

Pilot Designed Aircraft Displays in General Aviation:

An Exploratory Study and Analysis

by

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A Thesis Presented in Partial Fulfillment  
of the Requirements for the Degree  
Master of Science

Approved April 2016 by the  
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ARIZONA STATE UNIVERSITY

May 2016

## ABSTRACT

From 2001-2011, the General Aviation (GA) fatal accident rate remained unchanged (Duquette & Dorr, 2014) with an overall stagnant accident rate between 2004 and 2013. The leading cause, loss of control in flight (NTSB, 2015b & 2015c) due to pilot inability to recognize approach to stall/spin conditions (NTSB, 2015b & 2016b). In 2013, there were 1,224 GA accidents in the U.S., accounting for 94% of all U.S. aviation accidents and 90% of all U.S. aviation fatalities that year (NTSB, 2015c). Aviation entails multiple challenges for pilots related to task management, procedural errors, perceptual distortions, and cognitive discrepancies. While machine errors in airplanes have continued to decrease over the years, human error still has not (NTSB, 2013).

A preliminary analysis of a PC-based, Garmin G1000 flight deck was conducted with 3 professional pilots. Analyses revealed increased task load, opportunities for distraction, confusing perceptual cues, and hindered cognitive performance. Complex usage problems were deeply ingrained in the functionality of the system, forcing pilots to use fallible work arounds, add unnecessary steps, and memorize knob turns or button pushes.

Modern computing now has the potential to free GA cockpit designs from knobs, soft keys, or limited display options. Dynamic digital displays might include changes in instrumentation or menu structuring depending on the phase of flight. Airspeed indicators could increase in size to become more salient during landing, simultaneously highlighting pitch angle on Attitude Indicators and automatically decluttering unnecessary information for landing. Likewise, Angle-of-Attack indicators demonstrate a great safety and performance advantage for pilots (Duquette & Dorr, 2014; NTSB, 2015b & 2016b), an

instrument typically found in military platforms and now the Icon A5, light-sport aircraft (Icon, 2016).

How does the design of pilots' environment—the cockpit—further influence their efficiency and effectiveness? To explore the possibilities for small aircraft displays, a participatory design investigation was conducted with 9 qualified instrument pilots. Aviators designed mock cockpits on a PC using pictorial cutouts of analog (e.g., mechanical dials) and digital (e.g., dynamic displays) controls. Data was analyzed qualitatively and compared to similar work. Finally, a template for GA displays was developed based on pilot input.

## Dedication

I would like to recognize my family, for their undying love and support in pursuit of all that I have accomplished. From becoming a Captain in the U.S. Marine Corps, to seeking this degree and a new career in aviation through post-service education. I am proud to be the first in my family to receive a graduate degree.

*“Aviation in itself is not inherently dangerous.*

*But to an even greater degree than the sea,*

*it is terribly unforgiving of any carelessness, incapacity or neglect.”*

— Captain A. G. Lamplugh

*“When once you have tasted flight,*

*you will forever walk the earth with your eyes turned skyward,*

*for there you have been,*

*and there you will always long to return.”*

— attributed to Leonard DiVinci

## ACKNOWLEDGMENTS

I would like to recognize my academic advisors, Robert Gray, Russell Branaghan, and Randy Gibb for their professionalism, expertise and patience in my relentless pursuit of more. I could not have done this without your help.

To the staff of the Pat Tillman Center at Arizona State University, Steve Borden, Christian Rauschenbach, and Joanna Sweatt, for making life as a student veteran enjoyable and connected.

To my classmates, for the thoughtful, enlightening discussions, making class fun and interesting.

To my friend, fellow pilot, and former U.S. Army Warrant Officer, John Yaşar for his tireless assistance in developing my data collection method.

To the rest of my veteran peers, thank you for reminding me every day “the Captain” is in the office.

Finally, to my Marine Corps instructors, seniors, peers and Marines. Thank you for your example, inspiration, and leading me to always seek excellence. Semper fidelis.

## TABLE OF CONTENTS

	Page
LIST OF TABLES.....	ix
LIST OF FIGURES.....	x
INTRODUCTION.....	1
Purpose Of The Research.....	3
REVIEW OF THE LITERATURE.....	3
Dangers Of General Aviation.....	3
Experience And Frequency Of Flying.....	4
Complexities In The Cockpit.....	5
Information Overload.....	8
HUMAN-COMPUTER INTERACTION (HCI) ISSUES.....	9
Pilot Study.....	9
Design.....	11
Situation Awareness.....	12
Participatory Design.....	14
Information Access.....	14
METHOD.....	17
Participants.....	17
Design.....	18
Materials.....	18
Aircraft Design Board.....	18

	Page
Phase of Flight (IV) .....	18
Information Item (DV) .....	19
Origin Distance (DV).....	19
Clock Angle (DV) .....	19
Item Area (DV) .....	19
Location Justification (DV) .....	19
Visual Angle (DV).....	20
Pre-Test & Questions.....	20
Procedure.....	20
Pilot Testing.....	21
Data Analysis.....	21
Measurements.....	21
Origin Distance (Image Center And Distance).....	21
Clock Angle.....	22
Location Code.....	22
Visual Angle.....	22
RESULTS.....	22
Participant Sample.....	22
Statistics.....	23
Data.....	23
Items Removed.....	23

	Page
Information Categories.....	24
Origin Distance.....	24
Clustering.....	24
Phase Of Flight Consistencies.....	24
Phase Of Flight Inconsistencies.....	24
Clock Angle.....	25
Phase Changes.....	25
Item Area.....	26
Location Justifications.....	26
Visual Angle.....	27
Expert And Novice Differences.....	27
DISCUSSION.....	27
Method.....	27
Results.....	28
Origin Distance.....	28
Clock Angle.....	29
Experience Comparisons.....	29
Location Justifications.....	31
Visual Angle.....	32
Strengths Of The Research.....	32
Limitations Of The Research.....	32

	Page
Future Research.....	33
REFERENCES.....	60
APPENDIX	
A PRE-TEST QUESTIONS.....	66
B ORIGIN DISTANCE (IMAGE CENTER AND DISTNACE)	
CALCULATIONS.....	70
C CUSTOM ITEMS REMOVED.....	72
D CRITICAL NAVIGATION ITEMS REMOVED AND ANALYZED	
SEPARATELY.....	75
E INFORMATION CATEGORIES.....	77
F PHASE OF FLIGHT INCONSISTENCIES.....	81
G ITEMS REMOVED FOR EXPERT-NOVICE COMPARISONS.....	83
H VISUAL ANGLE CONVERSION.....	85
I NOTIFCATION OF IRB APPROVAL FOR RESEARCH USING HUMAN	
SUBJECTS.....	87

## LIST OF TABLES

Table	Page
1. Takeoff And Landing Accident Data With All Phases.....	35
2. Takeoff And Landing Accident Data.....	35
3. GA Accident Data For 2013.....	36
4. Mean Origin Distance Between All Phases And All Participants.....	37
5. Mean Origin Distance For All Participants And All Phases Of Flight.....	38
6. Mean Origin Distance For All Participants By Phase Of Flight.....	39
7. Mean Clock Angle For All Phases Of Flight.....	30
8. Mean Clock Angle By Phase Of Flight For All Participants.....	41
9. Item Area For Taxi Phase.....	42
10. Item Area For Takeoff Phase.....	42
11. Item Area For Enroute Phase.....	43
12. Item Area For Descent Phase.....	43
13. Item Area For Landing Phase.....	44
14. Mean Origin Distance For Expert Participants By Phase.....	45
15. Mean Origin Distance For Novice Participants By Phase.....	46
16. A Table From Priorities, Organization, And Sources Of Information Accessed By Pilots In Various Phases Of Flight (Schvaneveldt, Beringer, Lamonica, Tucker & Nance, 2000).....	47

## LIST OF FIGURES

Figure	Page
1. A Photo Of The Major Phases Of Flight.....	48
2. The Garmin G1000 Flight Deck In A Cessna 172SP.....	48
3. An Analog Cockpit From A Cessna 172.....	49
4. Work Activity Affinity Diagram For Synthesis Of Contextual Inquiry Data.....	50
5. NTSB Animation, Display Mode Causing Inter Air.....	51
6. The NTSB Accident Animation, Flight Path Angle Vs Vertical Speed Mode.....	52
7. Angle-Of-Attack (AOA) Indicator.....	53
8. A demonstration of AOA, relative to aircraft attitude.....	54
9. An Example PowerPoint Slide, Showing Options Of RPM Options.....	54
10. Axure Dynamic Panel Using A Cessna Cockpit.....	55
11. Axure Dynamic Panel, The 36"x12" Background .....	55
12. Clock Tool.....	56
13. Calculations Image.....	56
14. A Clock Image Representing Quadrants Used To Cluster Items.....	57
15. Taxi Phase Template.....	57
16. Takeoff Phase Template .....	58
17. Enroute Phase Template .....	58
18. Descent Phase Template .....	59
<b>19. Landing Phase Template .....</b>	<b>59</b>

## Introduction

Over the last 100 years, advances in human factors research and aerospace engineering have transformed aviation in ways never before imagined, with early cockpits relying on simple mechanical linkages to controls and only basic instruments for engine operation (Andyboy, 2012). As needs of the military, general and commercial aviation grew, so did the complexity of the cockpits by adding dials, switches, controls, systems monitoring equipment, and more. Increasing complexity in recent years has contributed to aviation deaths in commercial and General Aviation (GA), the two most common forms (AOPA, 2015). GA being all civilian flying except scheduled passenger airlines (AOPA, 2015), while commercial is for hire to transport people or cargo (“Commercial Aviation”, 2015). In August 2006, ComAir Flight 5191 crashed on takeoff, killing 49 and severely injuring the First Officer (FO) aboard the CRJ-100. The National Transportation Safety Board (NTSB) determined the probable cause was due to flight crew failure to use cockpit cues which identified aircraft location and runway direction. The crew also violated the sterile cockpit rule (i.e., conversing about anything other than the flight), further drawing their attention from the available cues (NTSB, 2007). Alternatively, in June 2013, the commercial air carrier pilot flying Asiana Flight 214 descend too low during landing from being “stressed and nervous” (“Asiana Airlines”, 2013). A fatal mistake for 3 passengers and 150 injured, which was attributed to unfamiliarity, complexity and lack of experience with manual flying of the Boeing 777 (NTSB, 2014a).

Despite these tragedies, commercial accident rates are considerably low due to training standards, general experience, frequency of flying (King, 2015) and automation,

to name a few mitigating factors. These aspects naturally keep U.S. air carrier and commuter accident rates down – 5.7% of all accidents in 2013 to be exact. GA pilots have not been so lucky, as they were involved in over 94% of accidents in 2013 (NTSB, 2015c),

In April of 2013, the pilot flying (PF) a small, high-wing aircraft in St. Lucie, FL, lost attention of airspeed, exceeded the wing critical angle-of-attack (AOA) (i.e., the point at which an airfoil loses aerodynamic lift) and stalled on the final turn to landing, resulting in the pilots' death (NTSB, 2015d). In August 2013, near East Haven, CT, during a circling approach in a twin turboprop Rockwell International 690B, the PF attempted a 45-degree bank turn to final with a gusty tailwind in the clouds. Loss of airspeed and exceeding critical AOA caused the aircraft to crash into a house, killing the pilot, passenger, and two children inside the home (NTSB, 2014c).

From 2008 to 2014, fatal events such as these accounted for 47% of all GA airplane crashes in the U.S., totaling 1,210 accidents. So, why are there so many more accidents in GA airplanes? Especially now that digital displays, controlled by computer-based avionics – referred to as Technically Advanced Aircraft (TAA) – are common in light fixed wing airplanes. Should not more technology make flying safer? Not necessarily. On March 1, 2016 in Abilene, TX, an experimental Vans RV-6 – TAA utilizing a Dynon Avionics flight deck – was witnessed entering a nose-high attitude just after takeoff, resulting in a spin and crash killing the pilot and passenger (NTSB, 2016a).

## **Purpose of the research**

This study was conducted to inspire a redesign of TAA systems for small aircraft pilots whom fly infrequently, are typically inexperienced, and are subject to the same environmental and socio-technical systems as their professional counterparts. This population is disadvantaged. For these individuals, the knowledge required to safely operate is the same as any other pilot. However, the nature of GA flying is a personally expensive pursuit, currency requirements are time consuming and it is largely a recreational activity, typically subsumed by some other career.

Ideally, this would be the first of many studies striving to achieve the ideal piloting experience in small piston airplanes. In many ways, this research parallels aspects of Schvaneveldt, Beringer, Lamonica, Tucker, & Nance's (2000) investigation of the information priorities of flight, but from a design and layout perspective. In addition to exploring what information was most important for each phase of flight, where items should be placed was discovered (i.e., location), how they should be placed (i.e., size, orientation, or clustering), how they should be emphasized (i.e., size, location and angle), why they should be placed in a specific location (i.e., importance, frequency of use, etc.), and when they should be used (i.e., phase of flight).

## **Review Of The Literature**

### **Dangers of General Aviation**

To begin, the different phases of flight need to be separately considered (Figure 1). For all types of flying, landing presents the highest risk, followed by takeoff. (NTSB, 2015c). There are many factors associated with takeoff and landing performance which

increase the level of danger: proximity to the ground, increased frequency of maneuvering, slower speed and air traffic density (Cox, 2013 & NTSB, 2015b), all of which result in reduced recovery time and a much smaller margin of error. Combined with elaborate, technology compensating procedures, poor weather, and inexperience, one can begin to understand why so many aircraft crash near airports compared to transitional phases.

An NTSB (2015a) query of GA flights since 1982, in single and twin-engine, piston airplanes, produced 14,380 fatal and non-fatal accidents or incidents (Table 1). Takeoff and landing data accounted for more than half (53.5%) of all thirteen categories of flight phase, and of those two phases, 19.9% (Table 2) occurred during the takeoff phase and 33.5% during landing.

### **Experience and frequency of flying**

There is a large difference in accident rates between commercial pilots whose skills are regularly tested by training requirements and GA pilots (King, 2015 & Wiegmann et al., 2005) who only fly often enough to maintain their 90-day currency and avoid paying an instructor. The difference is 7 times lower (Hopkins, 1994). Infrequent flying is destructive to awareness of positive aircraft control and decision making, as skill-based errors are involved in over 80% of all GA accidents (Wiegmann et al., 2005). While most physical flying skills remain intact between long breaks in flying, cognitive expertise inevitably suffers. Often it is due to technological dependence and when combined with infrequent flying, produces more serious problems (Casner, Geven, Recker & Schooler, 2014). An NTSB (2010) study highlighted the digital dependency

problem by finding that total accident rates decreased with the introduction of glass cockpits, but fatal accidents rates actually increased. This was due to a false sense of security. Pilots were willing to fly longer flights and accept riskier conditions than they would have otherwise considered in an analog airplane as the only pilot flying (NTSB, 2010). Five years earlier, Wiegmann et al., (2005) found that weather assessment (e.g., VFR into IMC) held a 28% involvement in accident causation, further supporting the improved decision making training need.

Decision-making quality combined with aircraft control safety training must be emphasized – through realistic training scenarios – when introducing any new technology into aircraft because GA pilots are involved in more accidents than airline pilots (King, 2015) and they generally make more takeoffs and landings, which are high-risk maneuvers (Hackworth et al., 2007). Even though analog pilots are more likely to fly shorter flights – implying more takeoffs and landings – pilots in glass cockpits have shown to lose control of their aircraft more often (NTSB, 2010). Along with stagnant fatality and accident rates, it is no wonder, how in 2013, 90% of all U.S. civil aviation (i.e., all non-military aviation) fatalities occurred during GA flights (Table 3).

### **Complexities in the cockpit**

As aircraft have been updated with more powerful computing, electronic fly-by-wire controls and digitally monitored systems, it was assumed that pilots could easily transition from older style, analog cockpits, to modern day control panels. Despite this common belief, Hamblin, Gilmore, and Chaparro (2006) discovered that pilots require completely new skill sets to safely operate in TAA due to the unforeseen complexities.

Not only do student pilots need training on new systems, they want more training in TAA (McCracken, 2011). Casner et al. (2006) also found that regular flying or teaching and biannual flight reviews were not enough to keep pilot knowledge fresh. It affects que recognition, slows working memory, and long term memory retrieval is dramatically impacted. Automaticity that would otherwise develop through regular practice is limited.

TAA complexity is demonstrating itself to be too great for the operational environment and pilot pool which it has been employed. As a result, pilot mental models and schemas are less accurate (Baxter, Besnard & Riley, 2007) – another finding of the contextual inquiry (e.g., multi-function display buttons have no perceived purpose) – and it causes distractions (Williams, Yost, Holland & Tyler, 2002) from aviating. System knowledge is not the only competency lacking, as NTSB has cited an aeronautical knowledge deficiency as the cause of many accidents (King, 2015). In addition to systems training and aeronautical understanding, GA pilots should be required recurrent training in effective decision making, since it is the cause of half of all accidents (Wiegmann et al., 2005). Aviation knowledge demonstrated only during (practical) exams holds little weight if applied carelessly after licensure. Students should also be subject to a higher testing standard of rote knowledge retention and flying skills. This could be accomplished in a similar manner to type rating qualifications, as a separate examination

Perceptions of glass cockpits are also a problem. At Purdue University, transition to digital airplanes had a negative impact on student check ride scores, citing they felt phase checks were difficult in the G1000 (McCracken, 2011). Surprisingly, it is also

believed by pilots that the G1000 enhances SA and makes flying easier for new pilots, when in fact it does not (Wright & O'Hare, 2014). This is due to the overabundance of available information naturally seizing novice attention, which is not easily accessed by unfamiliar users and the level of displayed, visually capturing, precision (e.g., altitude or airspeed). New pilots get 'sucked into' the system by visual clutter and the overly accurate representations (e.g., single digit speed versus 5 knot increment tick marks) entice newer pilots to seek an exact elevation or velocity, causing fixation and repetitive overcorrections – two discoveries of the contextual inquiry. Wright & O'Hare (2014) also confirmed it takes longer for new pilots to recover from unusual attitudes and it is harder to maintain precise aircraft control in the G1000, when compared to traditional analog cockpits. Extended recovery time and lack of aircraft control were supported by Wiegmann et al. (2005) as two defining events which have contributed to high GA accident rates. While features such as auto-pilot have been used for many years to reduce pilot fatigue (Amalberti, 1999), adding as many attributes as possible does not necessarily mean safer flying will occur.

In a cross-domain comparison supporting the need for information related fatigue reduction, endoscopic surgeons experience greater cognitive load from continuous visual scanning between monitors and the surgery location (DeLucia and Betts, 2008). This implicates a contradiction with the G1000 design and layout, as it presents hundreds of information points with up to 124 functions (Hamblin, Gilmore, & Chaparro, 2006) on two 10.4" (Garmin, 2003) digital screens, while analog cockpits only display about 35 information points (Hamblin, Gilmore, & Chaparro, 2006). To make matters more fatigue

laden, GA pilots have a composite cross-check inside and outside the aircraft. They have to scan for traffic, glance at the controls, and search for information downward on a knee board or in an iPad, in addition to monitoring the instrument panel. Attentional focus primarily should be outside the aircraft and on the control instruments, but G1000 visual capture is too much for novice pilots to ignore. And while analog cockpits have a large amount of information to manage, the amount of data viewable by the pilot is considerably less. TAA system designs provide what pilots need, but do not conform to how pilots need to receive, view, and retrieve information. These unintuitive displays increase visual scanning, thereby amplifying fatigue, hindering information interpretation, and delaying response times (DeLucia and Betts, 2008).

**Information overload.** While inexperience is a definite factor of accidents, training authorities are forced to seek solutions to poor aircraft interface designs through more procedure and more data, when volume and complexity of procedure, data or both are often the problem (Endsley, 2001). This data oversupply performance detriment was demonstrated using map and route recall tasks where learners remembered more information when using lower detail maps (Sanchez & Branaghan, 2007 & 2009). In saying this, it should be clarified that reduction of information responsibility (e.g., understanding chart symbology) by the pilot is not being proposed; only that data should be appropriately displayed and offered at the right moment. It is more important the pilot know and recognize what he or she is viewing (e.g., a radar tower 300 feet tall vs. a 500 foot tall mountain), rather than show every detail possible at every moment. For instance, depending on altitude and threat level, the system might only display terrain or obstacles

within 2,000 feet of aircraft altitude (i.e., well-beyond VFR obstacle clearance requirements), otherwise only displaying a simplified chart mode. This could be done with an integrated display set up, using one large digital display, which would not negatively impact visual search performance (DeLucia and Betts, 2008) and would offer a wider field of view, as opposed to the G1000 arrangement.

Admittedly, the force behind technological advancement in aircraft cannot be avoided. Therefore, as concerned researchers and aviators, we should embrace the opportunity to respond with a flexible solution for technological integration which improves pilot performance, rather than hindering it.

### **Human-Computer Interaction (HCI) issues**

**Pilot Study.** As a result of these statistics and personal experience, a pilot study was conducted using the contextual inquiry method to discover the current experience with the Garmin G1000 (Figure 2), an electronic flight deck commonly found in light airplanes. User experience (UX) findings confirmed many assumptions about the system, such as deeply cascading menus, multiple modes per function, and confusing or frustrating interactions. Example findings included:

- 1) a menu auto-reset feature causing pilots to lose menu position during a search task and after 3-4 seconds of inactivity;

- 2) the “IDENT” feature required five steps to access. IDENT is required to self-identify aircraft on radar and does not occur at a time of the pilots choosing.

Traditionally, this has been a dedicated button in analog systems (Figure 3). Furthermore,

control yoke interference was not considered, which forced the pilot to reach over the controls in order to prevent an inadvertent bump of the yoke;

3) Instrument Landing System/ Localizer (ILS/LOC) (i.e., precision landing guidance) Approach Mode control using the Glide Slope Indicator (i.e., vertical approach indication) was visually confusing, as it was positioned in front of the artificial horizon, creating overlapping indications of movement. The horizontal alignment indication (LOC) for horizontal approach guidance was also not co-located with the vertical Glide Slope Indication;

4) Emergency checklists were buried in menu layers;

5) Alerts were not audible;

6) The bugged “Altitude” alert did not populate a warning until 200 feet below the intended altitude, beyond legally safe limits;

7) The G1000 provides information in different locations and in different ways than the standard 6-pack;

8) Limited screen area and difficult to use soft keys were noted complaints, along with more complex aircraft, such as the CRJ, having an “easier layout”;

9) The turn coordinator was in a confusing location;

10) Finally, the overabundance of data options, menus, and colorful visual capture encouraged system dependency, perpetuating the distractibility (Williams, Yost, Holland & Tyler, 2002) problem for novice pilots.

Contextual data was synthesized and categorized using a work activity affinity diagram (Figure 4), revealing four major categories with sub-categories of principle violation/user need:

- 1) Human Information Processing
  - a. Information Overload, Situational Awareness, Deep Menus/Buried Information, Combining Systems Artifacts, Miscellaneous
- 2) Cognition
  - a. Grouping & Proximity, Confusing Interactions
- 3) Perception
  - a. Signal Detection
- 4) Physical Design Issues
  - a. Ergonomics/Layout

**Design.** Problems such as these are not unique to small aircraft flight decks. Confusion caused by an HCI design flaw aboard Air Inter Flight 148 killed 87 people in January of 1992. During final approach, the pilot entered “33” into the auto pilot Vertical Speed Mode (Figure 5), equating to what he thought was an 800 foot per minute (fpm) decent rate. He intended to enter a descent *angle* of “-3.3°” into the Flight Path Angle Mode, in the same display position, using the same knob. This error caused the Airbus A320 to descend at 3,300fpm (Figure 6), in the weather, and crash into a mountainside while still over 10 nautical miles (NM) from the runway. While this was an input error, as a result of a perceptual error, it highlights parallel issues in GA – small mistakes can lead to drastically dangerous outcomes. Clearly, bad design can kill.

In GA, what we know about TAA designs is that it causes pilots to increase the amount of time spent looking down in the cockpit (Williams, Yost, Holland, & Tyler, 2002). Pilots spend more time searching information screens, backtracking through data options and take more time to look at the displays (Wiggins & O'Hare, 1995) rather than fly the airplane.

A more human centric design for GA is needed to improve task management and situational awareness (SA) and as Sheppell and Wiegmann (2000) noted, accidents cannot be attributed to one single cause or individual. Therefore, it is imperative that a holistic approach between training, policy and computing is taken to guard the lives of aviators and passengers using subject matter expert (SME) knowledge as a design basis.

***Situation awareness.*** In HCI, application of affordance principles aim to mitigate system misuse and misunderstanding by tailoring design to user needs (Hartson & Pyla, 2012), centralizing the user at the center of system development (Endsley, 2011). This aspect is well aligned with the goals of human factors engineering, enhancing performance, increasing safety and user satisfaction (Wickens, Lee, Liu & Becker, 2004). Given a proper GA design, a highly usable system should involve Endsley's (2011) three major principles, focused on SA:

First, the system should have features which target user goals, tasks and abilities. Not only should this system know what the pilot needs to accomplish, the system would increase aviator effectiveness by knowing when specific goals should be completed (i.e., phase of flight) and preparing for those goals accordingly.

Second, it needs to conform to human information processing and how people make decisions. As mentioned, an over-supply of data becomes noise, and therefore, increases response times as it is wasted in the visual/physical scan and search process. The design should avoid confusing the user when grouping related sets of information; it should visually enhance understanding, and reduce processing and information search time (e.g., assign associated menu features to the physical location of instruments). It needs to emphasize caricaturing of objects, afford the pilot the ability to see and immediately understand what is being viewed (Norman, 1988) without explanation (i.e., icons) and function intuitively, requiring as little training as possible (NTSB, 2010). Glass cockpits should prevent obtrusiveness and clarify looming perceptual issues in real time, (e.g., quantifying dangerous nose attitude using an AOA indicator) all while creating an overall useful product (Rams, 2012; Domingo, 2016) that improves pilot efficiency and effectiveness.

Last, the ideal system should keep pilots up-to-date on system status without alarming them, while allowing necessary manual control (Endsley, 2011) over phase of flight changes or emergency operations. Not adhering to these principles would likely prevent GA from future safety improvements (Abbott, 2001) and would not bridge the information gap between perceiving and comprehending large amounts of information (Endsley, 2000). Therefore, it is imperative that a holistic approach between training, policy and computing is taken to guard the lives of aviators and passengers. This study focuses on the later.

***Participatory Design.*** When it comes to developing the ideal system, who better to ask than the people who perform the job regularly? Using a participatory design approach when creating the best GA cockpit is most appropriate because the process is as much about research as it is about design (Spinuzzi, 2005) – it develops the ideal user experience by building upon the current experience. By eliciting information from SME’s, data can be gathered that would otherwise take months or years to accurately obtain, since it uses methods of (behavioral) observation, interviews, data and artifact analysis, protocol analysis, and tacit knowledge collection (Spinuzzi, 2005). All of this is used to create each iteration of the resulting design and is especially useful in human-computer interaction as a part of the user-centered design process (Spinuzzi, 2005). The project becomes a collectively, creative product (Sanders & Stappers, 2008) and not just the ideation of one, or a small handful of, un-empathetic engineers. By collecting what users need to know, when, and in what quantities, a system can be formulated to meet specific operator needs and goals, while eliminating informational noise. This study exploits that process.

**Information access.** Access methods have improved substantially in business jet and light turbo prop class aircraft. However, menu structures and a balance between information availability and when and how it should be presented still needs much work in light TAA (Hamblin, Miller, & Naidu, 2006). Companies such as Garmin, Honeywell, Gulfstream and Rockwell Collins have released flight decks (e.g., G2000™/G5000™, Symmetry Flight Deck™, and Pro Line Fusion®) within recent years which utilize icon based menu systems with desktop-like functionality, a significant improvement in HCI

affordances. It is these methods of on-call access to information using shallow menu structures that need to be applied to the light aircraft class while considering information priority pilots attribute to functions and information sources (Hamblin, Gilmore, & Chaparro, 2006).

There is a considerable need for improved information access and visual layout which might redirect pilot attention to the flight controls. Such a system would not only improve the usability of the menu systems for light aircraft, but it would lend to a more effective piloting experience, e.g. decrease cognitive workload and as a result, accident rates. Features should focus on assisting pilots with their goals, such as an airspeed and attitude control related accident in December 2013: the PF a Piper PA 24-250 lost SA of airspeed at low altitude in a mountainous area, resulting in an inadvertent stall/spin and the death of all 3 onboard (NTSB, 2014b).

Presenting the right information at the right time is key to fatigue reduction and safety for an already distractible population of pilots. Giving the pilot what is needed, only when it is needed, while still allowing full access to data and control over the system in an emergency, is how the issue should be approached. In supply chain operations, the most efficient product vendors utilize a Just-In-Time (JIT) inventory system developed by Toyota (Monden, 2011). JIT is an improved supply process where demand (i.e., customer need) interval determines storage quantities of an exact number of a particular product (Mittal, Abbasi, & Pareek, 2012). The result, is a decrease in overhead costs, waste reduction of expired or unsold material, less data management, and a smaller storage footprint. Similarly, the JIT inventory concept can be applied to the information

layout, presentation, accessibility and menu structuring in TAA, i.e., a JIT information system. The system would present the exact control instruments, data and flight management system (FMS) options required based on the phase of flight and whether or not aircraft status was normal. The result would be a decrease in cognitive load, waste reduction of visual scan or opportunities for distraction (i.e., less data visually present), and a larger field of view, distributing cockpit information over the entire instrument panel, rather than confinement to small screens.

Not only should designs include a restructuring of menus, but technologically familiar artifacts, such as mobile icons, should be incorporated. In this case, training time would be reduced through highly familiar visual representations (i.e., affordances) and a shallow menu structure, reducing time spent using menu functions. Currently, Gulfstream Aerospace and Garmin, International are the only known manufacturers using FMS's with these features.

Finally, displays should include an Angle-of-Attack (AOA) (NTSB, 2015b & 2016; Duquette & Dorr, 2014) (Figures 7 & 8) indication as a primary control gauge, an instrument typically found in military aircraft and offered as an add-on feature from Garmin or others. AOA indicators assist the pilot by displaying and avoiding aircraft critical AOA, a condition where the aircraft enters an aerodynamic stall situation, causing loss of lift. With AOA, data required for landing is reduced, as aircraft weight, attitude, descent rate, and speed do not need to be individually considered. An AOA gauge calculates these factors and provides feedback on a displayed set of colored lights, indicating what the pilot should do – pitch up or down, decrease or increase power – to

maintain a safe glide path to the runway. Additionally, the pilot only needs to reference two or three sets of visual information – runway aim point, altitude, and the AOA gauge itself – further reducing fatigue from visual scan and limiting distractibility. This also makes AOA easy to understand and quickly learn.

This benefit was specifically recognized by the Icon Aircraft company, an organization that has incorporated an AOA gauge as standard equipment in their light sport aircraft (Icon, 2016). What makes this application and design unique is that the gauge is rarely used in general aviation and Icon is targeting an even lesser experienced population, sport pilots. Sport pilots legally require only about half as much training as a private pilot (AOPA, 2016), making them excellent candidates for the use of an AOA system. Due to the ease of use, high learnability factor, added affordance and layer of safety, the addition of AOA as a primary instrument cannot be overstated.

## **Method**

### **Participants**

A total of seventeen pilots with an Instrument rating were recruited, twelve completed the pre-test and nine participated in the study. Pilots were recruited by referral through Arizona State University's (ASU) flight department, Human Systems Engineering department staff and students, and participant, peer referral. Two attrited due to medical reasons, two participants attrited for airline flying duties and four were not able to be contacted. All participants digitally signed consent of information use forms at the conclusion of the pre-test survey.

## **Design**

The study was an experimental, multi-variable, single-treatment design with a pre-test questionnaire. There was one variable condition of aircraft display type with five phase levels. Participants were asked to provide consultation – in the form of participatory design using the “digital” Velcro model method – on display layouts for phase levels. The attitude indicator was constrained to a vertical axis, front-and-center of the PF. Pictorial cutouts of cockpit information items and instruments were provided for placement. Participants were also asked to justify instrument placement after each phase while being video recorded.

## **Materials**

**Aircraft Design Board.** Using Axure RP Pro 7.0 and Microsoft PowerPoint 2013, participants selected items from a list of 113 instruments or information items (all referred to as items) within 3 sets of PowerPoint slides (Figure 9) and placed them on an Axure “Dynamic Panel” (Figures 10 & 11). Each item was a digitally cut image of a Garmin G1000 item or analog cockpit item. Location justifications were verbalized and recorded in 720p HD at 30 frames-per-second (fps) using an iPhone 6 on iOS 9.2.1. All data was record using Excel. Location justification was coded for analysis utilizing the videos.

**Phase of Flight (IV).** Aircraft operations occur in phases based on physical location. There were five independent variables (phase of flight level) in the study, which each contain further divided sub-phases. For simplicity, sub-phases were grouped by similarity: Pre-Flight & Taxi (1 – Taxi), Take-Off & Initial Climbout (1 – Take-Off),

Enroute (3 – Enroute), Descent & Approach (4 – Descent), and Landing & Taxi Back (5 – Landing).

**Information Item (DV).** Item data collected was sourced from a list of 113 possible options in all categories of flight, i.e., aircraft control, navigation, communications, systems and powerplant. The master choice list was condensed to 57 more general items.

**Origin Distance (DV).** Origin Distance is the physical distance measured in pixels (px) – on a theoretical, 36”x12”Axure design screen – from the center of the Attitude Direction Indicator (ADI) to the center of all other items. Axure grid settings used 5px spacing, 1px vertical and horizontal Snap to Margin settings and a 120 dot-per-inch (DPI) setting.

**Clock Angle (DV).** Clock Angle is the Minute-of-Angle measured at the approximate clock position from the center of the Attitude Direction Indicator (ADI) to the center of all the items placed by participants. An object tool was created using Axure for measurement (Figure 12).

**Item Area (DV).** Image area was calculated for all items in Excel based on (x,y) components provided by Axure.

**Location Justification (DV).** After each phase template was complete, the participant was asked to answer the question, “Why did you choose to place the item \_\_\_ in that location?” There are five reasoning codes the researcher used to categorize responses: Importance, Frequency of Use, Similarity (Relatedness), Co-Occurrence (Relatedness), Other.

A sample of responses for the “Other” category were recorded in a notes file. Additional notes were made using Windows Notepad during participant recordings and placed in the participants’ file.

**Visual Angle (DV).** Visual Angle (VA) is the physical distance across the digital screen, measured in degrees, from a standard viewing distance of 57cm (22.44 inches). It is used to translate pixel dimensions to a real world measurement, which is usable across all types of software and displays.

**Pre-Test & Questions.** One pre-test was given to all participants prior to their scheduled design session. To qualify for study participation, candidates were required to hold at least an Instrument rating (APPENDIX A).

## **Procedure**

Participants were contacted via email for scheduling. Twenty-four hours prior to the participants’ session, a Google Forms survey link was provided with directions to the lab. Response data automatically populated into a Google Sheet to be used for analysis. At the end of the survey, participant’s digitally signed a consent form.

Participants were asked to select an ADI from PowerPoint slides containing items. The chosen ADI was placed on the Axure 36”x12” design area (Figure 10), about the blue vertical line. Participants were allowed to select items from the set of three categorized (Control, Systems and Comm, Nav and Flight Info) PowerPoint presentations to build an appropriate flight deck conforming to the participants’ phase preference. If an item was not available, the participant created a custom item using the “place holder” box in Axure using an appropriate name. Participants were asked why the location was

chosen on video for each item at the end of each phase and data was recorded in Excel.

Sessions lasted approximately 2 hours with rest breaks, as required. Phases were limited to time in order to prevent sessions from being too long as they would cause participant fatigue. Phase 1 (Taxi) was 45 minutes and required the most time for the participants to become familiar with, select, place and manipulate objects. Phases 2-5 (Takeoff, Enroute, Descent and Landing) were 15 minutes in length each. No monetary compensation was provided, except when a non-ASU participant traveled to campus for the session. In this case, participant parking was paid for using the ParkMobile App.

**Pilot Testing.** An eight hour rehearsal of the proposed design session was conducted with a qualified pilot holding 758 flight hours in fixed and rotary wing aircraft to ensure efficient and timely collection of data. Data collected during pilot testing was retained and not used in the results.

### **Data Analysis**

A qualitative analysis was conducted with Phase of Flight (IV), Information Item (DV), Origin Distance (DV), Clock Angle (DV), Area (DV), and Location Justification (DV), Visual Angle (DV) as within-subjects factors. Excel was used to visually identify data spikes, troughs, expert-novice differences, and phase differences.

### **Measurements**

**Origin Distance (Image Center and Distance).** For each of five phases, measurements were taken by clicking on an item in Axure and recording the image size (pixels) and  $(x, y)$  position in an Excel sheet. Axure provides the upper left corner as the position for the chosen image, as well as to its dimension. The center of images were then

calculated by applying the Distance Formula to image data to determine the pixel-distance between items (Figure 13) (APPENDIX B).

**Clock Angle.** Clock Angle was determined by using a “Clock Tool” created in Axure (Figure 12), copying and pasting it over the top of participant designs, and manually reading item position at intervals of ¼ MOA accuracy. Data was recorded in Excel in decimal format (e.g., 1:30 = 1.5 and 11:15 = 11.25).

**Location Code.** Codes (1-5) were used for Location Justification to easily analyze items between phases. A nested If-Then formula was used in Excel to auto-populate codes based on justification text.

**Visual Angle.** Visual Angle was determined by converting pixel measurements for Origin Distance and Item Area to degrees visual angle (APPENDIX I).

## **Results**

### **Participant Sample**

Five professionals and four student participants were divided into expert and novice categories according to professional pilot (i.e., airline pilot or instructor) or student pilot status. The population consisted of two aeronautical/simulator instructors, one non-aviation manager, an airline captain, a certified flight instructor, and four university, student pilots. Licensure included four Private Pilots, Two Airline Transport Pilots, One Commercial Pilot, and Two Certified Flight Instructor-Instrument/Multi-Engine Instructors. Eight pilots began training in analog only cockpits and six have training in high-performance aircraft, including commercial jets and military platforms. Two experts were military flight instructor-instructors and one of those experts has never

used a digital cockpit, in addition to the most inexperienced novice. Only two pilots were restricted to piston aircraft, while the remainder had type ratings in turbofan, turbojet, and turboprop powered aircraft. One novice had an experimental type rating.

Mean flight hours for nine participants was 4,082 hours (17,810 hour range) with an average of 14 years of experience and a mean age of 37. Participants held a total of 16,885 hours in digital cockpits and flew 13,010 hours using analog systems before transitioning to digital flying – 35% of the cohorts’ total flying hours. Additionally, participants possessed a total of 735 hours of flight time using the Garmin G1000.

### **Statistics**

**Data.** Data collected from 9 participants totaling 113 item types, including custom generated objects, was categorized (e.g., aircraft control) and regrouped (e.g., RPM options 1-4, changed simply to RPM) to make information easier to interpret during visual, qualitative analysis of graphs.

**Items removed.** Data was filtered for items not used in every phase of flight by all participants, which resulted in the removal of 22 custom items (APPENDIX D) and an “Artificial Horizon” option. 16 navigational items (APPENDIX E) which are critical for flight, but only used between one and three phases (e.g., approach plate is only used for approach), were separated from the main data group and analyzed separately. Data was further reduced by 17 items through grouping multiple options of the same type of item. Analysis at the expert-novice levels revealed usage of items used by one or the other group, but not both. Due to the low level of data which would remain in all phases by all

participants, filtering was stopped after the item type grouping. Resultant data encompassed 57 items.

**Information categories.** Item types were further categorized into cluster types: Aircraft Control, Navigation, Communications, Systems, and Powerplant (APPENDIX F).

**Origin Distance.** Design board dimensions were 1045 x 280 pixels (px). Between all phases and participants, the closest item to the “Attitude Indicator” was the “Rudder Position Indicator” located at a mean distance of 86px and the furthest item was the “Switch to Topographical Map Button”, a mean distance of 668px (582px range). 40 of 57 (70%) items were located within 400px of the ADI. Items between 400 and 668px were in the Navigation or Powerplant categories, except for the “Transponder”, a Communications item. Standard deviation for all items was  $\sigma = 216$  (Table 4).

**Clustering.** Categories also revealed differences of within-category distance variability: Aircraft Control 408px ( $\sigma = 97.5$ ), Communications 153px ( $\sigma = 67.8$ ), Navigation 453px ( $\sigma = 161.5$ ), Powerplant 268px ( $\sigma = 87.3$ ), and Systems 140px ( $\sigma = 57.4$ ) (Table 5).

**Phase of flight consistencies.** There were 51 items (89%) within all 5 categories which had no variability or such little variability that comparing mean locations between phases would be visually unnoticeable (i.e., less than a 200px difference) (Table 6).

**Phase of flight inconsistencies.** The below list contains 6 items which varied greater than 200px in distance between all phases of flight (Table 6) (APPENDIX G).

**Clock Angle.** Mean Clock Angles resulted in 8 out of 57 items (14%) between the 2-3 o'clock positions, 32 out of 57 (56%) items occurring between the 3-6 o'clock positions and the remaining 17 (30%) items in the 6-12 o'clock range. No items produced a mean clock angle between 0-2 o'clock (Table 7).

**Phase Changes.** Between phase results produced very little angular change, with the exception of 10 items below. Interpretations with clock changes and quadrant assignments follow (e.g., Quadrant 1 (Q1), 12-3 o'clock; Q2, 3-6 o'clock; Q3, 6-9 o'clock; and Q4, 9-12 o'clock.) (Table 8) (Figure 14).

1) Aircraft Control

- a. Glide Slope Indicator (Q2) – 5 to 6 o'clock range in takeoff, descent and landing. Consistent with other systems of participant familiarity.
- b. Heading (Q2) – Typically 8 o'clock, except in taxi it is at 4 o'clock, an implication of importance to bring the item into visual, runway heading crosscheck.
- c. Course – Invaluable variation.

2) Navigation

- a. Flight Planner Menu (Q2) – Moves from 6 o'clock in taxi to 3 o'clock for all other phases. Possibly so it's easier to reach.
- b. Distance to next waypoint – Uninterpretable variation.
- c. Waypoint Selection Name – Uninterpretable variation.

3) Systems

- a. Advisory Indication (Q2) – Remains between 5 and 6 o'clock, except during descent, where it has a 4 o'clock shift into primary field of view.
- b. Traffic Warning (Q2) – 4 o'clock range during takeoff, enroute and descent, where it can be seen in the primary field of view.
- c. Local Time (Q2) – Moves into primary field of view at 3 o'clock during Descent to monitor so the pilot can meet the landing time, consistent with other movements to the second quadrant.
- d. Alerts Indication (Q2) – Shifts from 8 o'clock in taxi and landing, to the 5 to 6 o'clock range in all other phases. Again, primary field of view shift.

**Item Area.** This information proved useful in determining the proportion of information categories would encompass on a resulting template, but a major challenge lies in determining the shape of each category. Since area can be converted to an infinite number of four-sided objects, only a visual estimate based on proportional area, could be used to infer a template (Table 9).

**Location justifications.** The most frequently used reasoning was 'Other' for both groups. Pilots often cited "familiarity" to another system, which is the reason for the high frequency of this choice. The least used justification was 'Importance' for experts and 'Co-Occurrence (Relatedness)' for the novice group. This was slightly unexpected and could be a result of a coding error or may have been a true and accurate representation.

The rating scale was difficult to use for the aviation environment, since all five categories can be attributed to single items. For example, an airspeed indicator is a highly important instrument, but it is also frequently used, contains information similar to ground speed and true airspeed, and always occurs with the attitude indicator and other primary instruments. It makes precise categorization, exceedingly difficult.

**Visual Angle.** Original position (x,y) and image area data was used to convert pixel measurements to visual angle. Results showed that those items with less than a 200px change in distance (89% of items), had varied movement less than or equal to 17.5° VA. 70% of items moved within a 0° – 35° VA range and the remaining items which varied between 400px and 668px, moved greater than or equal to 35° VA.

**Expert and novice differences.** Only distance data between experts (Table 14) and novices (Table 15) was analyzed. Items used by experts and novices was significantly different. Novices used 17 more items than experts, resulting in the removal of 19 items from both lists with 38 items remaining for experience comparisons. Analysis of experts revealed a standard deviation of  $\sigma = 168.3$ , but novices showed tighter grouping toward the origin, with a standard deviation of  $\sigma = 121.9$  (APPENDIX H).

## **Discussion**

### **Method**

Data was collected using a participatory design method utilizing Axure and digital cutouts. Information was compiled and analyzed entirely using Excel. Important information was derived from the consistencies and inconsistencies between phase and experience level with regard to distance, angle, area and justification for placement.

## Results

**Origin Distance.** When compared to the information priorities of flight (Schvaneveldt, Beringer, Lamonica, Tucker & Nance, 2000) (Table 16), it does not appear that distance in this experiment equates with the previous study's determined information priorities of flight. In some ways, there are similarities, such as aircraft control instruments being higher on the list. However, there are factors outside of the cockpit (e.g., runway aim point) in the prior mentioned study which do not have a similar variable here. This does not necessarily mean that distance does not implicate priority. There is definitely a re-prioritization of information from phase-to-phase based on distance and like the information priorities of flight, items are 'pushed aside' for later use. Pilot re-prioritization simply means that items are not as important during specific phases of flight. This one of the biggest reasons justification coding was a challenge.

In terms of overall change, the standard deviation ( $\sigma = 216$ ) suggests very little spread occurred between all phases and all participants. It also implies that the screen is being underutilized. The available screen width is just over 1000 pixels and yet, distance data shows just under a 600 pixel range among all items. This could suggest a forecasting of possible ergonomics issues by participants, i.e., lack of reach. However, item measurements were performed from center-to-center, not edge-to-edge, and the majority of items observed on the far right side were large objects, such as charts and published plates. Therefore, centered measurements would be moved further left on the screen, shortening the range in distance results. Also, it would be very hard to discern these types of numerical calculations without having the opportunity to simply look at what

participants made or even observe them. This idea in itself suggests that there is more value in basic observation and qualitative, descriptive analysis, than a purely quantitative one.

It should also be noted, that pixel distance varies depending on the resolution capability of the display being used. In order to create a working prototype and equate design results to real world size, conversions need to be considered (e.g., inches of screen) for a translatable measurement.

Visual angle was chosen as the method to neutralize differences in display capabilities and limitations and between design platforms. For example, on a 720p monitor, 100 pixels in distance does not equal the same length as 100 pixels on a 4k LED screen, i.e., distances would become shorter using higher quality displays. To account for this in the resulting templates, the design board dimensions were converted to centimeters and then to degrees per pixel (APPENDIX I).

**Clock Angle.** An interesting set of results in this area showed that of those with varying degrees of angle shifted toward the 4 o'clock range. Since the majority of items occurred in the 2-6 o'clock region, it is only fitting that items with movement between phase regressed to the middle of the second quadrant. Significance might lie in the fact that non-flight control items gravitate towards the central plane (center of the screen). Exactly what this means, is yet to be determined.

**Experience comparisons.** Differences in the number of options available was most obvious; novices used more items. This is an interesting finding, especially when considering that non-experts are more easily distracted by highly technical systems. It

seems that initial comparisons reveal both groups know what they want, but novices may actually not know what they need in all instances or they may not admit this to themselves. However, when considering that the novice pilots are instrument rated and based on statements during justifications, precautions were likely taken “just in case” to compensate for not being completely certain of an items use in a particular phase. It’s also very possible that novices show less discretion in minimizing clutter than experts do, supporting an information hoarding thought process. Novices are either planning for every possible outcome and therefore want to have every item visible, it was habit, or both. It seems to be both. As far as experts are concerned, it’s possible they may want the same options available as novices, but they do not feel showing those items is necessary. They seem to want a simpler display, regardless of analog or digital flight time. This may be one reason for the higher standard deviation. Finally, there were clearly observed and verbalized decisions made by novices which led to a visual replication of the G1000, i.e., a much tighter grouping based on a smaller screen size of 10.4”. In either case, there is a clear difference in the number of choices desired between groups. The most important or most frequently used items in any particular phase were closest to the center of gaze (i.e. Attitude Indicator). Novices exhibited little deviation from the designs they operated the most. Lack of exposure to different designs encouraged G1000 or analog cockpit replication, whereas experts more frequently chose their locations based on desired improvements of familiar systems.

Last, it should be asked, in what aspect does each class inform us well on this topic? Experts foundation of aeronautical knowledge and proven, real-world experience,

would tend to support their design structures and justifications, despite any error in justification coding in this study. While novices have a basic understanding of the meteorological effects on the airplane and associated instrumentation use, they simply do not have the experience to definitively say that a GA display should be designed in any particular way. Their designs are not novel, since they reproduce only the very few cockpits they have witnessed. Sometimes this in only one type of airplane or cockpit. However, novices would still prove valuable in the design process. Since they are not constrained by knowing what designs work, do not work and why, novices would be most useful in co-designing novel, technological ideas for information access methods (e.g., touch screen or voice activation features). Their ideas could then be validated or re-oriented by experts within the same cohort.

**Location Justifications.** There was much ambiguity in determining position justifications and likely involves considerable error. Pilots often combine designs from aircraft containing the best or most preferred features, e.g. Airbus and Garmin G1000, CRJ-100 and Garmin G1000, etc. Articulating location justification is the most direct and clear among expert pilots. Whereas novices tend to explain why an instrument is important or why they like it, rather than why they chose its location; a data dump of sorts. Like experts, however, novice locations defaulted to the aircraft with which they were most familiar, even if they weren't aware of that fact.

Largely, pilot preferences for item placement are not very telling beyond primary control instruments and directly related information bits. In particular, their placement

preferences do not inform research very well what their needs are as much as it tells a few 'nice-to-haves'.

**Visual Angle.** VA was very useful in producing a real-world template for phase designs. Display capabilities are not a limitation for further analysis as pixel density now becomes irrelevant. Only expert data was used in this instance because novice information does not provide consistently valid data (e.g., distance) in terms of design. Novices do not have the requisite experience to provide usable data for a consistent design. Visual angle showed slight, but not drastic changes between phases of flight.

### **Strengths of the research**

The method used was very effective for collecting very dense information from each participant and recording location justifications was a time saver for participants. Population diversity through word of mouth recruiting and referrals was helpful in launching data collection. Extreme users, such as the most in-experienced novice, demonstrated an exception to the norm in terms of younger pilots whom are expected to prefer more technology in the cockpit. This specific participant design seemed to more accurately reflect the needs of new pilots and not their preferences, which is atypical of this sub-population. VA data was very useful in identifying where expert participants placed items, resulting in a by-phase template (Figures 15-19) for a new GA design.

### **Limitations of the research**

Location justification data proved to be ambiguous. Either the researcher did not ask why the participant put the item where they did in appropriate way, the participant did not fully understand the question, the participant did not know why the location was

chosen, or all of these. The researcher was forced to resort to inferences, personal experience, or both to derive answers from video records. Sessions required 2 hours per participant and may have had a fatigue effect.

In order to produce a consistent research method, each participant started by building a taxi phase. This could have produced a design bias, since the first design participants created was not randomized.

Phases could have also been better grouped and better defined. The definition of landing caused confusion when choosing which items to use and where to place them, e.g., “Is landing at touchdown, or is landing ‘final-to-landing’? This likely had an effect on the results of item choice, location and position for the landing phase.

Creating a template for phase designs presents a consistency issue in training for pilots. While the area of item clusters morph through flight, it would be very detrimental for pilots to have instrument location change. However, the phase designs could be very useful for displaying items which change between phase due to only being utilized during one phase (e.g., approach plates within the navigation cluster).

### **Future research**

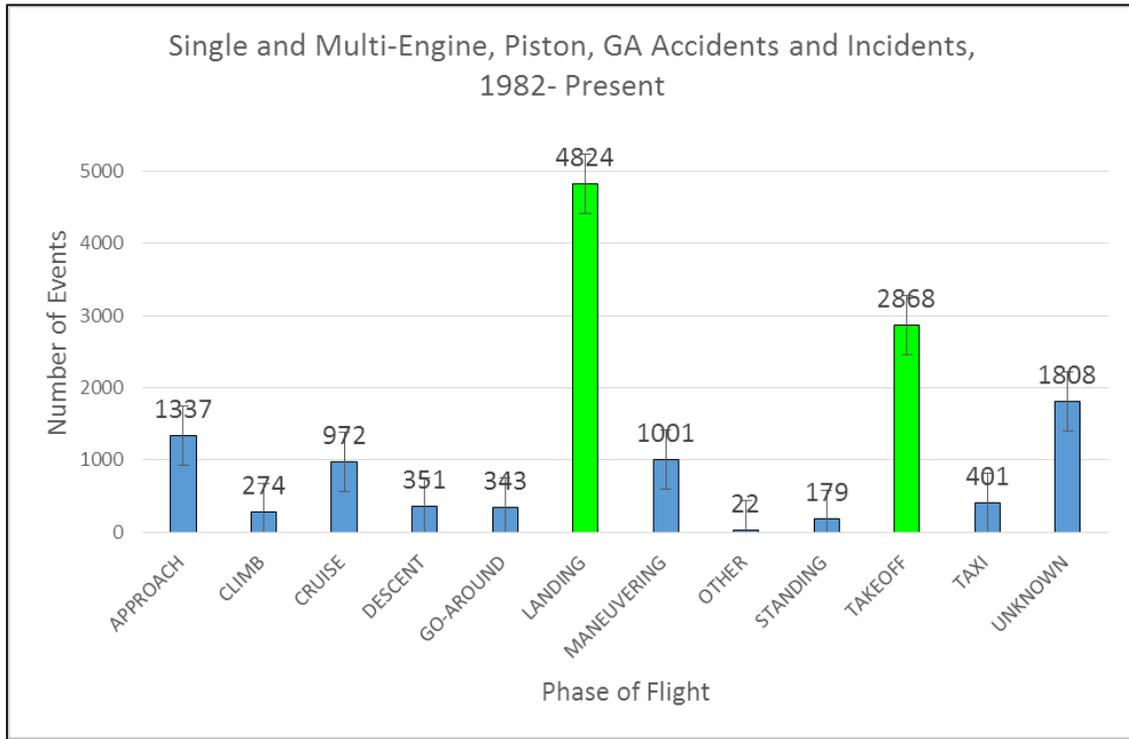
If this experiment were conducted again, additional categories should be created for justifications, such as familiarity and expectancy. Pilots should be asked to draw lines, grouping items together for easier coding during video reviews. Consider conducting the future research collection as a participatory design focus group with experts only, beginning with the compiled data in this study to spring board their work. Additionally,

participants should be asked why they chose the item they did, since pilots seem to love to talk about this.

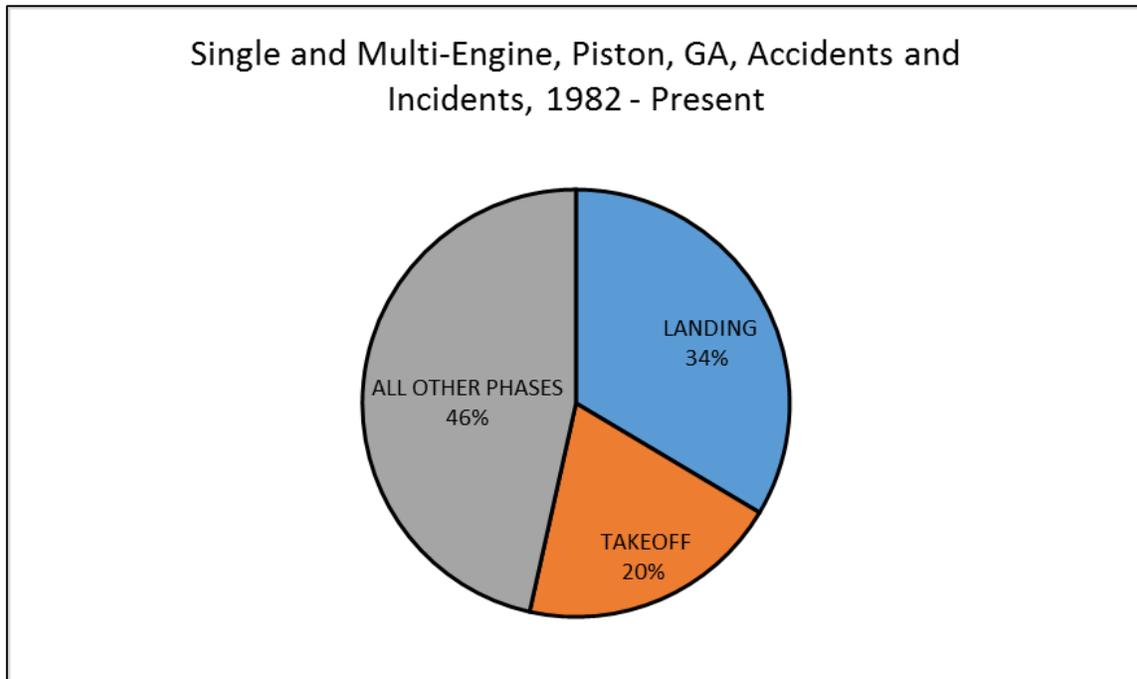
Future research should be broken down into parts to better manage the richness of data. For example, conduct one study on distance, then a follow on observing only clock angle, etc. Limiting the dependent variables would result in much shorter sessions, data management would be easier and compilation of the data would require less time. In each of the studies, still aim for 12 participants.

Last, after a definitive design is created, an interesting addition might be to research how pilots should interact with instruments through the use of mobile gesturing techniques (e.g., pinch-zoom and rotate charts with the fingers, instead of a scroll knob).

## Tables

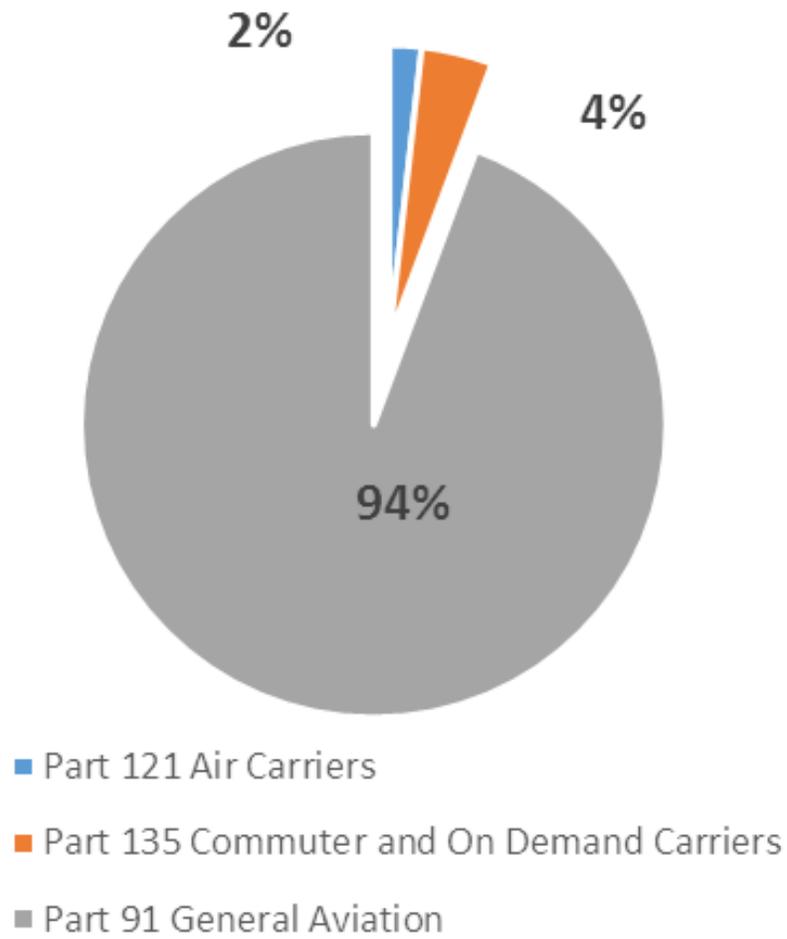


*Table 1 - Takeoff and Landing accident data with all phases..*



*Table 2 - Takeoff and Landing accident data.*

## CY13 GA Accidents and Incidents



*Table 3 - GA accident data for 2013.*

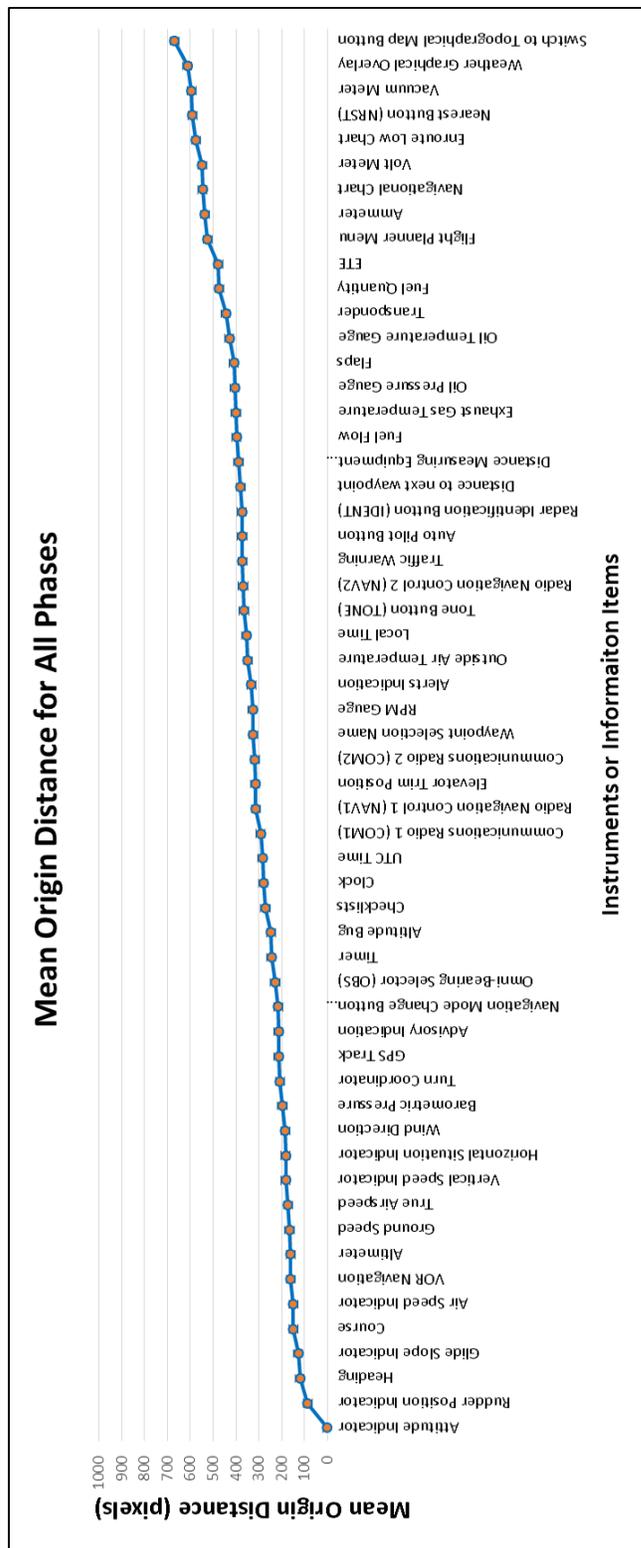


Table 4 - Mean Origin Distance between all phases and all participants.

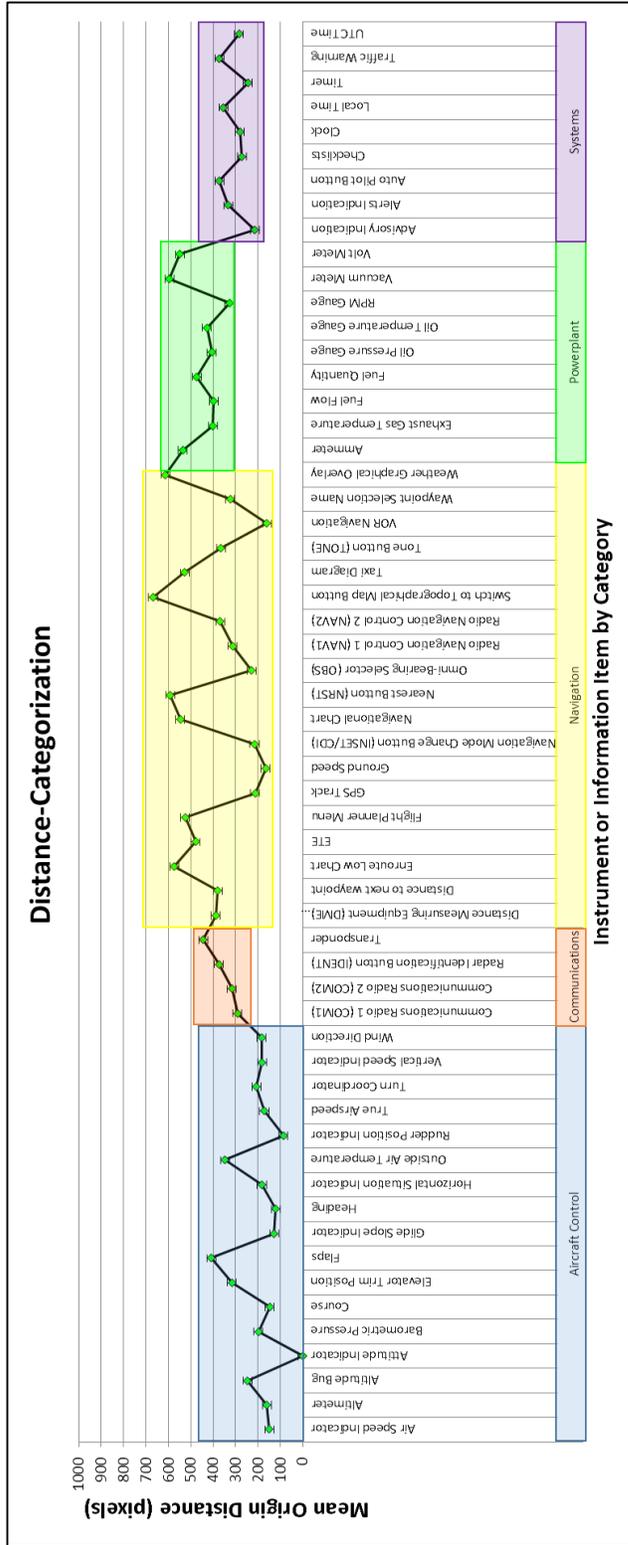


Table 5 - Mean Origin Distance for all participants and all phases of flight.

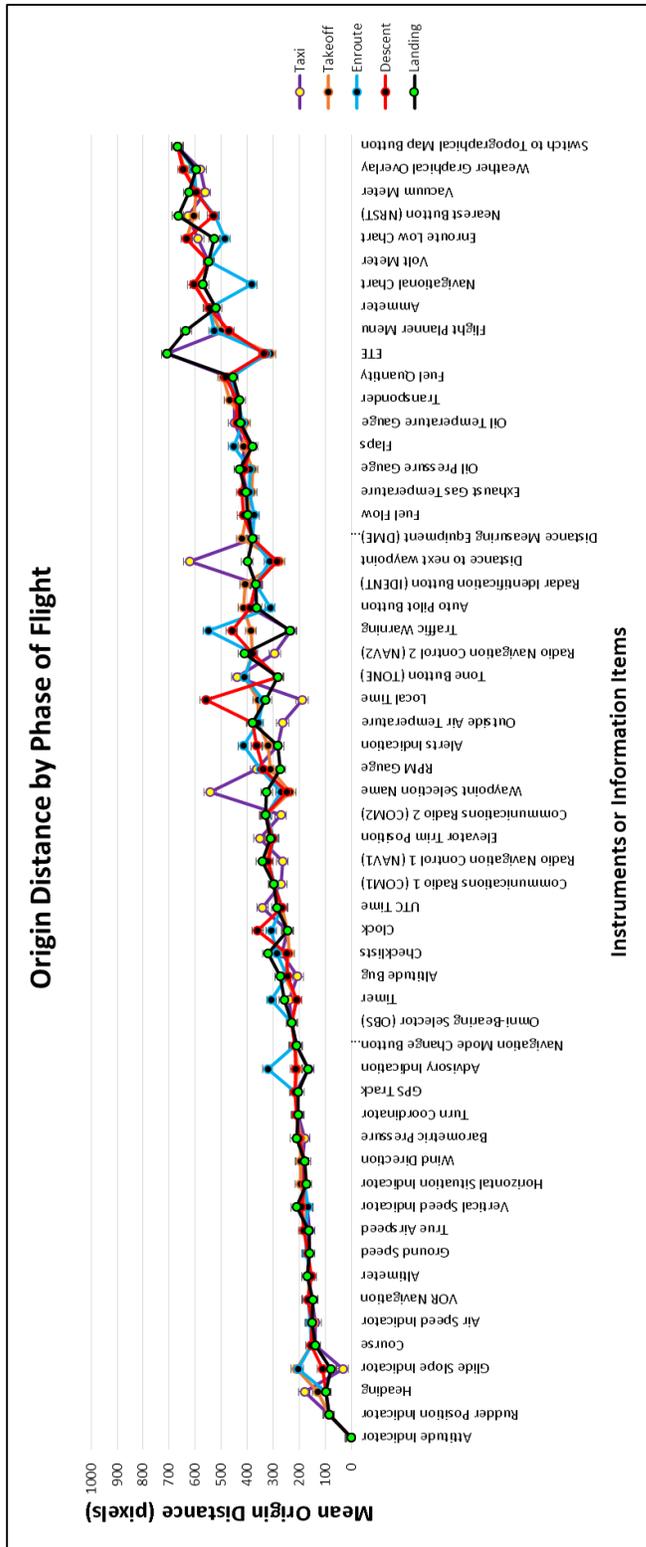


Table 6 - Mean Origin Distance for all participants by phase of flight.

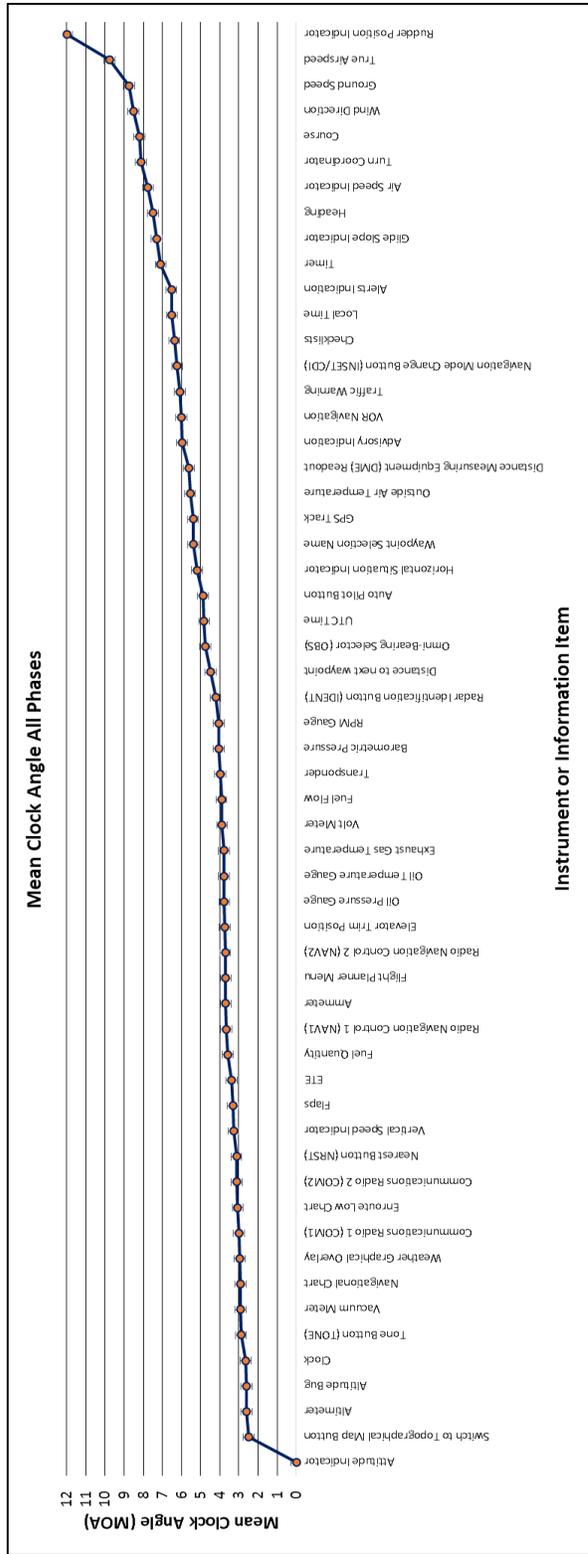


Table 7 - Mean Clock Angle for all phases of flight.

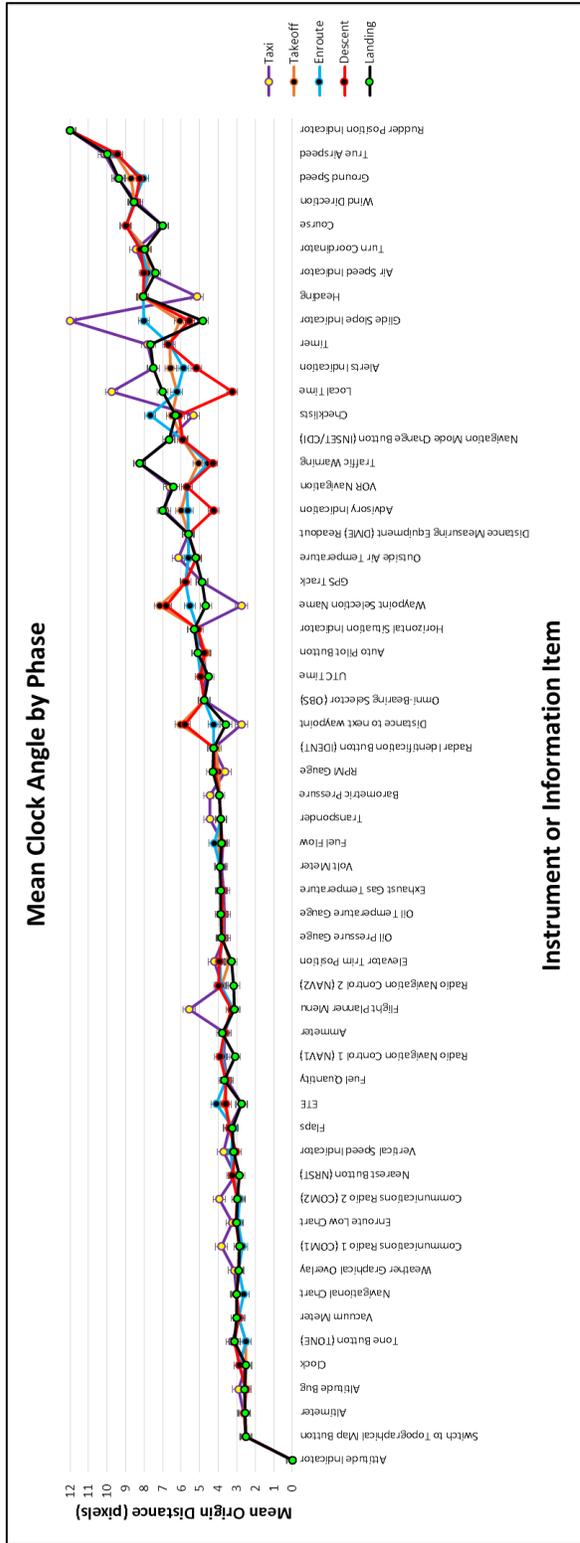
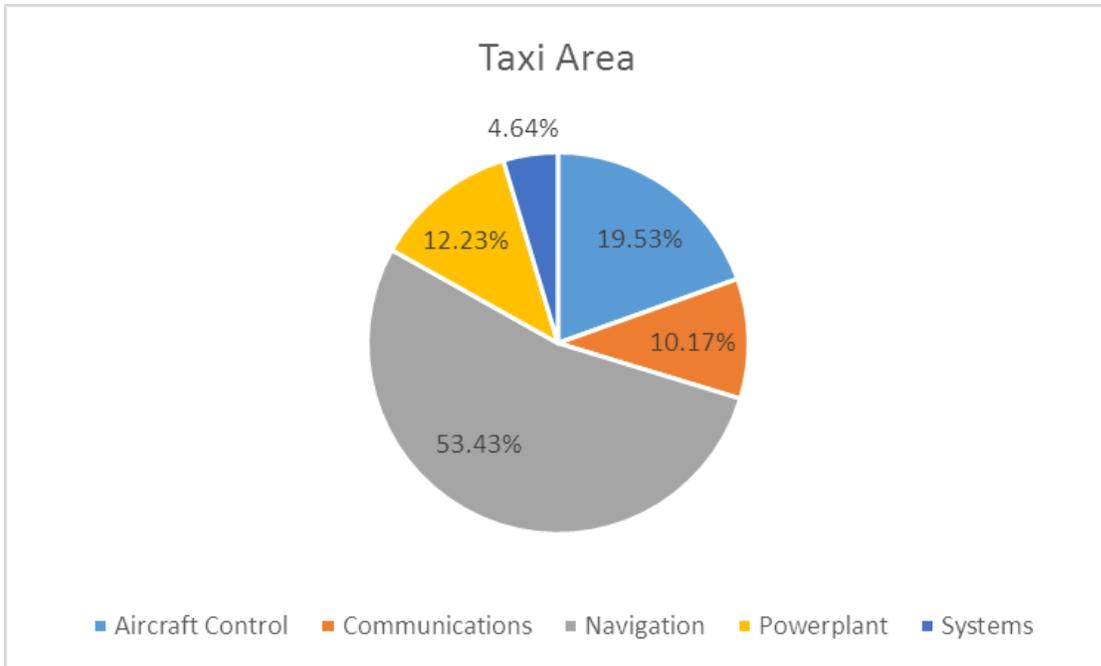
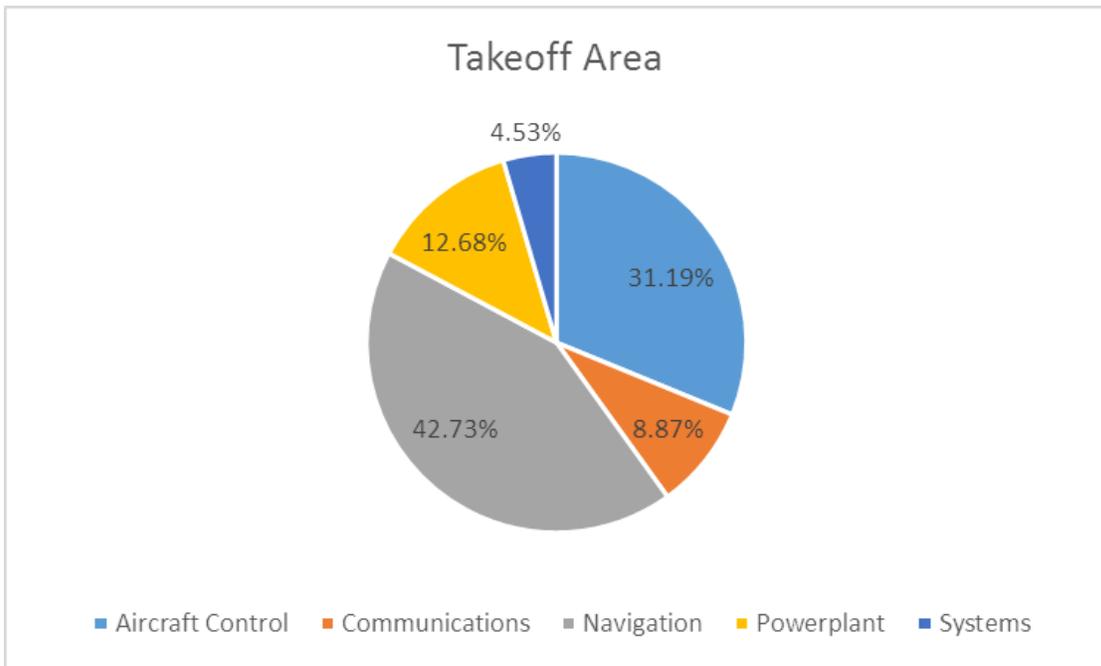


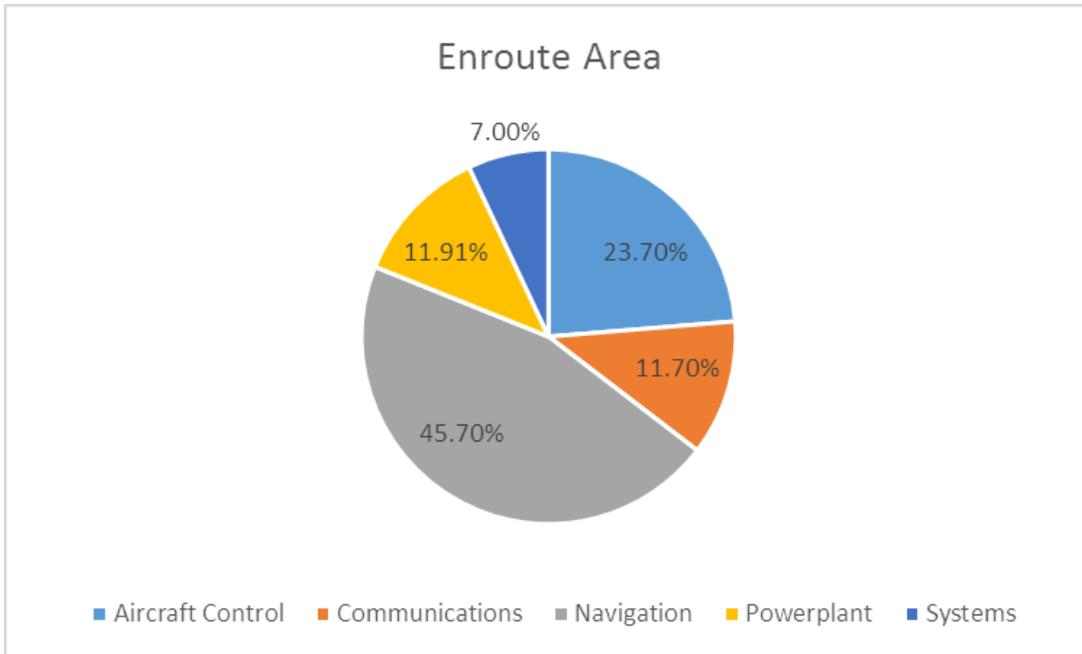
Table 8 – Mean Clock Angle by phase of flight for all participants.



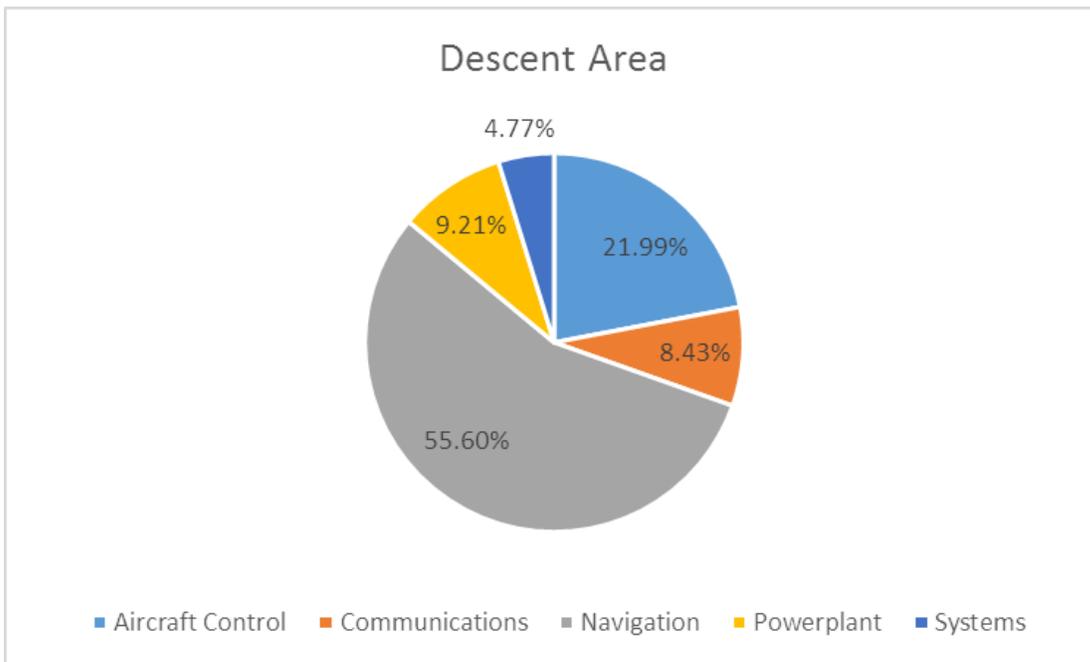
*Table 9 - Item Area for Taxi Phase.*



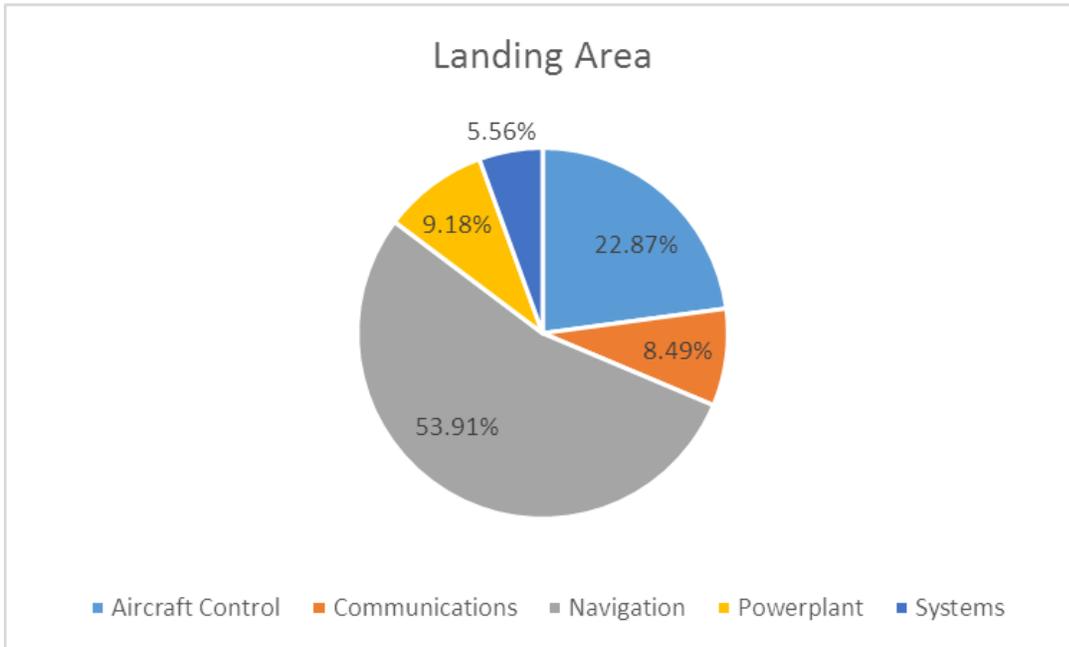
*Table 10 - Item Area for Takeoff Phase.*



*Table 11 - Item Area for Enroute Phase.*



*Table 12 - Item Area for Descent Phase.*



*Table 13 - Item Area for Landing Phase.*

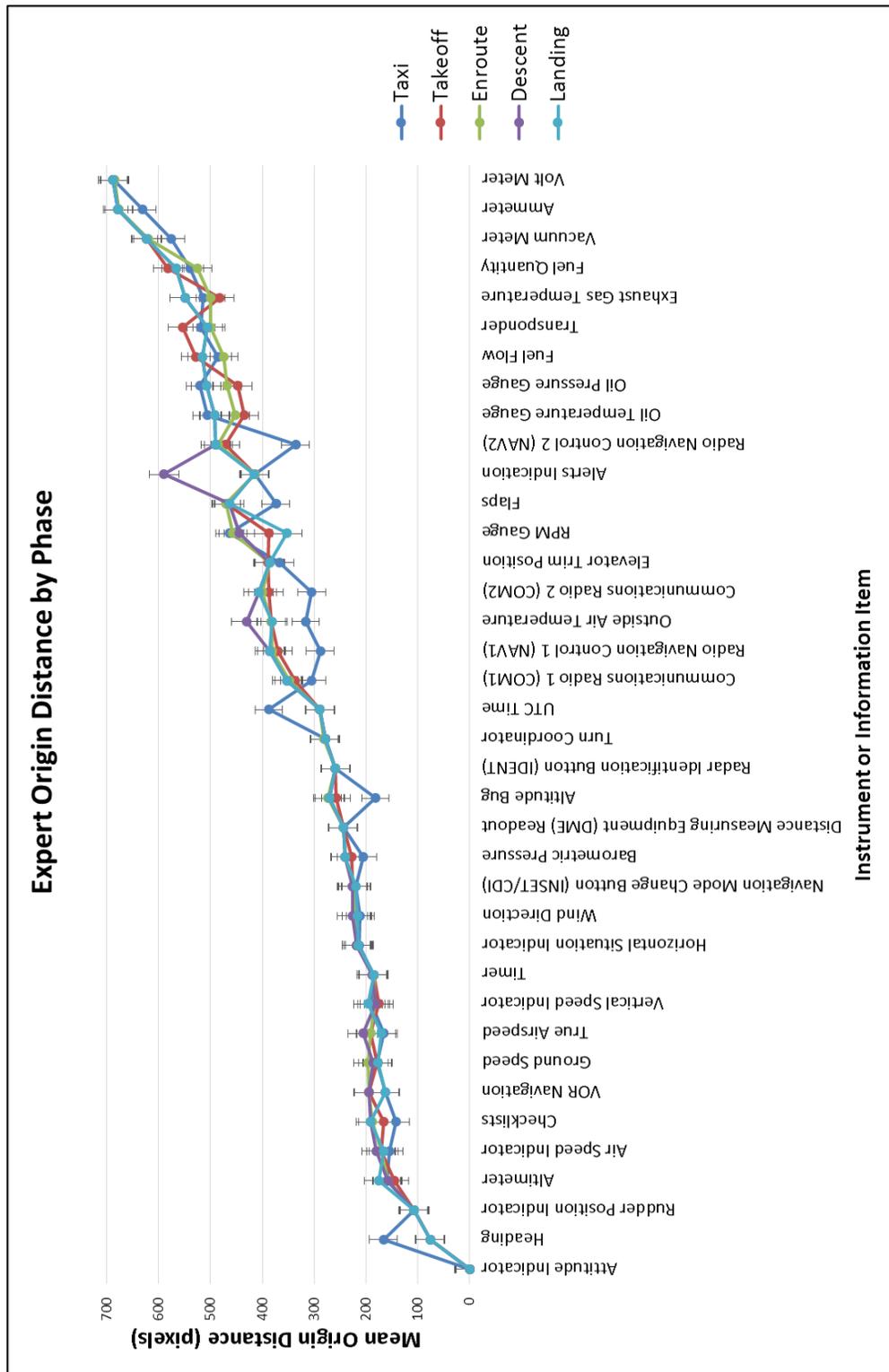


Table 14 - Mean Origin Distance for expert participants by phase.

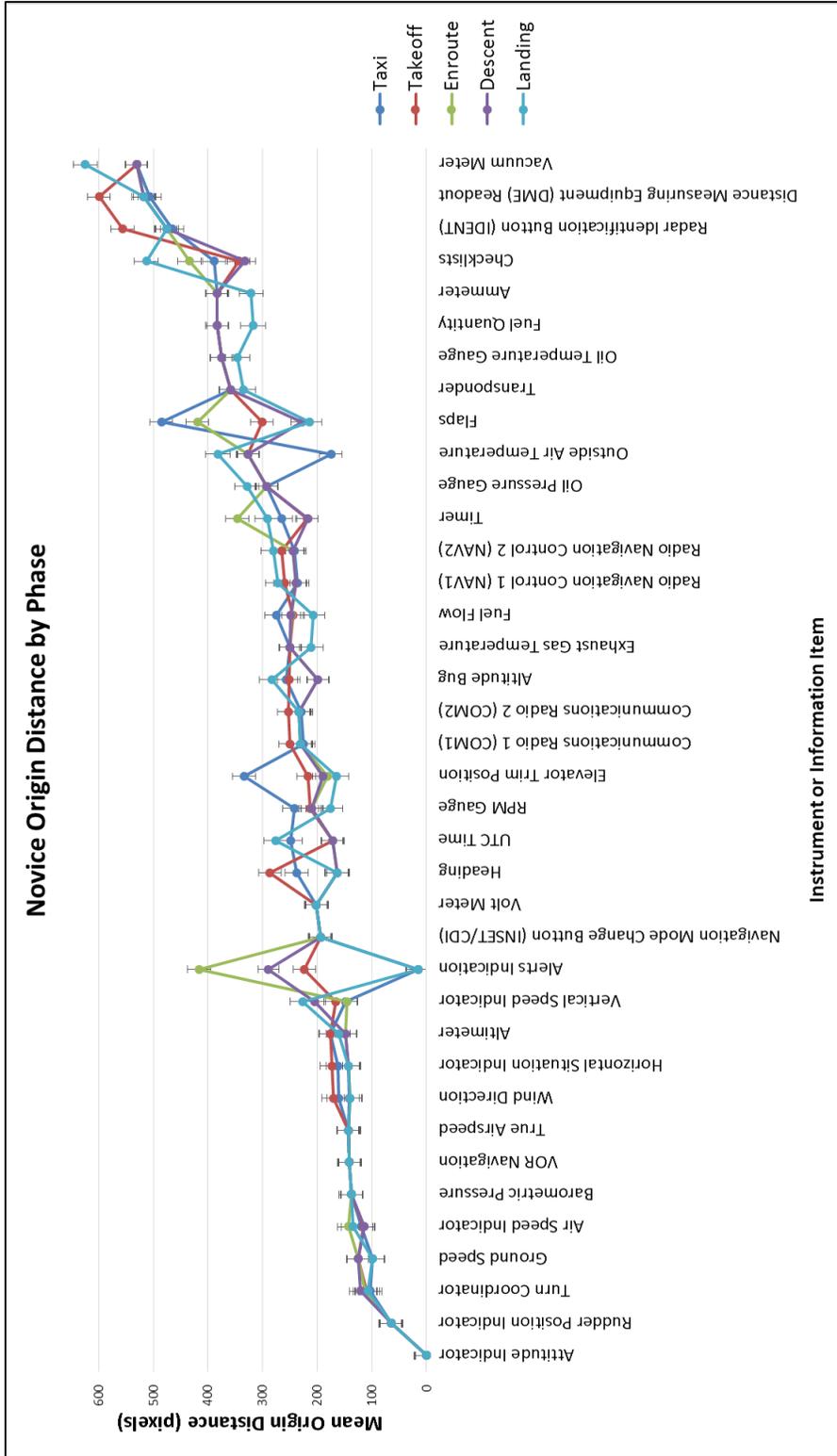


Table 15 - Mean Origin Distance for novice participants by phase.

**Table 8.** Highest priority information by phase of flight.

Information Element	Flying								Planning		
	TO	Clmb	TTC	Cruse	Desc	App	Land	Num	PP*	IFP+	Num
Aircraft configuration	X	X				X	X	4	X		1
Engine health	X	X	X	X	X	X	X	7			0
Fuel quantity	X							1	X	X	2
Fuel selection	X					X		2			0
RPM (power)	X	X	X	X	X	X	X	7			0
Altitude - AGL	X	X	X	X	X	X	X	7			0
Altitude - MSL		X			X	X	X	4	X	X	2
Distance								0		X	1
Bank		X				X	X	3			0
Pitch (attitude)	X	X			X	X	X	5			0
Yaw	X					X	X	3			0
Course		X	X	X	X			4		X	1
Heading	X	X		X		X		4		X	1
Track		X		X	X	X		4			0
Waypoints				X				1	X	X	2
Airspeed	X	X	X	X	X	X	X	7		X	1
Ground speed				X				1		X	1
Vertical velocity						X	X	2			0
Time - ETA/ETE								0	X	X	2
Airport configuration					X	X	X	3	X	X	2
Runway aim point						X	X	2			0
Runway remaining							X	1			0
ATC comm	X	X	X	X	X	X	X	7		X	1
Traffic / other comm	X	X			X	X	X	5			0
Obstructions	X	X				X	X	4	X		1
Traffic	X	X	X	X	X	X	X	7			0
Airspace		X			X	X		3	X	X	2
General weather	X			X	X	X	X	5	X	X	2
Wind	X					X	X	3	X	X	2

\* Preflight planning

+ In-flight planning

Table 16 - A table from *Priorities, Organization, and Sources of Information Accessed by Pilots in Various Phases of Flight* (Schvaneveldt, Beringer, Lamonica, Tucker & Nance, 2000).

## Figures

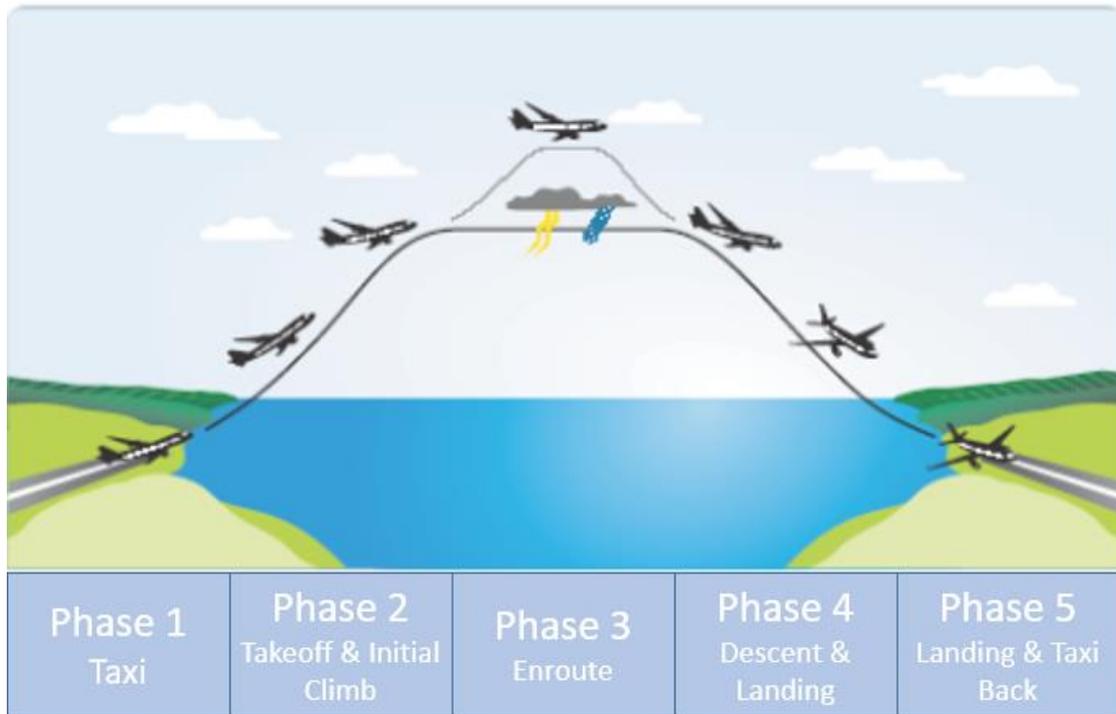


Figure 1 - A photo of the major phases of flight.



Figure 2 - The Garmin G1000 flight deck in a Cessna 172SP.



*Figure 3 - An analog cockpit from a Cessna 172.*

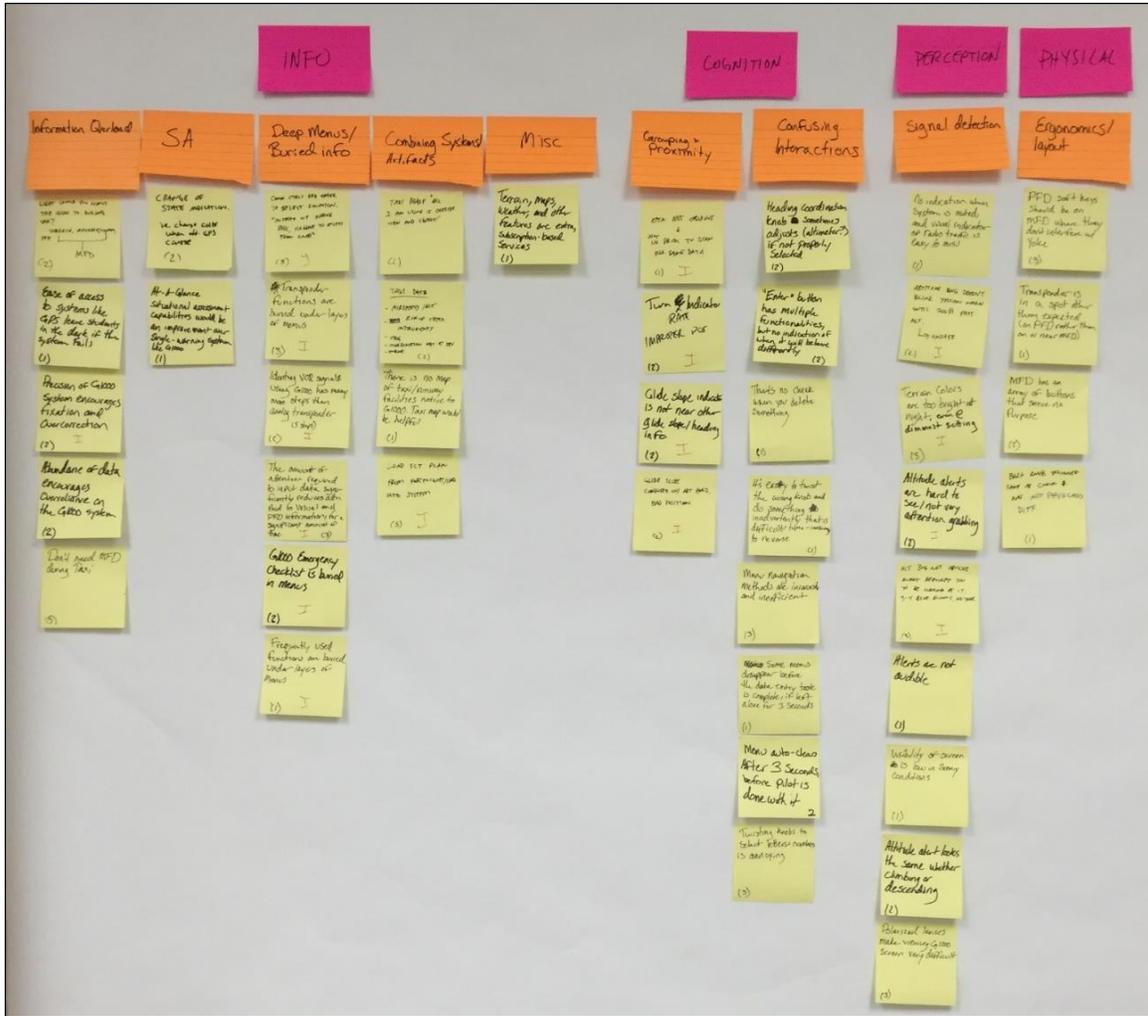


Figure 4 – The work activity affinity diagram for synthesis of contextual inquiry data.

### Air Inter Flight 148 Flight Path Animation

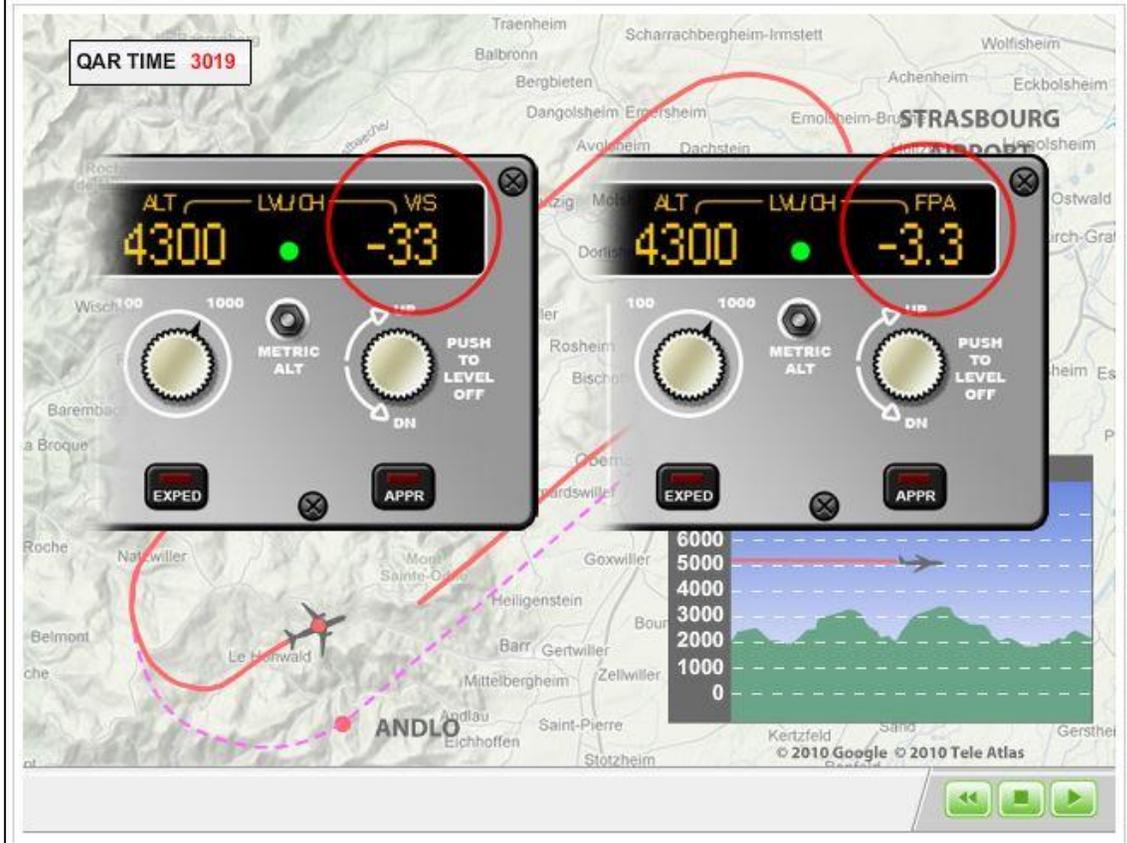


Figure 5 - An NTSB animation of the display mode which caused Inter Air Flight 148 to crash.

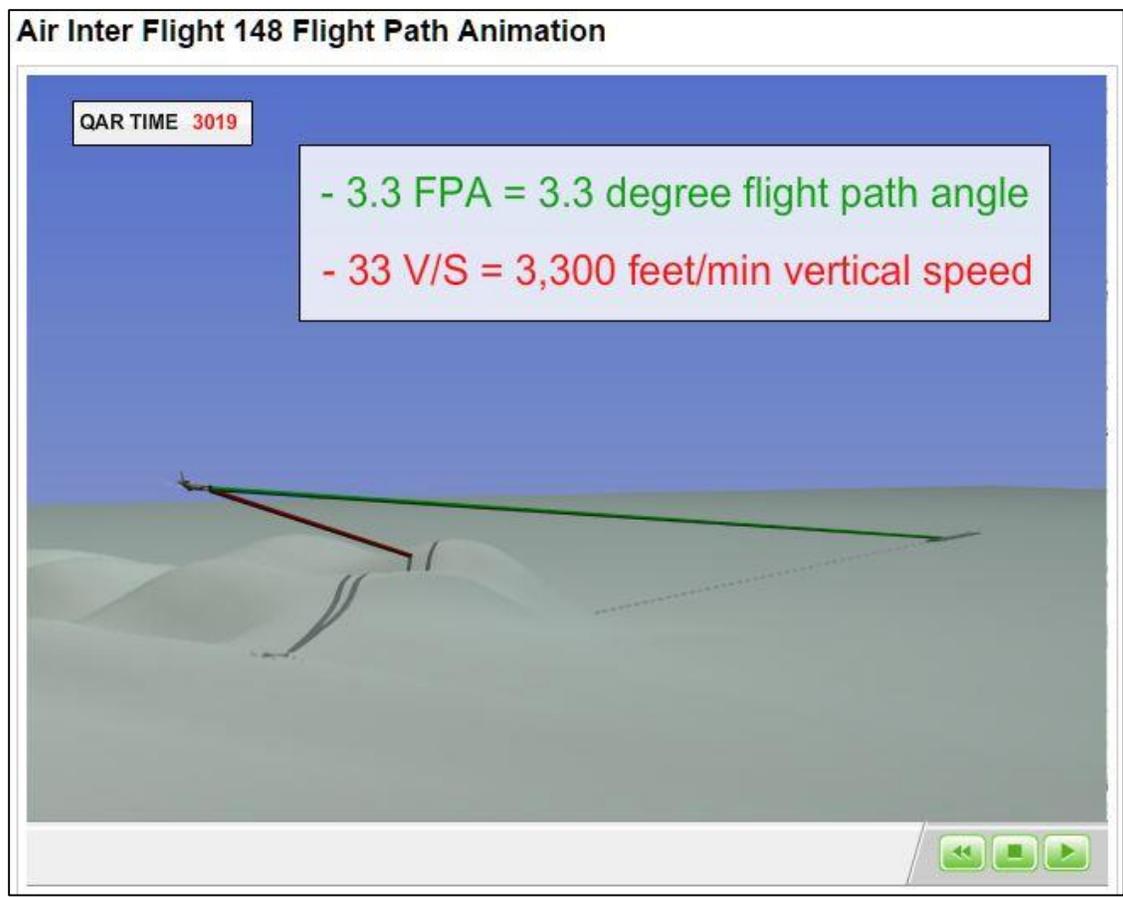


Figure 6 - Screen shot from the NTSB accident animation demonstrating the intended Flight Path Angle vs Vertical Speed Mode, flight paths.



*Figure 7 - An Angle-of-Attack (AOA) indicator mounted on the dash of a small aircraft. The red down arrow indicates that AOA is too high, airspeed is too slow and the nose should be pointed down. The yellow arrow indicates that AOA is too low, airspeed is too fast and the nose should be pulled up. The green circle illuminates when AOA is in the optimum zone for landing. A green bottom bar (not illuminated) represents straight and level flight.*

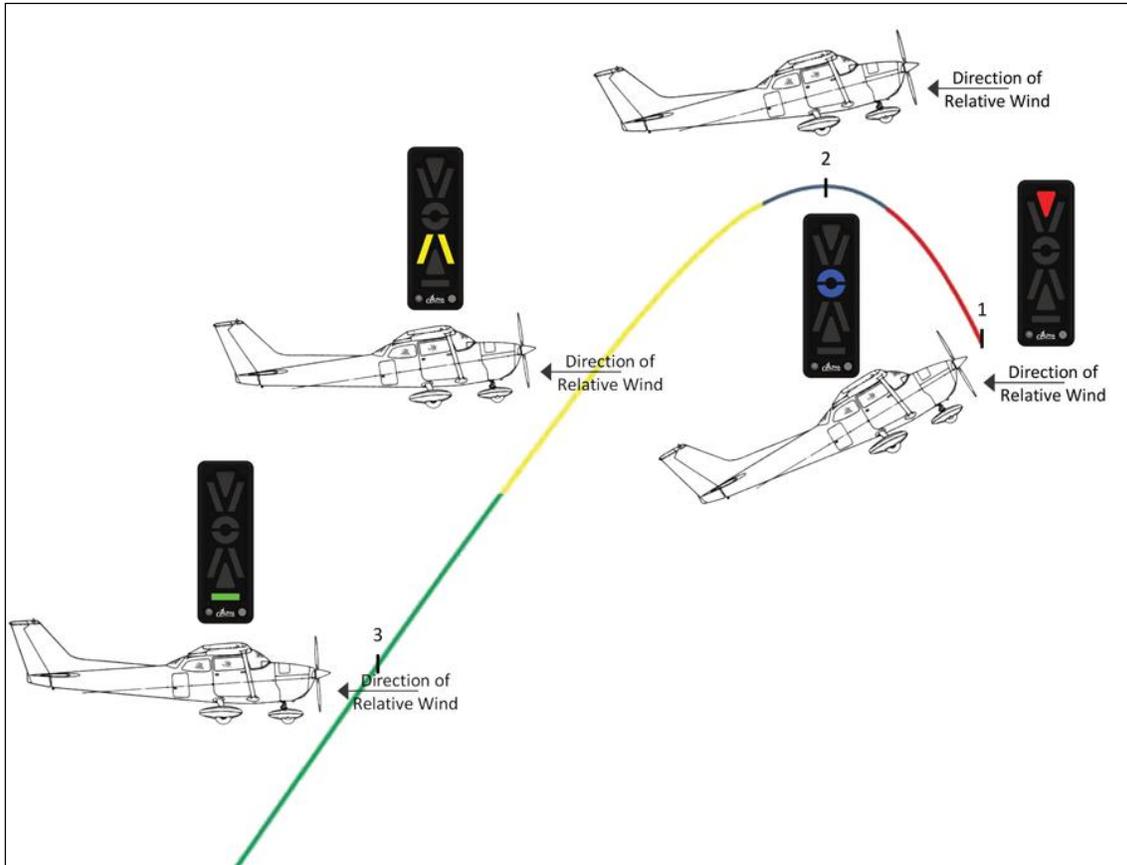


Figure 8 – A demonstration of AOA, relative to aircraft attitude.

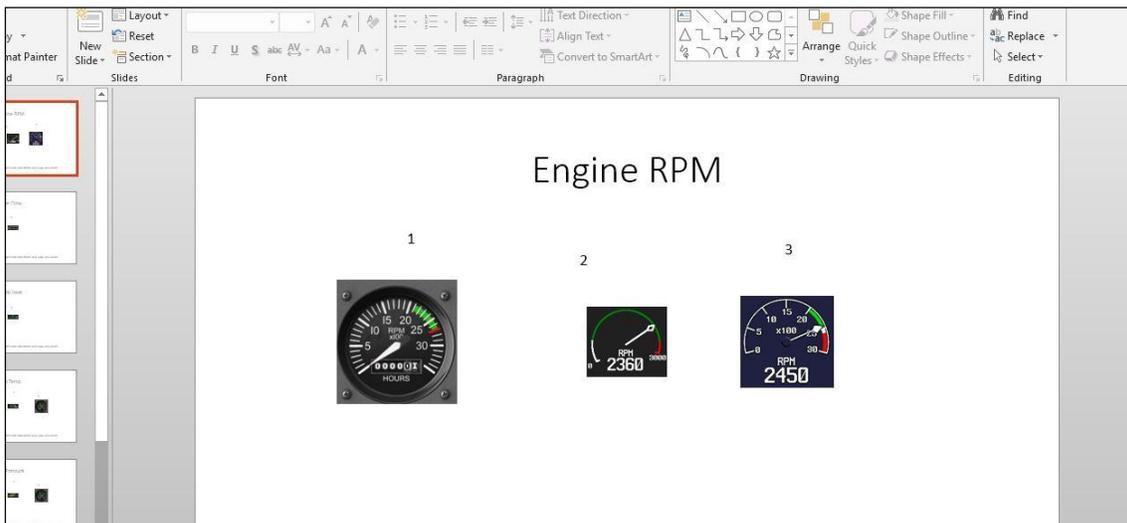


Figure 9 – An example PowerPoint slide, showing options of RPM options.

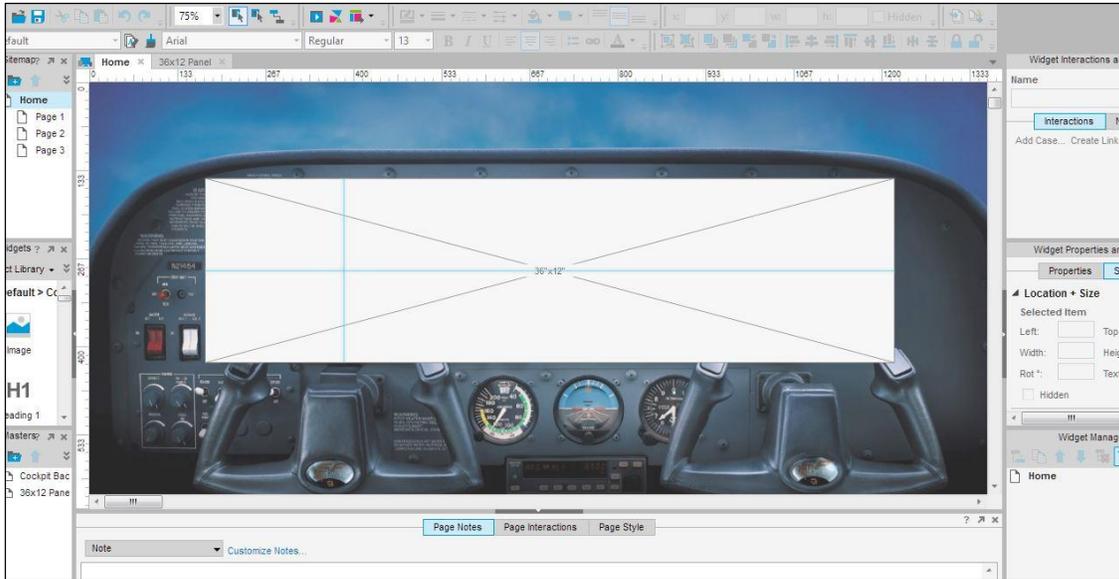


Figure 10 – Axure Dynamic Panel using a Cessna cockpit for context during sessions.

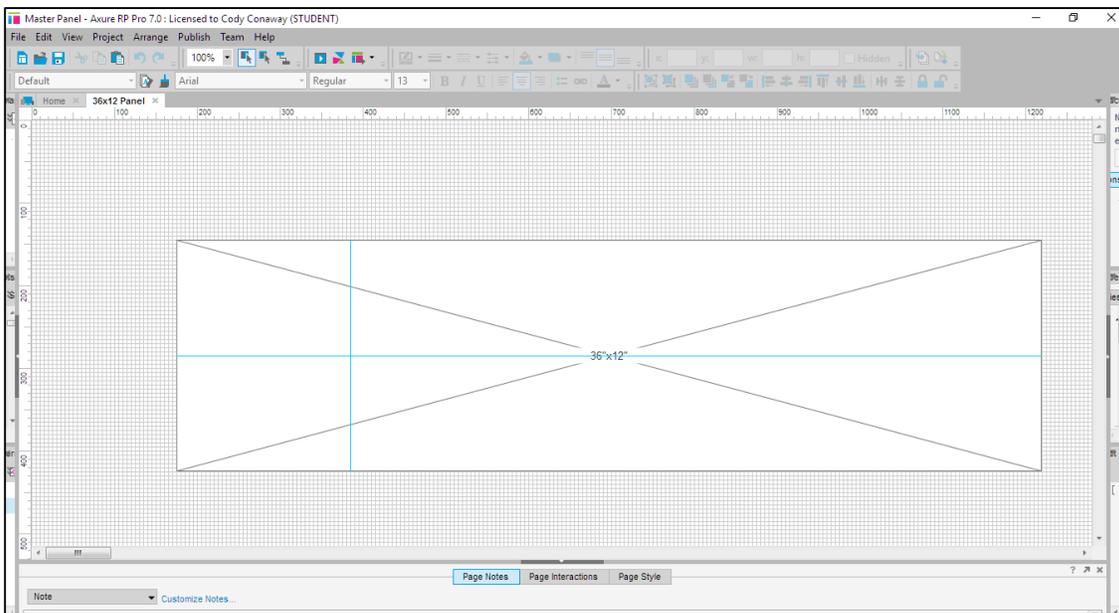


Figure 11 – Axure Dynamic Panel. The 36"x12" background in Axure used to place items.

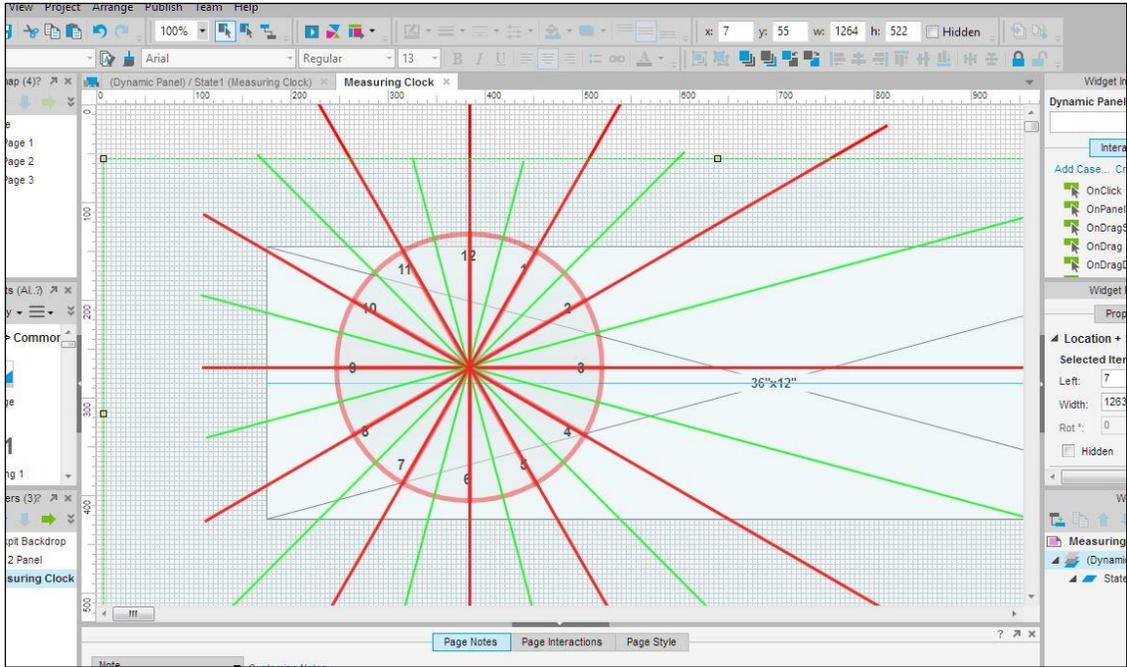


Figure 12 – The Clock Tool created for measuring Clock Angle. The tool is copied and pasted over the top of a participant’s ADI for measurement.

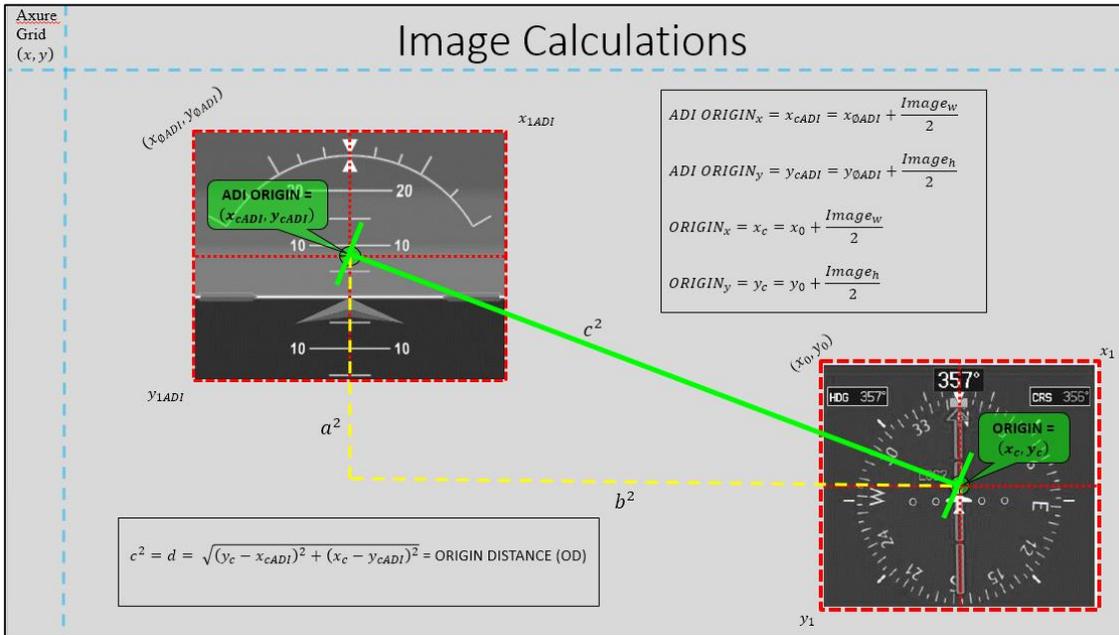


Figure 13 - A photo of how image calculations were performed.



Figure 14 – A clock image representing quadrants used to cluster items.

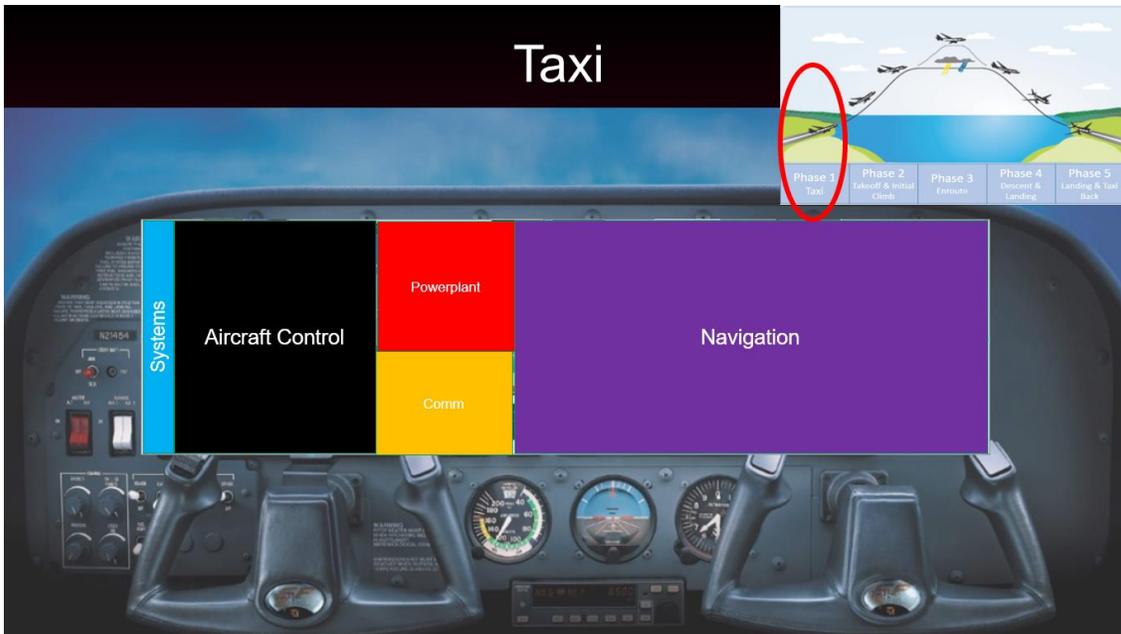


Figure 15 – Taxi Phase Template

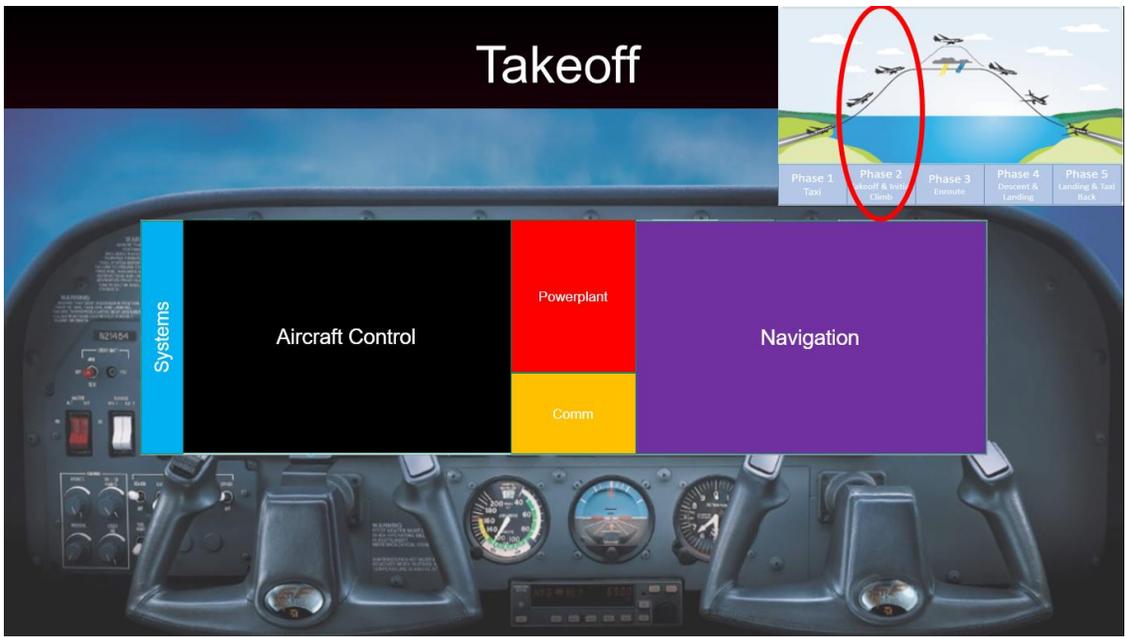


Figure 16 – Takeoff Phase Template



Figure 17 – Enroute Phase Template



Figure 18 – Descent Phase Template



Figure 19 – Landing Phase Template

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APPENDIX A  
PRE-TEST QUESTIONS

- 1) Do you possess an Instrument Rating in a fixed-wing aircraft? Yes or No.
- 2) What is your age?
- 3) How many total flight hours do you have?
- 4) Approximately, how many years have you been flying airplanes?
- 5) What is the highest level of fixed-wing pilot license you currently possess?
  - a. Private Pilot
  - b. Commercial Pilot
  - c. Airline Transport Pilot (ATP)
  - d. Certified Flight Instructor (CFI)
  - e. Certified Flight Instructor-Instrument (CFI-I)
  - f. Certified Flight Instructor Multi-Engine (MEI)
  - g. Experimental Test Pilot
- 6) Other than Instrument, what other ratings or endorsements do you currently possess? (Check all that apply)
  - a. Single-Engine Land
  - b. Single-Engine Sea
  - c. Multi-Engine Land
  - d. Multi-Engine Sea
  - e. Complex Aircraft
  - f. High-Performance
  - g. High-Altitude
  - h. Aerobatic

- i. Tail-Wheel
- 7) Do you also have a rating in a rotary-wing aircraft? Yes or No.
- 8) Select the type of aircraft engine(s) you have been trained to operate.
- a. Turbojet
  - b. Turboprop
  - c. Turbofan
  - d. Turboshaft
  - e. Experimental
- 9) Which type of cockpit did you use when first learning to fly?
- a. Completely analog (steam gauges)
  - b. Completely digital (only backup steam gauges)
  - c. Hybrid (part analog and part digital, e.g. analog with a stand-alone GPS)
- 10) I have never flown an aircraft with an analog cockpit. True or False.
- 11) I have never flown an aircraft with a digital cockpit. True or False.
- 12) If you began training on an analog system, how many hours did you accumulate prior to beginning digital cockpit use?
- 13) Approximately, how many flight hours have you spent using a digital cockpit?
- 14) Approximately, how many flight hours have you spent using the Garmin G1000 flight deck?
- 15) What is the date of your most recent flight?
- 16) My most recent flight was \_\_a VFR flight\_\_ or \_\_an IFR Flight\_\_.
- 17) What was the date of your most recent actual IMC flight?

18) Do you have military or government (any level) agency flight experience? Yes or No.

19) In what military service or government organization were/are you a pilot?

- a. US Marine Corps
- b. US Navy
- c. US Air Force
- d. US Coast Guard
- e. Federal Law Enforcement Agency (NSA, CIA, FBI, DHS, ICE, BATFE, etc.)
- f. State Law Enforcement
- g. Local Law Enforcement

20) Of your total flying hours, how many are from the military or government environment you selected above?

21) Are you rated in a fixed-wing aircraft?

22) Are you rated in a rotary-wing aircraft?

23) Were you a fixed-wing Instructor Pilot?

24) Were you a rotary-wing Instructor Pilot?

25) Did you train other flight instructors on providing instruction to students? (Were you an Instructor Pilot-Instructor?)

26) If you were an Instructor Pilot, how many total hours did you log in this capacity?

## APPENDIX B

### ORIGIN DISTANCE (IMAGE CENTER AND DISTANCE) CALCULATIONS

- 1) Using the given image location, calculate the image origin (x, y) using the Center of Gravity (COG) Formula (Figure 13), where subscript “c” is the image center, and

$$COG = (x_c, y_c), \frac{x_2 - x_1}{2} = x_c \text{ and } \frac{y_2 - y_1}{2} = y_c$$

- 2) Axure design board origin for the Attitude Indicator (ADI) is given as an (x, y) coordinate in the upper left corner of the image ( $x_{ADI}, y_{ADI}$ ). Origin Distance was calculated by first determining origin coordinates ( $x_{cADI}, y_{cADI}$ ). Using the COG formula,

$$COG = (x_{cADI}, y_{cADI}), \frac{x_{1ADI} - x_{\emptyset ADI}}{2} = x_{cADI} \text{ and } \frac{y_{1ADI} - y_{\emptyset ADI}}{2} = y_{cADI}$$

where  $x_{1ADI}$  is the top right corner of the ADI image,  $y_{1ADI}$  is the bottom left corner of the ADI image, and ( $x_{\emptyset ADI}, y_{\emptyset ADI}$ ) is the Axure given coordinate and upper left corner of the ADI, calculate the COG ( $x_{cADI}, y_{cADI}$ ) for the Attitude Indicator and insert the result into the Excel sheet for item calculation.

- 3) Perform the same procedure to find the center of every remaining item using,

$$COG = (x_c, y_c), \frac{x_1 - x_0}{2} = x_c \text{ and } \frac{y_1 - y_0}{2} = y_c,$$

where  $x_1$  is the top right corner of the item image,  $y_1$  is the bottom left corner of the item image, ( $x_0, y_0$ ) is the Axure image coordinate, and the result is the item COG ( $x_c, y_c$ ). Insert the result into the Excel sheet for item calculation.

- 4) Using the distance formula,

$$d = \sqrt{(y_c - x_{cADI})^2 + (x_c - y_{cADI})^2},$$

determine the pixel distance between ( $x_{cADI}, y_{cADI}$ ) and ( $x_c, y_c$ ) for every item. Insert the result into Excel for item calculation.

APPENDIX C  
CUSTOM ITEMS REMOVED

- 1) ATC instructions for arrival and approach. Clearances recorded and transcribed to text.
- 2) ATC instructions for clearance and taxi route. Recorded and transcribed to text.
- 3) ATC instructions for landing/taxi. Recorded and transcribed text.
- 4) ATC instructions for takeoff. Recorded and transcribed text.
- 5) Diagram button
- 6) Directions/waypoints/altitudes/frequencies/recorded and transcribed text.
- 7) Dual cue FD bars ADI display
- 8) Altimeter digital readout.
- 9) North up/track up button
- 10) Radar altimeter
- 11) AMPS2 engine gauges
- 12) EGT2 engine gauges
- 13) FUELFLOW2 engine gauges
- 14) FUELQTY2 engine gauges
- 15) OILTEMP1 engine gauges
- 16) OILTEMP1 engine gauges
- 17) VOLTS1 engine gauges
- 18) MENU11 CHKLST electrical buses, circuit breakers
- 19) MENU11 CHKLST shutdown taxi
- 20) MENU11 CHKLST start up after startup, taxi run up
- 21) Speed bug button

22) Line select keys button

APPENDIX D

CRITICAL NAVIGATION ITEMS REMOVED AND ANALYZED SEPARATELY

- 1) GPS RNAV Approach Guidance (HSI)
- 2) Departure Plate (SID)
- 3) Approach Plate
- 4) Automatic Direction Finder
- 5) Composite Navigation View
- 6) Cross Track Deviation
- 7) Direct Track
- 8) Highway Chart
- 9) Localizer Indication
- 10) Marker Indicator Light Button
- 11) Marker Indicator Lights
- 12) Standard Arrival Procedure (STAR)
- 13) Terrain Mode Button
- 14) Topographical Map
- 15) VFR Chart with GPS
- 16) Taxi Diagram

APPENDIX E  
INFORMATION CATEGORIES

1) Aircraft Control

1. Air Speed Indicator
2. Altimeter
3. Altitude Bug
4. Artificial Horizon
5. Attitude Indicator
6. Barometric Pressure
7. Course
8. Elevator Trim Position
9. Flaps
10. Glide Slope Indicator
11. Heading
12. Horizontal Situation Indicator
13. Outside Air Temperature
14. Rudder Position Indicator
15. True Airspeed
16. Turn Coordinator
17. Vertical Speed Indicator
18. Wind Direction

2) Navigation

1. Distance Measuring Equipment (DME) Readout
2. Distance to next waypoint

3. Enroute Low Chart
  4. ETE
  5. Flight Planner Menu
  6. GPS Track
  7. Ground Speed
  8. Navigation Mode Change Button (INSET/CDI)
  9. Navigational Chart
  10. Nearest Button (NRST)
  11. Omni-Bearing Selector (OBS)
  12. Radio Navigation Control 1 (NAV1)
  13. Radio Navigation Control 2 (NAV2)
  14. Switch to Topographical Map Button
  15. Tone Button (TONE)
  16. VOR Navigation
  17. Waypoint Selection Name
  18. Weather Graphical Overlay
- 3) Communications
1. Communications Radio 1 (COM1)
  2. Communications Radio 2 (COM2)
  3. Radar Identification Button (IDENT)
  4. Transponder
- 4) Systems

1. Advisory Indication
2. Alerts Indication
3. Auto Pilot Button
4. Checklists
5. Clock
6. Local Time
7. Timer
8. Traffic Warning
9. UTC Time

5) Powerplant

1. Ammeter
2. Exhaust Gas Temperature
3. Fuel Flow
4. Fuel Quantity
5. Oil Pressure Gauge
6. Oil Temperature Gauge
7. RPM Gauge
8. Vacuum Meter
9. Volt Meter

APPENDIX F  
PHASE OF FLIGHT INCONSISTENCIES

1) Navigation

- a. Distance to next waypoint
- b. ETE
- c. Navigational Chart
- d. Waypoint Selection Name

2) Systems

- a. Local Time
- b. Traffic Warning

## APPENDIX G

### ITEMS REMOVED FOR EXPERT-NOVICE COMPARISONS

- 1) Advisory Indication
- 2) Auto Pilot Button
- 3) Clock
- 4) Course
- 5) Distance to next waypoint
- 6) Enroute Low Chart
- 7) ETE
- 8) Flight Planner Menu
- 9) Glide Slope Indicator
- 10) GPS Track
- 11) Local Time
- 12) Navigational Chart
- 13) Nearest Button (NRST)
- 14) Omni-Bearing Selector (OBS)
- 15) Switch to Topographical Map Button
- 16) Tone Button (TONE)
- 17) Traffic Warning
- 18) Waypoint Selection Name
- 19) Weather Graphical Overlay

APPENDIX H  
VISUAL ANGLE CONVERSION

- 1) Theoretical display size fit to a Cessna instrument panel is 36" x 12" @ 57cm (22.44 inches) standard viewing distance.
- 2) *Design board* = 1045 x 280 *pixels* (36" x 12")
- 3) 1 *inch* = 2.54 *cm*  $\approx$  1 *degree Visual Angle*
- 4) 36" \* 2.54*cm* = 91.44*cm*
- 5) 12" \* 2.54*cm* = 30.48*cm*
- 6)  $\frac{91.44\text{cm}}{1045\text{px}} \times \frac{30.48\text{cm}}{280\text{px}} = 0.0875 \frac{\text{deg}}{\text{px}} \times 0.1088 \frac{\text{deg}}{\text{px}}$
- 7) *Design board* = 1045 x 280 *px* (36" x 12") = 91.44° x 30.46° *Visual Angle*

APPENDIX I

NOTIFICATION OF IRB APPROVAL FOR RESEARCH USING HUMAN SUBJECTS

*Template:IRB\_T\_Post-Review\_Approved*

## **Notification of Approval**

**To:** Robert Gray

**Link:** STUDY00003525

**P.I.:** [Robert Gray](#)

**Title:** Evaluating aviation displays

**Description:** This submission has been approved.

To review additional details, click the link above to access the project workspace.