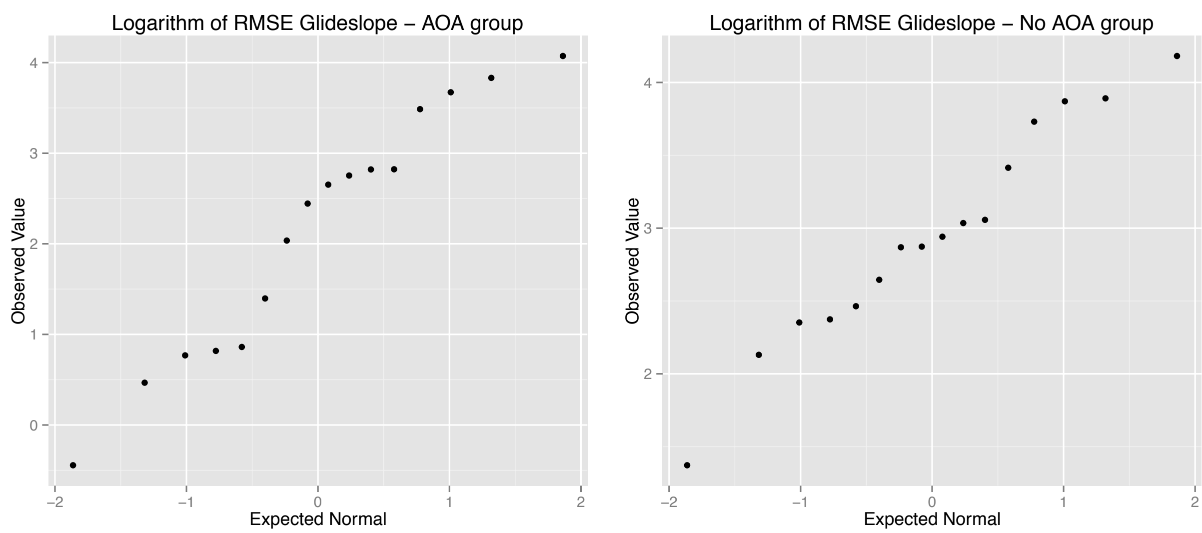

Figure 17. Q-Q plot of RMSE glideslope (transformed data). Data for the AOA group is presented in the left plot and data for the No-AOA group in the right plot.

The Q-Q plot in Figure 17 supports the assumption that, after logarithmic transformation, the data is more normal than before the transformation was applied. Skewness values are now reported at -0.28 in the AOA, and -0.15 in the No-AOA condition. Furthermore, results by the Shapiro-Wilk test indicate normality of the transformed data (AOA group: $W = 0.943$, $p = .393$;

No-AOA group: $W = 0.970$, $p = .845$). The resulting boxplot, shown in Figure 18, further supports these assumptions and shows that the extreme score has been eliminated.

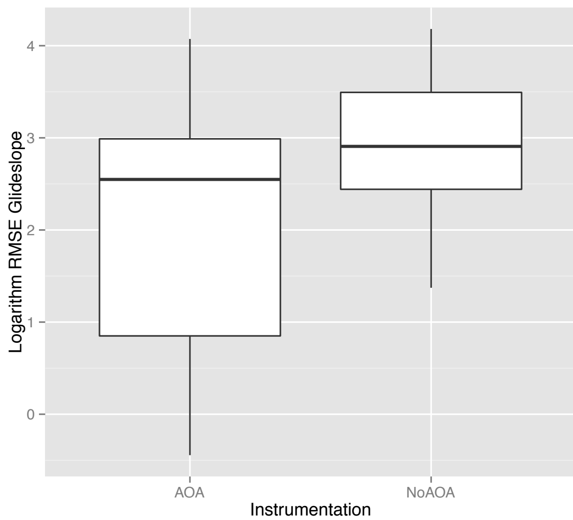

Figure 18. Boxplot of RMSE glideslope (transformed data).

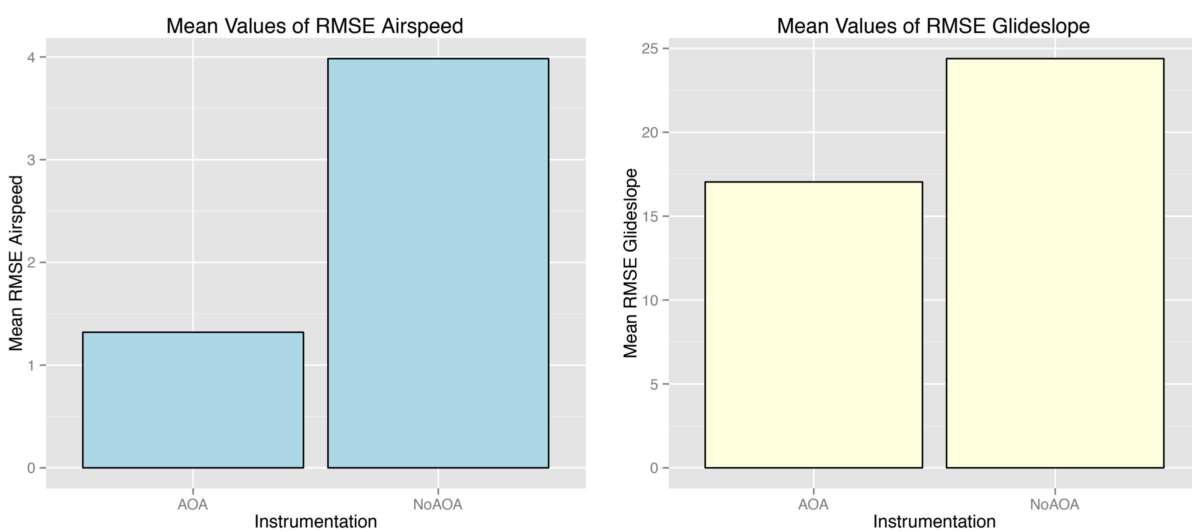

Figure 19. Mean values of RMSE airspeed and RMSE glideslope. Data for RMSE airspeed is presented in the left plot and data for RMSE glideslope in the right plot.

Figure 19 shows the means of untransformed data. Confidence intervals are deliberately not displayed because they do not represent an accurate estimation if derived from skewed data in combination with small sample sizes. Figure 20 shows bar charts for the transformed data with the respective 95% confidence intervals. The relatively large confidence interval for RMSE glideslope in the AOA condition is discussed in the *Discussions, Conclusions, and Recommendations* chapter.

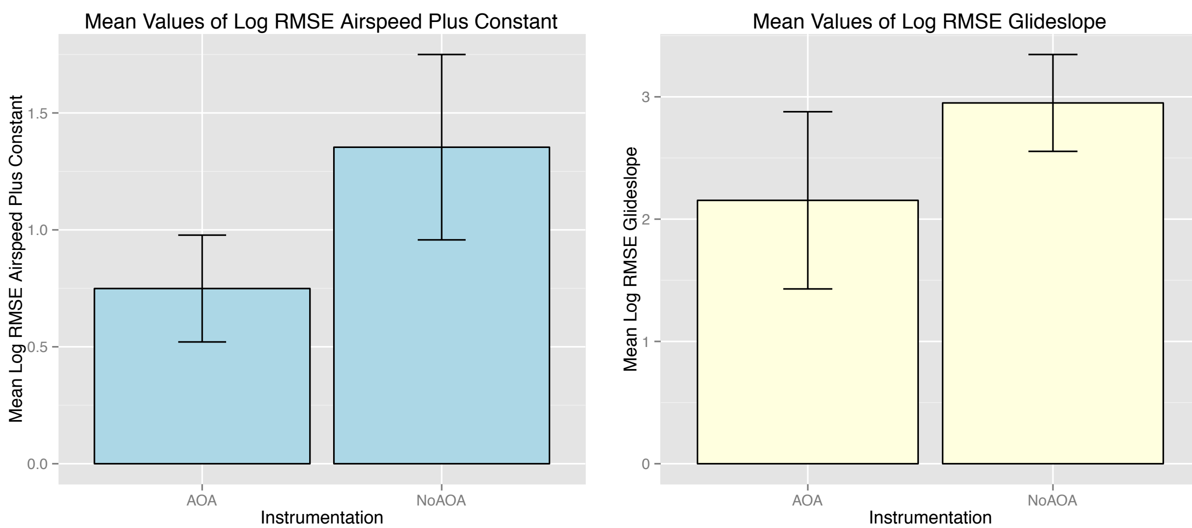

Figure 20. Mean values of RMSE airspeed and RMSE glideslope (transformed data). Error bars represent a 95% confidence interval. Data for RMSE airspeed is presented in the left plot and data for RMSE glideslope in the right plot.

Hypothesis Testing

A multivariate analysis of variance (MANOVA) was performed to determine if there is a difference in groups (AOA versus No-AOA) for the dependent variables RMSE airspeed and RMSE glideslope. The test was followed-up with two separate analyses of variance (ANOVAs).

All tests were performed using the transformed data. The descriptive statistics for the transformed data can be found in Table 4.

Table 4

Descriptive Statistics for the Log-Transformed Data

Measure	Condition	*n*	$\overline{X}$	*SD*	Min.	Max.
Log RMSE Airspeed	AOA	16	0.75	0.43	0.23	1.50
	No-AOA	16	1.35	0.74	0	2.76
Log RMSE Glideslope	AOA	16	2.15	1.36	-0.44	4.07
	No-AOA	16	2.95	0.74	1.37	4.18

Note. The airspeed data represents the log-transformed data after the constant +1 had been added.

The assumptions for a MANOVA and ANOVA were tested using the transformed data. Assumptions for a MANOVA are independence of the observations, random sampling, multivariate normality, and homogeneity of covariance matrices (Field et al., 2012). The former two assumptions were met by the research design. In addition, homogeneity of variance was tested for both dependent measures in order to test this assumption for the follow-up ANOVAs that were performed.

Multivariate normality. To test for multivariate normality, the Shapiro-Wilk test of multivariate normality was performed. In the case of the transformed RMSE airspeed data, the Shapiro-Wilk test of multivariate normality indicated that multivariate normality can be assumed ($W = 0.947$, $p = .446$). The same is true for the transformed RMSE glideslope data ($W = 0.968$, $p = .808$).

Homogeneity of variance. Homogeneity of variance was assessed using Levene's test of equality of error variances. The test revealed that sample variances in transformed RMSE airspeed data did not differ in the AOA and No-AOA groups, $F(1, 30) = 2.212$, $p = .147$. Thus, for the airspeed data, homogeneity of variance can be assumed. However, when applied to the transformed RMSE glideslope data, the test revealed a difference between sample variances, $F(1, 30) = 8.225$, $p = .007$, indicating that homogeneity for this data cannot be assumed. The ANOVA is considered a robust test concerning the violation of the assumption of homogeneity of variance (Howell, 2012). As such, the results of the ANOVA will still provide valid results, even when the assumption is violated, as is the case of the transformed RMSE glideslope data.

Homogeneity of covariance matrices. Homogeneity of covariance matrices was tested by submitting the transformed data to Box's M. Box's M produced significant results at $p = .003$ indicating that the covariance matrices are unequal. However, Box's M is highly susceptible to deviations from multivariate normality (Field et al., 2012). In any case, the Hotelling's Trace statistic is robust to violation of the assumption of homogeneity of variances when sample sizes are equal (Field et al., 2012; Howell, 2012).

MANOVA and follow-up results. Using Hotelling's Trace statistic, a significant effect of airspeed RMSE and glideslope RMSE was found for group (AOA versus No-AOA), $T = 0.275$, $F(2, 29) = 3.991$, $p = .029$, $\eta^2 = .216$. Univariate ANOVAs of the dependent measures also revealed an effect of group. Participants in the AOA group produced lower airspeed deviations than participants in the No-AOA group, $F(1, 30) = 7.930$, $p = .009$, $\eta^2 = .209$. In addition, participants in the AOA group produced less glideslope deviation than participants in the No-AOA group, $F(1, 30) = 4.228$, $p = .049$, $\eta^2 = .124$. The hypothesis that pilots flying with in-cockpit AOA indications are able to fly a more stable approach than pilots flying without AOA indications in the event of an airspeed indicator malfunction is supported.

Time until airspeed indicator malfunction was noticed. Participants were instructed to press a button on the yoke when they noticed any malfunction during the experimental trials. During the actual experiment, most of the participants who noticed a malfunction forgot to press the button and some of them, as discussed later, did not notice any malfunction even though the airspeed indicator was frozen at 70 kts. As such, this measure did not produce required data for analysis and the hypothesis that pilots flying with in-cockpit AOA indication are able to identify an airspeed indicator malfunction earlier than pilots flying without AOA information could not be tested. However, additional measures provided further insight into the effectiveness of AOA indications and will be discussed later in this chapter.

Correlation Between Flight Hours and the Dependent Variables

In the *Methods* chapter, it was noted that the difference in mean flight hours of participants in the two groups ($\overline{X}$ = 1114.69 hrs in the AOA group, $\overline{X}$ = 368.00 hrs in the No-AOA group) was relatively large. The correlation between flight hours and the dependent variables (airspeed RMSE and glideslope RMSE) was assessed to determine if the difference in flight hours biased the outcome of the experiment. A Mann-Whitney U test was performed on flight hours to determine if flight hours were significantly different between the two groups. The Mann-Whitney U statistic was not significant, supporting the null hypothesis that the distribution of flight hours is the same across both conditions (AOA versus No-AOA), p = .809. Furthermore, scatterplots of the data were generated to visually inspect the relationship of flight hours with the dependent variables airspeed (shown in Figure 21) and glideslope (shown in Figure 22) deviations.

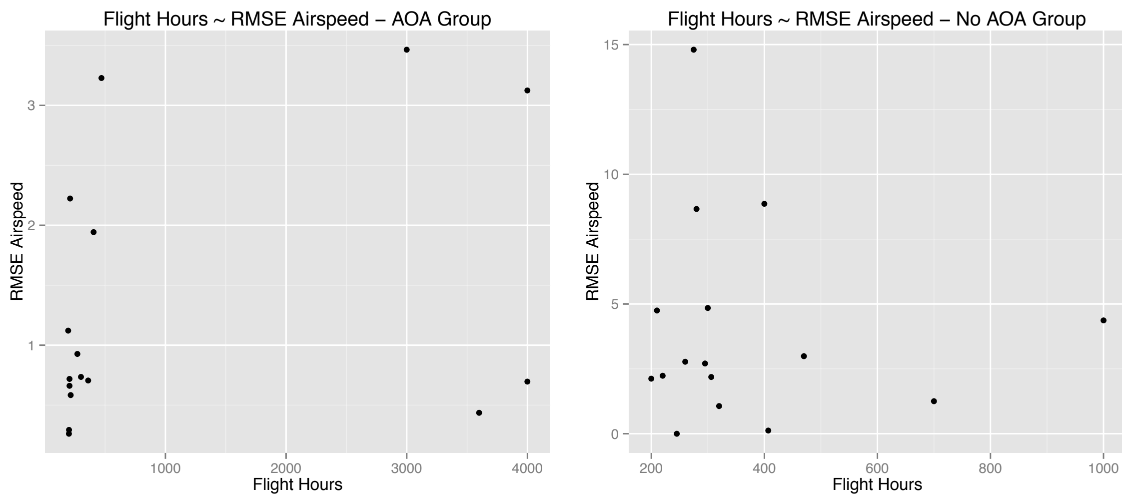

Figure 21. Scatterplots of flight hours plotted against RMSE airspeed for the AOA group (left) and the No-AOA group (right).

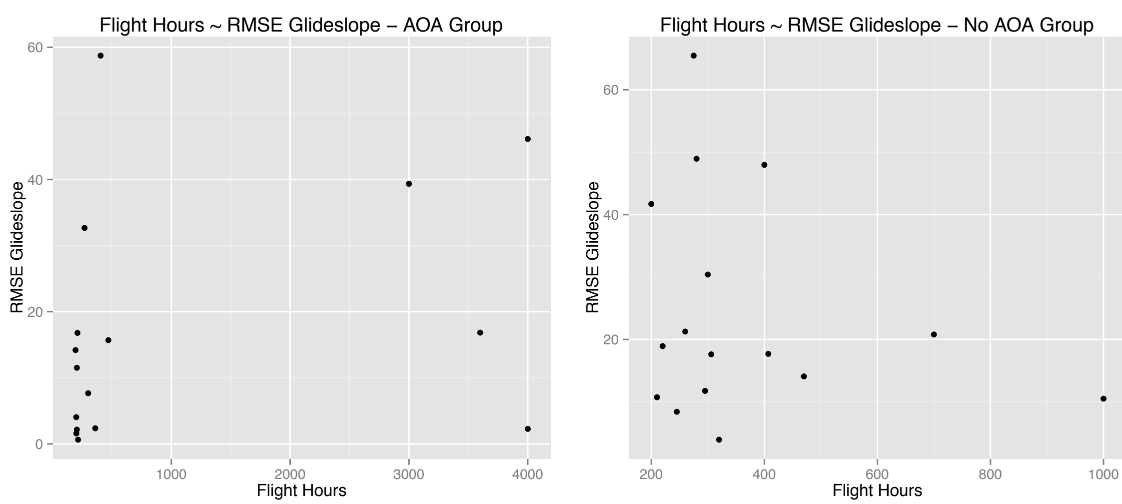

Figure 22. Scatterplots of flight hours plotted against RMSE glideslope for the AOA group (left) and the No-AOA group (right).

Both Figure 21 and Figure 22 suggest the absence of a relationship between flight hours and performance measures. In order to quantitatively evaluate the relationship, correlation coefficients were computed. Flight hours do not have a normal distribution and could not be normalized through transformation. Due to the non-normal distribution of one variable, the non-parametric Spearman correlation coefficient was computed. The coefficients and associated probability values are presented in Table 5 and indicate that none of the relationships are significant at $p < .05$.

Table 5

Spearman's Correlation Coefficient (r_s) for the Relationships between Participant Flight Hours and Performance Measures

Correlation of Flight Hours by	r_s	p
Airspeed RMSE (AOA group)	.384	.142
Airspeed RMSE (No-AOA group)	-.017	.928
Glideslope RMSE (AOA group)	.445	.084
Glideslope RMSE (No-AOA group)	-.179	.506

Note. The assumed null hypothesis is that there is no linear relationship.

Additional Measures

Stall warning horn activation during flight. The number of occasions on which participants let the aircraft come close to a stall after the airspeed indicator failed was examined. Data from the beginning to the end of data recording were examined for activation of the stall warning horn. Results indicate that, in the AOA group, only 2 out of 16 participants, or 12.5%, let the airspeed decline all the way to the activation of the stall warning horn. However, in the No-AOA group, 8 out of 16 participants, or 50%, let the airspeed decline to the point at which the stall warning horn was activated. In order to determine whether activation of the stall warning was contingent on the experimental condition that the participants were in, Pearson's Chi Square was calculated. The corresponding 2x2 contingency table can be found in Table 6.

Table 6

Contingency Table (Stall Warning Horn Activation in the AOA versus No-AOA Condition)

	Stall Warning		Total
Condition	*Yes*	*No*	
AOA	2 (5)	14 (11)	16
No-AOA	8 (5)	8 (11)	16
Total	10	22	32

Note. Expected frequencies if condition and stall warning horn activation were independent of each other are listed in parentheses.

The resulting χ^2_1 = 5.236 was statistically significant at *p* = .022. This indicates that stall warning horn activation and the condition that the participants were in (AOA versus No-AOA) were related. In this particular case, as noted above, in the No-AOA group more participants let the airspeed decline to the stall warning than in the AOA group. A more detailed analysis reveals that some of the participants let the airspeed decline on more than one occasion to a point at which the stall warning horn activated. Table 7 shows the number of distinct occasions on which the stall warning activated by participant and group.

Table 7

Number of Stall Warning Horn Activations by Participant

Condition	
AOA[a]	*No-AOA*[a]
-	-
2	1
-	2
-	-
-	-
-	1
-	-
1	-
-	4
-	1
-	-
-	-
-	-
-	4
-	1
-	3

Note. For ease of readability, a dash is displayed if there was no stall warning horn activation.

[a]$n = 16$.

Identification of the malfunction. Immediately after the experimental trial during which the airspeed indicator malfunction was induced, participants were asked if they had noticed any malfunction during the final approach. Fewer participants in the AOA group than in the No-AOA group identified the airspeed indicator malfunction correctly. In the AOA group, 10 out of 16, or 62.5%, of the participants identified the airspeed indicator malfunction. In the No-AOA group, 14 out of 16, or 87.5%, of the participants were aware that the airspeed indicator had malfunctioned. The data were plotted in a 2x2 contingency table and can be found in Table 8.

Table 8

Contingency Table (Correct Identification of the Malfunction in the AOA versus No-AOA Condition)

	Identified Malfunction		Total
Condition	*Yes*	*No*	
AOA	10 (12)	6 (4)	16
No-AOA	14 (12)	2 (4)	16
Total	24	8	32

Note. Expected frequencies if condition and correct identification of the malfunction were independent of each other are listed in parentheses.

Due to the fact that the expected frequencies of two cells in Table 8 had an expected count of less than five, Fisher's Exact Test was used instead of Pearson's Chi Square (Howell, 2008) to test the null hypothesis that the two variables are independent. Fisher's Exact Test was non-significant, $p = .22$ and it can be concluded that the condition that the participants were in (AOA versus No-AOA) was independent of whether they identified the malfunction correctly or not.

CHAPTER V

DISCUSSIONS, CONCLUSIONS, AND RECOMMENDATIONS

Overall, this experiment showed that pilots flying with in-cockpit AOA indication were able to fly a more stable final approach than pilots flying without in-cockpit AOA indication when confronted with an airspeed indicator malfunction. Furthermore, 8 out of 16 participants in the No-AOA condition allowed the aircraft to come too close to a stall during final approach, indicated by the activation of the aircraft's stall warning horn. This only happened to 2 out of 16 participants in the AOA condition, suggesting that participants in the AOA condition not only flew a more stable approach but also a safer approach than participants in the No-AOA condition. These findings support the effort of educating GA pilots about AOA and the push for installation of AOA devices in GA aircraft (e.g., FAA, 2012; GAJSC, 2012; Hirschman, 2012).

The results of the experiment further indicated that a device such as an AOA indicator may be useful after just a short training period, albeit the fact that the full potential might not have been understood by the pilots. The short training period, however, should not be understood as sufficient to train pilots on the usage of AOA indicators. The AOA indicator develops its full potential only after the concept is well understood and proficiency in using the indicator has been acquired. Therefore, it would be interesting to see what kind of results would be obtained if the study would be replicated using pilots who are already experienced with flying with an AOA indicator. It is assumed by the researcher that results would become stronger and more uniform in the AOA condition. Not all pilots in GA have experience with flying with AOA indications. While it could be argued that maybe military pilots who are experienced in flying with AOA indicators might be used for such a study, it is doubtful that the results could be generalized to the GA community due to the fact that military and GA pilots arguably present different populations.

Effect Sizes, Confidence Intervals, and Possible Confounds

The study produced relatively small effect sizes, indicating that there might have been other variables that influenced performance. In addition, confidence intervals for airspeed and glideslope deviations were relatively large. In general, it can be assumed that once research moves from basic to applied research, there will always be more confounding variables to deal with and effort must be taken to identify these. Possible confounds are now further discussed.

The experiment used flight simulation with a generic Cessna 172 cockpit layout and relatively primitive controls lacking feedback about the actual forces that would act on the control yoke during actual flight. In addition, trim for the aircraft had to be established using buttons on the yoke, as opposed to a control wheel in a real Cessna 172. It might have been that some participants were able to adjust to these conditions better than others. In addition, in recent years, more and more pilots are solely trained in technologically advanced cockpits, also referred to as glass-cockpits. Thus, when presented with standard instrumentation, the adaption time of those pilots may vary.

During the experiment and interviews with the pilots, it was observed that some of the pilots were able to adopt different strategies of controlling airspeed in the absence of airspeed information. Some of the pilots seemed to utilize visual pitch pictures, known power-settings, and vertical velocity indications. The varying headwind that was introduced in the experimental trials, albeit a much stronger headwind than used in the practice approaches, might not have been enough to render unusable certain “techniques” pilots use to control airspeed in the absence of airspeed information. Methods can be utilized in future research to minimize the use of these techniques. For example, the final approach segment could be flown without visual references in a setting that would require participants to fly a precision instrument approach, although this would limit the participants to instrument-rated pilots only. While this would reduce the possibility of using visual pitch pictures, pitch can nevertheless still be set on the attitude indicator. In addition, other instruments such as the vertical velocity indicator cannot be taken away from the instrumentation as the setting would progressively become more and more unrealistic.

The question is whether it is even desired to negate the effects of techniques used by certain pilots because the goal is to establish the usage of AOA indication as a secondary source to already tried and tested concepts such as pitch and power. The effects of already established techniques might vary from pilot to pilot but it will be difficult, if not impossible and undesired, to isolate these effects.

Motivational Effects

Motivation effects might have biased the outcome of the experiment. It was noticed that participants flying with an AOA indicator were visibly hyped about the fact that they got to experience a new instrument. AOA indicators are common for military aircraft, especially for fighter-type airplanes. Some participants remembered seeing AOA indicators used for aircraft carrier landings. It could be argued that this provided strong motivational effects and a “coolness” factor that increased overall performance for participants in the AOA group. Further experiments could introduce another instrument to the control group that provides the same motivational factors, although it might be hard to find such an instrument.

Misconceptions

Misconceptions about AOA were noticed in some participants while the training on the AOA indicator was given. Some pilots had previously heard about AOA indicators and were thinking that an AOA indicator would show indications about the glideslope. They thought for example that, if the downward pointing chevron illuminates on the AOA indicator, this would indicate that they are above the glideslope for final approach and had to descent. These misconceptions had to be eliminated during the training but might still have had some carryover effects to performance. This might contribute to the relatively large confidence interval evident in the RMSE glideslope data for the No-AOA group (see Figure 21).

Floor Effect

A floor effect in airspeed RMSE was due to the fact that the participants were given an airspeed range that could theoretically be flown without error. Interestingly, while not expected, one participant in the No-AOA condition was able to fly entirely within the desired airspeed range. This might have been purely due to luck or due to the fact that the participant was able to successfully employ one or more of the techniques described earlier in this chapter.

Theoretically, such a floor effect might have also been present in the glideslope data due to the nature of the PAPIs having an allowable range for a 3° glideslope indication. One way to avoid a floor effect for the glideslope measure would be to have participants conduct an approach with the usage of an instrument landing system which again would limit the participants to instrument-rated pilots only. The possible drawbacks of limiting the sample do not seem to outweigh the benefits of guaranteeing a measure without floor effects. This is especially true considering the fact that a floor effect in the glideslope measure seems to be possible but unlikely.

In the case of airspeed indications, there is no way to eliminate floor effects when using the relatively intuitive AOA indicator that was used in this experiment. The AOA indicator has an allowable range that maps to optimum AOA for an approach. This range will always translate to a range of airspeed and never to an exact airspeed value. The only way to counter this effect would be to use a different AOA indicator. It is questionable, though, whether one would want to sacrifice the intuitiveness of an AOA indicator for the sole reason of being able to collect better data. In addition, the fact that only one participant was able to fly the whole approach within the desired airspeed range, producing an airspeed deviation of exactly zero, leads to the conclusion that this effect might not have impacted the overall findings.

Stall Warning Findings

It is interesting in itself that only 12.5% of participants in the AOA group let the airspeed decline to a point at which the stall warning became active, whereas in the No-AOA group 50% of participants experienced a stall warning. This further strengthens the finding that an AOA indicator increases overall safety of flying by warning the pilot of a high AOA, which, if allowed to increase, could lead to a stall. Participants in the AOA condition most likely recognized the red downward pointing chevron and the need to decrease the AOA before allowing the AOA to increase to a point at which the aircraft would be getting too close to a stall. It can thus be argued that an AOA indicator can increase the safety buffer surrounding a stall threshold if its indications are acted upon.

Towards the Usage of AOA for GA

Experiments of this kind are beneficial not only as a scientific contribution but also by increasing overall awareness of a problem. Comments from participants such as that they learned a lot during the experiment and an overall resulting favorable attitude towards AOA indication indicate that they were eager to become more familiar with the overall concept of AOA instrumentation. "Getting the word out" to the pilots is the first step in making flying operations safer.

In terms of safety, the findings of this experiment speak for themselves. This research has established the AOA indicator as an instrument that can enhance aerodynamic awareness and act as a backup instrument in the case of an airspeed indicator malfunction. As such, displaying AOA to the pilot enhances safety in the absence of reliable airspeed information in the cockpit. Other possible benefits should be evaluated in future research in order to provide further scientific contributions to a topic that is deemed of utmost importance to flight safety (e.g., FAA, 2012; GAJSC, 2012).

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APPENDIX A

Permission to Conduct Research

Embry-Riddle Aeronautical University

Application for IRB Approval

Determination Form

13-142

Principle Investigator: Dr. Kelly Neville
Other Investigators: Claas Tido Boesser

Project Title: ***The Effects of Angle of Attack Indication on Maintaining System Resilience in the Event of an Airspeed Indicator Malfunction***

Submission Date: December 10, 2012

Determination Date: December 21, 2012

Review Board Use Only

Initial Reviewer: Teri Vigneau/Bert Boquet

Exempt: X Yes __ No

Approved: X Yes ___ No

Comments: The purpose of this research experiment is to evaluate a pilot's ability to maintain or regain aircraft control with the usage of an angle of attack (AOA) indicator in case of an airspeed indicator malfunction while flying a final approach. Participants will be required to fly final approaches in a flight simulator. Since this experiment takes place in a flight simulator, there will be no risks to participants and so this may be determined to be **exempt.** [Teri Vigneau 12-10-12]

This protocol is **exempt**. [Bert Boquet 12-10-12]

APPENDIX B

Informed Consent Form

The effects of angle-of-attack indication on maintaining system resilience when confronted with an aircraft malfunction

conducted by Claas-Tido Boesser
Advisor: Dr. Neville
College of Arts & Sciences
Human Factors Department
600 South Clyde Morris Blvd., Daytona Beach, FL, 32114

The experiment you are about to participate in is concerned with examining possible advantageous effects of in-cockpit angle-of-attack (AOA) indications during flight. Specifically, the purpose is to evaluate the importance of providing pilots with feedback about fundamental aircraft aerodynamics during emergency situations and unexpected disturbances. The outcome of this study might help improve flight safety by providing insight into the effectiveness of AOA indicators.

The study consists of six practice approaches flown to Daytona Beach International Airport, followed by experimental trial approaches. During the experimental trial approaches you will be confronted with a possible malfunction. Depending on the group you are in (non-AOA/AOA), all approaches will be performed with or without in-cockpit AOA indication.

The whole experiment will take no longer than one and a half hours and there are no known risks with this experiment. You will be compensated for this experiment with $20. You may terminate your participation at any time and will be paid for the time you have already completed. Your assistance will help us understand the effectiveness of in-cockpit AOA indication.

We will keep your personal records private and confidential. Any information collected during this session will only be used for scientific purposes. We may publish the results of this study. If we do, we will not include your name. We will not publish anything that would let people know who you are or how you are connected to this study.

Thank you for your participation. If you have any questions, please ask during the experiment or contact me at (940)-337-6455. If you have any questions or complaints that you might not want to address directly with me, you can contact my advisor at (386)-226-4922.

Statement of consent

I acknowledge that my participation in this experiment is entirely voluntary and that I am free to withdraw at any time. I have been informed as to the general scientific purposes of the experiment and that I will receive a remuneration fee of $20 upon completion of the study.

Participant’s name (please print): __________________

Signature of participant: __________________ Date: _________

Experimenter: __________________ Date: _________

APPENDIX C

Demographics Form

Thank you for your participation in this experiment. This form asks you about general demographic information and your piloting experience. We will use this information mainly to determine possible relationships between flight experience and experimental results.

Please provide the following information

1. Your age:

2. Circle the certificate(s) you are holding:

   Private

   Commercial

   Airline Transport Pilot

   Flight Instructor

3. Are you instrument-rated?

   Yes No

4. Approximate total number of flight hours:

5. Of the total flight hours, approximately how many hours were flown in technologically advanced aircraft, i.e. “glass-cockpit”?

APPENDIX D

Feedback for Participants of Angle-of-Attack Research

Human Factors Department
Embry-Riddle Aeronautical University

First of all, thank you for your participation in this experiment. The data recorded during this experiment will be of great value not only for my research but also for aviation safety. The experiment you have just completed will give more insight into possible advantageous effects of angle-of-attack (AOA) instrumentation. If you were part of the control group and did not get the opportunity to fly with an AOA indexer, please be assured that the data collected from your participation is of utmost importance in order to be able to make reasonable conclusions about differences between flying with or without AOA instrumentation.

Effectiveness of in-cockpit AOA indication is assessed in this research by posing three distinct questions. First, will pilots flying a final approach with in-cockpit AOA indications notice a frozen airspeed indication earlier than pilots flying without AOA indication? Second, will pilots flying with in-cockpit AOA indication be able to fly an overall more stable approach than pilots without in-cockpit AOA indication after being confronted with an airspeed indicator malfunction? And finally, if there is a degradation of aircraft control due to airspeed indicator malfunction, will pilots with in-cockpit AOA indication be able to recover from such degradation quicker than pilots flying without in-cockpit AOA indication. Together, these three questions aim at providing a starting point for quantitative AOA effectiveness research.

The Federal Aviation Administration underlines the importance of AOA and stall awareness and has just recently (August 2012) published Advisory Circular #120-109 (Stall and Stick Pusher Training) in the wake of related accidents. In addition, at the beginning of 2012, the FAA has declared the installation of certain AOA systems in GA aircraft as *minor alterations* requiring only a logbook entry instead of a full-up Form 337 installation approval process, thus facilitating the installation of such systems. The industry and experts agree that AOA information can be very beneficial to flight safety but there aren't any studies that exclusively employ quantitative measures like the current experiment does. You have been an essential part of helping to fill this gap. We might see more AOA indicators in modern cockpits, maybe some retrofitting of existing airplanes and maybe you even find yourself flying with an AOA indicator soon.

Allow me to ask you for one final favor:

Because this experiment is built around the airspeed indicator malfunction, it will be of utmost importance that you do not talk to your friends or colleagues about the exact activities of the experiment, especially not about the malfunction being an airspeed indicator malfunction, otherwise the results of this experiment will end up being distorted. Please be considerate and help me conduct research that can be beneficial to aviation safety in the future.

Should you wish to learn more about this research or have any other questions about the topic, please feel free to contact me at any time at boesserc@my.erau.edu. Thank you again for your participation.

APPENDIX E

Experiment Script

Before participant arrives:

- Load correct plane for condition
- Check joystick in XPlane / set throttle idle
- Check button mapping to 0
- Set weather: 10 kts headwind (lo-stratus 8000-8SM vis)
- Clear all malfunctions
- Press “s” and “key up” to setup view
- Release brakes
- Setup new folder with participant number and setup first approach

When participant arrives:

- Welcome participant
- Participant reads and signs informed consent
- Participant receives $20 and signs Participant Verification Form
- Participant fills out demographic worksheet

- “Thank you, this is a script I read to every participant”

- “The experiment you are about to participate in is concerned with examining possible advantageous effects of in-cockpit angle-of-attack (AOA) indications during flight.”

- “The study consists of six practice approaches flown to Daytona Beach International Airport, followed by experimental trial approaches. During the experimental trial approaches you will be confronted with a possible malfunction. Depending on the group you are in (non-AOA/AOA), all approaches will be performed with or without in-cockpit AOA indication.”

- “You will conduct 3 practice trials to familiarize yourself with the AOA indicator, followed by 3 practice trials to fly stabilized approaches”

- "Following the practice trials, you will fly experimental trials with different headwind settings and a encounter a possible malfunction"

- "The simulation starts with the aircraft located on a 3NM final Runway 34 at Daytona Beach, on glideslope, about 90 knots, 10 knots headwind"

- "Your task is as follows in order:
    - Maintain a 3 degree glideslope using the PAPIs and directional alignment with the centerline
    - Slowdown to 60-65 knots as quickly as possible for a no-flap straight-in
    - Fly a stabilized approach with a 3 degree glideslope and at 60-65 knots
    - If malfunction is encountered, continue to fly approach as stable as possible
    - The simulator will freeze before touchdown

- Explain the following
    - Brake light normal
    - Stall warning
    - Explain controls and Trim
    - Explain throttle movement at beginning of simulation

- Introduce procedure when resetting computer

- Show AOA presentation

- Any questions?

Practice Trials

- Setup for 6 trials combined
- After each, check throttle idle

Experimental Trials

- Inform participant about wind conditions
- Inform participant about possible malfunction and which button to press
- Inform participant not to break off approach "continue to fly as smooth as possible"
- First trial, set headwind to 30 knots
- **Hack clock**

- Third trial, choose Approach with ASI Failure and set headwind to 25 knots

After the experiment

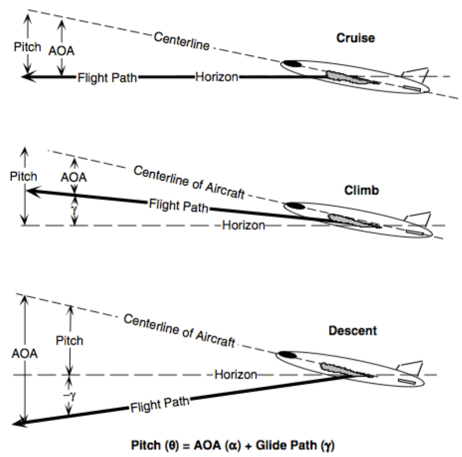
- Handout post-flight questionnaire

- Handout debriefing form

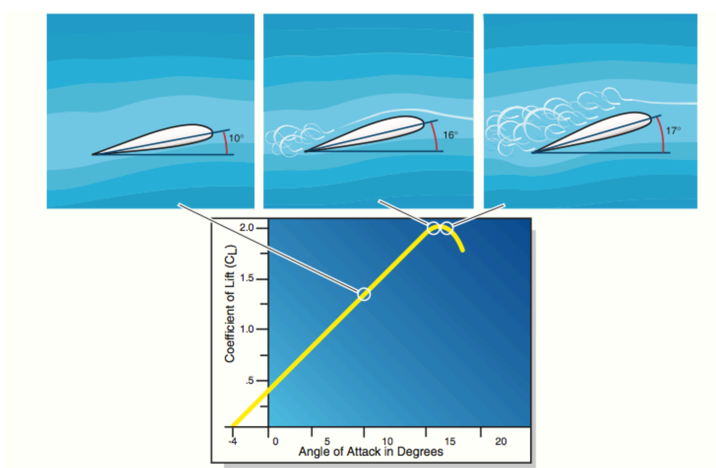
- Save participant data to USB stick and Laptop
- Write participant number on all sheets

APPENDIX F

PowerPoint Slides Used for Training Participants on Angle-of-Attack



Slide 1. Illustrating relationships between AOA, centerline of the aircraft, and actual flight path. Adapted from "*A Search for Meaning: A Case Study of the Approach-to-Landing*" by Flach et al., 2003.



Slide 2. Critical angle of attack and stall. Adapted from "*The Airplane Flying Handbook*" by the Federal Aviation Administration, 2004, p. 4-3.

Slide 3. Different possible indications of the AOA indicator. Screenshots taken from *X-Plane* by Laminar Research.

Appendix G

Excerpt from Excel Data Generated by the Plugin for X-Plane

1	Time (s)	Altitude MSl	Groundspee	IAS (kts)	Wind Speed	Wind Dir (de	Distance to	Vertical Glid	Horizontal D	Total Deviat	AC Slope (de	SE	Throttle Rat	ASI Failed	User Button	Stall Warning
445	109.667236	674.042966	40.554996	69.687668	15.433334	335.289337	11593.7104	26.202293	118.854315	121.708292	3.166674	11.032148	0.127	1	0	0
446	109.886963	673.100162	40.536903	69.65023	15.433334	335.289337	11579.9159	25.997461	118.717034	121.530248	3.165817	11.024076	0.127	1	0	0
447	110.089355	672.121637	40.494289	69.590294	15.433334	335.289337	11564.9719	25.818553	118.550554	121.329438	3.1651	11.014964	0.127	1	0	0
448	110.306885	671.245569	40.42968	69.530304	15.433334	335.289337	11550.1504	25.735438	118.399555	121.164222	3.164852	11.007462	0.127	1	0	0
449	110.527344	670.526215	40.356621	69.470261	15.433334	335.289337	11536.4047	25.751854	118.20693	120.979494	3.165085	10.999068	0.127	1	0	0
450	110.72998	669.829346	40.265663	69.389488	15.433334	335.289368	11521.3453	25.861285	117.959	120.760638	3.165795	10.989115	0.127	1	0	0
451	110.947754	669.236699	40.167332	69.299225	15.433334	335.289368	11506.8002	26.04741	117.72117	120.568413	3.166881	10.980365	0.127	1	0	0
452	111.160645	668.714413	40.057865	69.195648	15.433334	335.289368	11492.1358	26.310416	117.459923	120.370557	3.168353	10.971352	0.127	1	0	0
453	111.379639	668.260006	39.936916	69.080589	15.433334	335.289368	11477.3167	26.64975	117.171668	120.16409	3.170211	10.961938	0.127	1	0	0
454	111.598389	667.886142	39.80962	68.967232	15.433334	335.289368	11462.7828	27.054724	116.838308	119.929764	3.172398	10.951245	0.127	1	0	0
455	111.814209	667.586849	39.693817	68.874512	15.433333	335.289398	11449.3751	27.473761	116.550215	119.744561	3.174647	10.942786	0.127	1	0	0
456	112.014648	667.289719	39.587193	68.779785	15.433333	335.289398	11436.0587	27.890205	116.242124	119.541186	3.176887	10.933489	0.127	1	0	0
457	112.215576	666.939806	39.480701	68.675423	15.433333	335.289398	11421.6626	28.311715	115.909264	119.316847	3.179171	10.923225	0.127	1	0	0
458	112.427734	666.582111	39.388771	68.582314	15.433333	335.289398	11408.343	28.668116	115.543338	119.046727	3.181122	10.910854	0.127	1	0	0
459	112.631104	666.194849	39.302387	68.492889	15.433334	335.289398	11395.1203	28.989831	115.176812	118.769135	3.182901	10.898125	0.127	1	0	0
460	112.83252	665.768911	39.219341	68.409065	15.433333	335.289398	11381.6373	29.287022	114.7712	118.448966	3.184565	10.883426	0.127	1	0	0
461	113.033936	665.280218	39.137276	68.325142	15.433333	335.289429	11367.3133	29.566357	114.366977	118.126944	3.186155	10.868622	0.127	1	0	0
462	113.247803	664.752736	39.0625	68.248756	15.433334	335.289429	11353.0045	29.806352	113.918713	117.753522	3.187551	10.851429	0.127	1	0	0
463	113.469482	664.173375	38.994205	68.179932	15.433333	335.289429	11338.4898	30.005407	113.482876	117.382653	3.188746	10.834328	0.127	1	0	0
464	113.687744	663.563075	38.934868	68.116783	15.433333	335.289429	11324.2819	30.157622	112.975464	116.931335	3.189704	10.813479	0.127	1	0	0
465	113.901123	662.913114	38.883068	68.061241	15.433334	335.289429	11310.1677	30.265205	112.460905	116.46217	3.190439	10.791764	0.127	1	0	0
466	114.119873	662.266728	38.841633	68.019073	15.433333	335.289459	11297.0091	30.32516	111.972829	116.006596	3.190921	10.770636	0.127	1	0	0
467	114.321777	661.583786	38.806984	67.980721	15.433334	335.289459	11283.9202	30.344718	111.491724	115.547418	3.191198	10.749298	0.127	1	0	0
468	114.522461	660.798411	38.776947	67.946182	15.433334	335.289459	11269.7275	30.321374	110.935902	115.00505	3.191275	10.724041	0.127	1	0	0
469	114.739502	659.954633	38.754662	67.919304	15.433334	335.289459	11255.3802	30.24773	110.391932	114.460918	3.191098	10.698641	0.127	1	0	0
470	114.956055	659.073402	38.739925	67.902023	15.433334	335.28949	11241.2108	30.127313	109.827112	113.88437	3.190681	10.671662	0.127	1	0	0
471	115.174072	658.139482	38.731441	67.886658	15.433334	335.28949	11226.9372	29.959829	109.250026	113.28353	3.190024	10.643474	0.119	1	0	0
472	115.395264	657.16073	38.726761	67.873207	15.433333	335.28949	11212.6084	29.750465	108.675406	112.674017	3.189153	10.614802	0.147	1	0	0
473	115.611328	656.170006	38.724834	67.867447	15.433333	335.28949	11198.5086	29.516837	108.100849	112.058184	3.188154	10.585754	0.147	1	0	0
474	115.828125	655.163161	38.726418	67.865524	15.433334	335.28949	11184.4729	29.263756	107.515778	111.427145	3.187052	10.555906	0.147	1	0	0
475	116.042236	654.139119	38.732273	67.871284	15.433334	335.28952	11170.5109	28.989221	106.973636	110.831999	3.185836	10.527678	0.147	1	0	0