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Pilot Performance and Eye Movement Activity with Varying Levels of Display Integration in a Synthetic Vision Cockpit

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PILOT PERFORMANCE AND EYE MOVEMENT ACTIVITY WITH VARYING LEVELS OF DISPLAY INTEGRATION IN A SYNTHETIC VISION COCKPIT

by

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ABSTRACT

PILOT PERFORMANCE AND EYE MOVEMENT ACTIVITY WITH VARYING LEVELS OF DISPLAY INTEGRATION IN A SYNTHETIC VISION COCKPIT

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Old Dominion University, 2004
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The primary goal of the present study was to investigate the effects of display integration in a simulated commercial aircraft cockpit equipped with a synthetic vision display. Combinations of display integration level (low/ high), display view (synthetic vision view / traditional display), and workload (low/high) were presented to each participant. Sixteen commercial pilots flew multiple approaches under IMC conditions in a moderate fidelity fixed-base part-task simulator. Pilot performance data, visual activity, mental workload, and self-report situation awareness were measured.

Congruent with the Proximity Compatibility Principle, the more integrated display facilitated superior performance on integrative tasks (lateral and vertical path maintenance), whereas a less integrated display elicited better focus task performance (airspeed maintenance). The synthetic vision displays facilitated superior path maintenance performance under low workload, but these performance gains were not as evident during high workload.

The majority of the eye movement findings identified differences in visual acquisition of the airspeed indicator, the glideslope indicator, the localizer, and the altimeter as a function of display integration level or display view. There were more fixations on the airspeed indicator with the more integrated display layout and during high workload trials. There were also more fixations on the glideslope indicator with the more integrated display layout. However, there were more fixations on the localizer with the less integrated display layout. There were more fixations on the altimeter with the more integrated display and with the traditional view. Only a few eye movement differences were produced by the synthetic vision displays; pilots looked at the glideslope indicator and the altimeter less with the synthetic vision view. This supports the notion that utilizing a synthetic vision display should not adversely impact visual acquisition of data. Self-report mental workload and situation awareness data highlight additional benefits of display integration and synthetic vision displays. Design and retrofit implications are discussed and future research is suggested to further examine these issues.

This dissertation is dedicated to my daughter.

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LIST OF ABREVIATIONS

AGL	Above Ground Level
ASL	Applied Science Laboratories
ANOVA	Analysis of Variance
AOI	Area of Interest
ASRS	Aviation Safety Reporting System
ATC	Air Traffic Control
CFIT	Controlled Flight Into Terrain
DTED	Digital Terrain Elevation Data
EADI	Electronic Attitude Direction Indicator
EFIS	Electronic Flight Instrument System
EGE	FAA locator code for Eagle County, CO Airport
EGPWS	Enhanced Ground Proximity Warning System
FAA	Federal Aviation Administration
FMS	Flight Management System
GLM	General Linear Model
GPS	Global Positioning System
GS	Glideslope Indicator
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
LAAS	Local Area Augmentation System
LNAV	Lateral Navigation
NASA	National Aeronautics and Space Administration
NTSB	National Transportation and Safety Board
nmi	Nautical Miles
MSL	Mean Sea Level
OTW	Out The Window
PFD	Primary Flight Display
RA	Resolution Advisory (used in TCAS)
SVS	Synthetic Vision System
TA	Traffic Advisory (used in TCAS)
TAWS	Terrain Avoidance Warning System
TCAS	Traffic Alert and Collision Avoidance System
VFR	Visual Flight Rules
VNAV	Vertical Navigation
VMC	Visual Meteorological Conditions
VSI	Vertical Speed Indicator

INTRODUCTION

Technological advances have facilitated the design of a myriad of highly evolved aviation displays designed to enhance pilot performance. These advanced displays have led to improvements in aviation operations, as well as an overall reduction in aviation-related fatalities since the 1970s (NTSB, 1997). However, the unavoidable issue of reduced visibility continues to be a chief contributing factor in both minor and catastrophic aviation accidents (Khatwa & Roelen, 1999; NTSB, 2001; Wiener & Nagel, 1988). As such, the task of mitigating poor visibility situations continues to be of prime importance in the aviation industry.

An attempt to curtail limited visibility aviation incidents is being addressed by revolutionary new cockpit displays collectively known as synthetic vision system (SVS) displays. Synthetic vision system displays integrate database and real-time terrain and environment data with flight critical information to create an informative and visually appealing primary flight display. The focus of the current study was to investigate the impact of a new display designed to mitigate low visibility situations in

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The model for this dissertation is *Human Factors*.

commercial aviation, in terms of pilot performance, visual activity, subjective workload, and situation awareness.

Evolution of Cockpit Displays

Cockpit displays have profoundly matured since their original design (Meister, 1999; Newman, 2001; GAMA, 2000; Wiener & Nagel, 1988). Early human factors research influenced cockpit design and resulting changes were made to improve specific displays and overall cockpit layout (e.g., Birmingham & Taylor, 1954; Fitts & Jones, 1947). This type of research flourished after World War II to continue to improve aviation displays.

These decades of research have led to a proliferation of new aviation displays. Many newer displays aim to reduce controlled flight into terrain (CFIT) incidents; these incidents are among the leading causes cited for aviation related accidents and fatalities each year (Bliss, 2003; Khatwa & Roelen, 1999; NTSB, 1997; Shappell & Wiegmann, 1997). Graeber (1996) estimates that CFITs were responsible for 36.8% of aviation accidents and 53.6 % of aviation fatalities between 1988 and 1993.

Flight management systems (FMS) can also drastically mitigate circumstances that have the potential to lead to CFIT (Beevis, 1987; Curry, 1985; Nagel, 1988; Theunissen, 1993). These systems assist the pilot by combining error and error rate information to provide control command information. This information is then compared with the current control commands to determine a steering command. After entering the proper information into the FMS, the pilot must simply follow steering commands to stay on course. This type of automation utilized on modern commercial aircraft during typical flight operations alters the pilot's role to that of recognizing and following the steering commands. Although the FMS assists the pilot in precision tasks it does not reduce the attentional demands continuously imposed on the pilot.

One display designed to reduce CFIT related incidents is the Enhanced Ground Proximity Warning System (EGPWS) that provides a salient auditory alert if there is inadequate separation from the ground or an excessive sink rate to the ground. Other displays such as the Traffic Alert and Collision Avoidance System (TCAS) alert the pilot to potential traffic conflicts.

A TCAS display, for example, utilizes sophisticated algorithms to recommend the optimal maneuver to avoid potential traffic threats. This type of mathematical decision aid can resolve only simple one-on-one conflicts without consideration for other potential threats (e.g., terrain). There are two basic versions of TCAS, TCAS I and

TCAS II (see *Introduction to TCAS*, FAA, 1990 for a review). TCAS I provides traffic advisories (TAs) of potential conflicts. TCAS II provides both TAs and resolution advisories (RAs) of evasive maneuver commands.

A Congressional Mandate directed the FAA to require aircraft that carry more than 30 passengers to be equipped with TCAS II by December 30, 1991 (Public Law 100-223). The FAA also mandated that 10-30 passenger aircraft be equipped with TCAS I by 1993 (FAA, 1993; 1998). The algorithms for both TCAS I and TCAS II continue to evolve. The most recent version of TCAS II with logic version 7.0 aims to reduce false alarms. This version of TCAS II accounts for the higher number of aircraft near airports and omits repeated TAs about the same conflict (FAA, 2001).

Problems with Existing Systems. Current warning systems, wile improving aviation safety, still have problems. The TCAS display does not provide adequate visual representation of the aircraft in its current and future environment to facilitate a decision regarding successful avoidance of potential traffic threats. Excessive false alarms with TCAS continue to be a crucial concern (Bliss, 2003). Because TCAS still has a very high false alarm rate (Bliss, Freeland, & Millard, 1999; Edworthy, 1996), pilots often question the reliability of the RA which can retard the necessary evasive maneuver (Merwin & Wickens, 1996; Parasuraman & Riley, 1997). On the other hand, pilots have also been shown to overuse TCAS by delaying obvious evasive action while waiting for a RA (Rantanen, Wickens, Xu, & Thomas, 2004). Pilots also miss critical information because of loud TCAS alerts (FAA, 1998).

Current displays such as FMS and TCAS do not promote adequate spatial situation awareness. This inadequacy is illustrated by the alarming rate at which CFITs still occur even with aircraft equipped with these displays and warnings (Khatwa & Roelen, 1999; NTSB, 1997). This will become progressively more important as increasing numbers of commercial aircraft occupy the sky (Williams et al., 2001). Cockpit displays that facilitate situation awareness by portraying potential obstacles in a timely manner are needed (Endsley, 1999; 2000). Along this line, the next generation of cockpit displays must be designed to capitalize on human attentional processing capabilities.

Attention

The ongoing process of perceiving, comprehending, and interpreting flight-critical information creates profound attentional demands on the commercial pilot. Attention is a limited resource that facilitates perception of the proximal environment (Fracker, 1989; Parasuraman, 1998). As such, attentional demands cannot exceed available mental capacity to perform cognitive tasks (Pashler, 1998).

Components of Attention. Parasuraman (1998) identified selection, vigilance, and control as three distinct components of attention. Computational limitations of the human mind demand selectivity for processing multiple stimuli. The process of selective attention facilitates preferential processing of relevant stimuli to facilitate goal directed behavior in a coherent manner. Sustaining attention over a period of time is also vital in complex multi-tasking situations such as piloting a commercial aircraft. The second component of attention, vigilance, involves maintaining goal-directed attention over a long time period. However, the time during which people are able to remain vigilant is somewhat limited. People typically cannot remain vigilant for more than 30 minutes before performance on vigilance tasks begins to deteriorate (Davies & Parasuraman, 1982; Scerbo, 2001; See, Howe, Warm, & Dember 1995; Warm, 1984). Maintaining goal-directedness in a dynamic environment typically requires that behavioral and cognitive actions occur concurrently.

The third attentional component, control, coordinates informational processing activities in the brain. Sometimes referred to as divided attention, people use the control component of attention to distribute their attentional resources among multiple competing attentional sources. Parasuraman (1998) suggests that the success of control depends upon the nature of information involved in the perception of simultaneous events. Control, like selection, is also limited by the capacity of the human mind, especially during multi-tasking situations in which responses must be made to multiple input sources (Corker, 2000; Hockey, 1986). The impact a new cockpit display may have on attention and more importantly potential failures of attention must be investigated.

Mental Workload

Researchers agree that introducing a new display to an already complex environment has the potential to increase an operator's workload (Eggemeier, Wilson, Kramer, & Damos, 1991; Gopher & Donchin, 1986; Lysaght et al., 1989; Tsang & Wilson, 1997). However, there is still debate about how to define mental workload. Lysaght et al., (1989) suggest that workload should be defined in terms of 1) the amount of work to be performed and the mental resources available to perform that work, 2) performance time constraints, or 3) the operator's subjective workload experience. Damos (1991) defines mental workload as a hypothetical construct used to describe the cost of performing one task in terms of the reduction in mental capacity to perform concurrent tasks. Mental workload has also been described as an intervening variable that affects environmental demands and the capacity of a human operator Kantowitz, 1986). Eggemeier (1988) describes mental workload in terms of processing capacity that is necessary during task performance.

Central to these varying definitions is the notion that workload is related to the difference between available resources and resources demanded by a situation. Psychologists' definitions of workload tend to focus on the perceptual and cognitive demands imposed on the operator. Engineers, on the other hand, may take a more systems approach and define workload based on multiple task demands in a complex environment. Both the psychological and design aspects are of considerable importance when evaluating how a new cockpit display impacts workload.

It is important to consider the impact of a new cockpit display because operating a commercial aircraft has the potential to generate high workload, especially during critical periods of flight such as takeoff and landing (Andre & Hancock, 1995; Hart, 1982; Sanders, Simmons, Hofmann, & DeBonis, 1977; Shingledecker, 1983). Workload level can affect a person's attention because severely increased workload can interfere with selection and control activities whereas severely reduced workload could adversely affect vigilance (Andre & Hancock, 1995; DeDeyser & Javaux, 2000). For example, high workload can interfere with the pilot's ability to attend to and respond to multiple displays during critical periods of flight such as takeoff and landing (Mouloua, Hitt, & Deaton, 2001; Woods & Patterson, 2001).

High workload can also interfere with situation awareness (Endsley, 1991; Fracker & Davis, 1990; Vidulich, 2000; Wickens, 2001), allocation of effort strategies (Parasuraman, Sheridan, & Wickens, 2000; Stark, 1999), and can provoke human error (Kantowitz & Casper, 1988; Nagel, 1988; Reason, 1990, 2000). That is, human error is more likely during complex multi-tasking situations such as those encountered by pilots during takeoff and landing. As such, the Federal Aviation Administration requires certification of aircraft in terms of workload metrics and the US Air Force imposes workload criteria on new systems (Hancock & Desmond, 2001). On the other hand, unwanted effects of seriously reduced workload can manifest as high susceptibility to a vigilance decrement (Parasuraman & Hancock, 2001; Warm, Dember, & Hancock, 1996), boredom proneness (Sawin & Scerbo, 1995; Scerbo, 2001), or poor decision making (Andre & Hancock, 1995; Ruffell, 1979).

Managing mental workload is accomplished through allocation of effort; this in turn has a crucial effect on task performance (Bennett & Flach, 1992; Hancock & Caird, 1993; Pashler, Johnston, & Ruthruff, 2001; Stark, 1999). Wickens (1999) describes allocation of effort in terms of the cognitive processes required by each stage of the allocation process. Allocation of effort in a complex environment is moderated by the balance between mental resource supply and task demand.

Original explanations regarding capacity limitations of the information processing system led to single resource theories of attention (e.g., Kahneman, 1973; Moray, 1967). These theories suggested that one non-specific source of mental resources is shared by all mental processes and that high workload situations drain the one available supply. According to single resource theories, allocation of effort to one task simply leads to performance deficits on concurrent tasks (Moray, 1967). However, single resource theories do not provide an adequate explanation for effort allocation capability as a function of task type or modality (Sanders & McCormick, 1993).

This lack of explanation led to multiple resource theories to better understand allocation of effort. Wickens' Multiple Resource Theory suggests that several independent resources affect allocation of effort (Wickens, 2002a). Further, effort allocation is superior when concurrent tasks demand different mental resources. Wickens suggests that resources can be understood in terms of three dichotomous dimensions that are defined by stage (early versus late processing), modality (auditory versus visual encoding), and processing (spatial versus verbal coding). If concurrent tasks demand separate resources on any of these dimensions, allocation of resources will be more efficient and task difficulty is less likely to hinder peripheral task performance.

Evidence of effort allocation has been provided by numerous empirical studies that have demonstrated that performance on concurrent tasks is subject to processing capacity based limitations (Gopher, Brickner, & Navon, 1982; Schneider & Fisk, 1982; Sperling & Dosher, 1986). Proficiency of allocating effort in multi-tasking situations predicts performance and frequency of accidents (Sarter & Amalberti, 2000; Stark, 1999; Wickens & Hollands, 2000). For example, Damos (1978) demonstrated allocation of effort differences between novice and expert flight instructors. Recent research suggests that operators experiencing high workload in a multi-tasking environment may maintain overall performance but demonstrate inefficient allocation of resources to different tasks over time (Stark, 1999).

Allocation of effort capability is determined by the demands imposed on the operator and the degree of overlap in the processing resources required by concurrent tasks or functions (Schneider & Fisk, 1982; Wickens & Hollands, 2000). Functions requiring similar processing resources (e.g., concurrent central processing tasks) will be timeshared with less efficiency than functions requiring dissimilar resources (e.g., performing a central processing task and a motor output task simultaneously). These workload and allocation of effort issues must be considered when investigating a new cockpit display in an already complex environment.

Situation Awareness

Like mental workload, situation awareness is an important consideration in a complex environment. Smith and Hancock (1995) describe situation awareness as an adaptive construct that is "externally directed consciousness." Hendy (1995) suggests that situation awareness relates to a dynamic state of an operator's mental model that results from an ongoing process of interpreting newly acquired information. Wickens (2002b) incorporates multiple aspects of situation awareness in a recent definition. Wickens writes that "situation awareness is the continuous extraction of environmental information *about a system or environment*, the integration of this information with previous knowledge to form a coherent mental picture, and the use of that picture in directing further perception, anticipating *and responding to* future events (p. K2-1)."

Several of these researchers suggest that an operator's mental model of the operational environment affects his or her ability to maintain situation awareness. Wickens (1992) describes a mental model as a hypothetical construct that develops from cognitive representations of a system or environment. This representation forms through previous experiences and current observations to facilitate an understanding of system operation and performance consequences. The accuracy of an operator's mental model is pivotal for maintaining situation awareness, especially in complex systems such as aviation (Flach & Rasmussen, 2000; Fracker & Davis, 1990; Wickens, 2001).

Fracker (1988, 1989) suggests that the construct of situation awareness includes both spatial awareness (e.g., knowing where things are in space) and identity awareness (e.g., knowing exactly what the things in space are). Fracker identified important elements of situation awareness as the internal status of the system, the external status of the system, the relationship between the system and its environment, and the environment around the system. Endsley (1995a) used the elements identified by Fracker to specify three levels of situation awareness: 1) perception of pertinent elements in the environment; 2) comprehension of the current situation; and 3) projection of critical future events.

There are commonalities among these situation awareness definitions. First, situation awareness is both context dependent and extremely time sensitive. On the other hand, situation awareness is highly individual because it is based on the person's experience and knowledge. An accurate representation of automation mode, system status, and sub-system (i.e., the person's mental model) is pivotal to have good situation awareness. Two different people can have extremely different situation awareness given the exact same circumstances. This is partially because situation awareness is dynamic in nature in that it can change frequently without warning, especially in a complex system like a commercial aircraft cockpit.

Specific aviation-related aspects of situation awareness have been distinguished (Endsley, 1996a, 1999, 2000). She suggests that system situation awareness, spatial situation awareness, geographical awareness, and environmental situation awareness are important elements of situation awareness in aviation. Important components of system situation awareness include system status, mode awareness, equipment settings, ATC communications, projected effect of system malfunctions, and fuel management issues. Spatial situation awareness involves knowledge of attitude, altitude, heading, vertical velocity, flight path and clearances, aircraft capabilities and limitations, and projected flight path and landing routine. Geographical situation awareness involves operator awareness of the location of his or her aircraft relative to proximal aircraft, obstacles such as terrain, and landmarks such as waypoints and airports. Maintaining environmental situation awareness involves considering current and impending weather formations (including temperature, winds, etc.), visibility, turbulence, and areas to avoid.

Endsley (1996b) proposed a process model for categorizing situation awareness measurement techniques. Endsley based her model on the perception - action sequence of situation awareness. She notes that the stages are very closely related and identified separately only for the model. The stages include assessment processes, situation awareness, decisions, and performance. She identifies process indices, state of knowledge, behaviors, and performance as potential assessment techniques. Examining contributing processes that affect situation awareness can be useful in an overall assessment of situation awareness. This type of index could provide vital information about the relative priority of information sources. For instance, eye tracking apparati and other methods for measuring the acquisition of information can provide useful information regarding allocation of attention.

Subjective assessment of situation awareness provides useful insight into how much situation awareness an operator thinks he or she has in a given scenario. This is important because most operators of complex systems tend to know when they have adequate situation awareness or are experiencing periods of insufficient situation awareness (Endsley, 1999; Flach, 1994; Wickens, 2001, 2000). One subjective measure of situation awareness is the Situational Awareness Rating Technique (SART; Taylor, 1989). The SART is a questionnaire method that focuses on assessing the operator's knowledge in three main areas: 1) demands on attention resources, 2) supply of attention resources, and 3) comprehension of the situation. The SART assesses both environmental challenges and the operator's assessment of those challenges. The SART is reported to be a valid and reliable instrument (Selcon, Taylor, & Koritsas, 1991; Taylor & Selcon, 1991).

Eye Movements

Eye movements reflect underlying cognitive processes (Findlay, Walker, Kentridge, 1995; Hoffman & Subramanium, 1995). Eye tracking data can provide useful information about overall eye movement activity as well as insight into how pilots visually acquire data from specific flight instruments (Comstock, Harris, Coates, & Kirby, 1987; Harris et al., 1986; Kleiss, Curry, & Hubbard, 1988; Fitts, Jones, & Milton, 1950; Lintern, Thomley-Yates, Nelson, & Roscoe, 1987). A brief description of the human visual system and types of eye movements is provided before relevant research is introduced. Then, an eye tracking model that describes visual behavior in the cockpit is presented.

<u>The Human Visual System.</u> Eye movement activity creates the most numerous and frequent movements in the human body (Bachy-Rita, Collins, & Hyde, 1971; Bridgeman, 1992). The

physiology of oculomotor functioning is outside the scope of this paper (see Egeth & Yantis, 1997; Parasuraman, 1998; or Richardson & Spivey, 2004). Some basic characteristics of the human visual system are described here.

The human eye monitors a visual field of approximately 200 degrees. However, detailed information can be perceived only in the fovea, a small region approximately two degrees of visual angle (Fuchs, 1971; Graham, 1965; Levi, Klein, & Aitsebaomo, 1985). When people focus on an object, that object must be in the foveal region to be seen with great detail (O'Regan, Deubel, Clark, & Rensink, 2000). The eyeball can make pursuit and saccadic movements to accomplish this goal.

Types of Eye Movements. Pursuit movements, also known as smooth movements, allow the eye to follow a moving target. When humans view moving displays, pursuit eye movements are executed to focus on an item of interest. Saccadic movements, or saccades, consist of rapid movements between two discrete locations in the visual field that occur three to four times a second. Saccadic movements can be described in terms of the actual visual sampling process and the end result, a fixation. A fixation refers to a person's point of regard as he or she looks at a stationary target in a visual field. Mathematically, a fixation can be operationalized as the X and Y position coordinates measured during which the eye does not move more than one degree of visual angle for at least 100 msec. A dwell, on the other hand, occurs when a fixation or a series of contiguous fixations maintains within one area of interest. A dwell describes a time period in which a fixation, or a series of contiguous fixations, is within one area of interest.

Eye Movement Research. Eye movement research generally focuses on either visual search or visual scanning (Findlay et al., 1995; Gale & Johnson, 1984; Groner, Menz, Fisher, Monty, 1983). There has been extensive research examining visual search technique differences (Fisher, Coury, Tengs, & Duffy, 1989; Schneider & Fisk, 1982) in reading (Rayner, 1998), between parallel and serial tasks (Williams, Reingold, Moscovitch, & Behrmann, 1997; Zelinsky & Sheinberg, 1997), in graphs or maps (Lohse, 1993; Wickens, Kroft, & Yeh, 2000), and most recently web usability (Byrne, Anderson, Douglass, & Matess, 1999). Most of this research emphasizes search time to locate a target, although some visual search research has investigated search accuracy (e.g., Findlay, et al., 1995) and skill acquisition (e.g., Jordan, 1972).

Tullis' (1983) seminal work on display clutter introduced the concept of overall density to explain how search time increases as a function of number of items in a display (Biscaldi, Weber, Fischer, & Stuhr, 1995; Zelinsky & Sheinberg, 1995). Much research has been conducted to examine display clutter as well as other underlying cognitive principles of visual search (Baker, Morris, & Steedman, 1960; Findlay, et al., 1995; Jacob, 1991) including examining how color affects visual search (Bundensen & Pedersen, 1983; Carter, 1982; D'Zmura, 1991; Smith & Thomas, 1964).

The perceptual characteristics of visual activity during reading have also been studied at great length (see Rayner, 1998 for a review). Fixations can be influenced by semantics of the word (Just & Carpenter, 1980), text legibility (Kolers, Duchnicky, & Ferguson, 1981), syntactic difficulty (Ferreira & Clifton, 1986), conceptual difficulty (Rayner, 1995) and presentation modality (Levy, et al., 1985). Although people usually move their eyes forward when reading, approximately 10-15% of saccades move backward (Kennedy & Murray, 1987). Backwards saccades are thought to reflect processing difficulties (Murray & Kennedy, 1988).

Visual Search Research. Many visual search models have been proposed (e.g., Graham, 1965; Neisser, Novick, & Lazar, 1964; Wolfe, 1994). Zelinsky and Sheinberg (1995) offer two recent models to describe factors that may affect visual search behavior. The Variable Number Model predicts that increased visual display complexity should result in more fixations without increased duration during each fixation. Alternatively, the Variable Duration Model suggests that increased visual display complexity should result in increased time devoted to each fixation, without an increased number of fixations. They suggest that the Variable Number Model explains visual search behavior in complex serial tasks whereas the Variable Duration Model explains search behavior in complex tasks and with larger displays.

Visual Sampling Research. Another avenue of visual information acquisition research focuses on visual sampling, or scanning of information. Fitts and his colleagues conducted some of the earliest human factors research to examine pilots' visual sampling techniques (c.f., Fitts & Jones, 1947; Fitts, Jones, & Milton, 1950). Visual scanning research has continued to proliferate in applied settings such as driving (Dishart & Land, 1998; Gellatly & Kleiss, 2000; Theeuwes, 1994; Underwood, Chapman, Brocklehurst, Underwood, & Crundall, 2003) and aviation (Crawford, Burdette, & Capron, 1993; Harris, Glover, & Spady, 1986; Harris & Mixon, 1981; Kroft & Wickens, 2001; Prinzo, 2001; Sanders, et al., 1977; Spady, 1987; Stark, 2003; Tole, Stephens, Harris, & Ephrath, 1982; Wickens, Xu, Helleberg, Carbonari, & Marsh, 2000).

Differences between Visual Search and Visual Sampling. Visual search and visual sampling involve somewhat different higher cognitive processes (Stark & Ellis, 1981). For example, visual search requires the person to locate a static target within relatively consistent spatial locations. However, visually sampling information involves conducting multiple dynamic processes to attend to targets at varying locations (e.g., scanning a cockpit navigation display). The dependent variable utilized in visual search research is almost always response time whereas the proportion of visual activity distributed within specific areas of interest is measured in visual sampling research.

Finally, there is a very different cognitive process occurring in the two types of visual acquisition of information. Visual search studies generally assess how fast a person can visually acquire a specific target. Visual sampling research investigates a more complex cognitive process. The user's attention allocation to visual acquire a particular target at a particular time is assessed (i.e., assessing if the person knows *when to look* for a one of multiple targets). This process requires the user to maintain full understanding of the dynamic processes of the environment (Kowler, 1990). That is, effective visual sampling involves knowing when to look at a particular target as opposed to devoting visual attention to a different target.

Effective visual sampling is moderated by attention allocation (Chapparro, Groff, Tabor, Sifrit, & Gugerty, 1999; Eriksen & Yeh, 1985; Parasuraman, Sheridan, & Wickens, 2000). Allocation of visual attention is primarily impacted by expectancy and value (Smallwood, 1967; Sheridan, 1970). Visual sampling frequency is also affected by the effort required to access information (Liu & Wickens, 1992; Sheridan, 1970; Wickens, Helleberg, Goh, Xu, & Horrey, 2001). Of course, the features of the display also have serious ramifications for visual sampling (Deffner, 1995; Jorna & Snyder, 1991; Wolfe, 1994). For example, Deffner found that participants fixated on high quality images more frequently than they fixated on poor quality images.

The SEEV Model. Wickens and his colleagues combined earlier visual sampling models (e.g., Senders, 1964) with task management models (e.g., Dismukes, 2001) and a situation awareness model (Wickens, Helleberg, Kroft, Talleur, & Xidong, 2001) to provide a descriptive model of visual sampling (Wickens, Helleberg, Goh et al., 2001; Wickens, Xu, Helleberg, Marsh, 2001). Known as the SEEV model, this model describes visual sampling as a function of Salience, Expectancy, Effort, and Value. Salience is stimulus-driven (e.g., flashing lights will attract a person's attention) whereas expectancy is knowledge-driven (i.e., previous knowledge of the environment dictates what the person expects to see and where he expects to see it and therefore focuses attention accordingly). Visual sampling is also influenced by value in that people will direct their attention to where they expect to obtain key information. Finally, scanning is modulated by the amount of effort that is required to attend to a particular area of interest. For example, people are less likely to attend to information that requires large head movements (Previc, 2000). Increased spatial separation requires more effort to visually acquire information in a complex environment (Wickens, Xu et al., 2001).

This model is particularly useful to describe visual sampling in the cockpit where certain tasks must take priority over other tasks. In the cockpit, for example, aviating (controlling parameters such as pitch, roll, and yaw that sustain flight) must take priority over navigating (directing the aircraft in a particular direction to stay on path and avoid conflict) which must take priority over communication (Schutte & Trujillo, 1996; Wiener, Kanki, Helmreich, 1993). The SEEV concept supports the notion that visual behavior in a complex, familiar layout such as a pilot scanning the cockpit typically reflects top-down information processing (Theeuwes, 1994; Sarter & Amalberti, 2000). This knowledge-driven processing is somewhat due to expectancy (Wickens, Gordon, & Liu, 1998). However, eye movement activity also can be directed by bottom-up processing such as a salient event (Wickens & Hollands, 2000). Moreover, an emergent feature (e.g., combining two or more simple components into something perceived as one object) in a display can increase fixation likelihood (Itti & Koch, 2000; Li, 2002).

Along this line, human eye movements can provide insight into the cognitive processes that occur during information extraction (Biscaldi, et al., 1995; Hoffman & Subramanium, 1995; Maioli, Benaglio, Siri, Sosta, & Cappa, 2001; Norton & Stark, 1971). Memory moderates effortful eye movements (Kramer & McCarley, 2003; Leek, Reppa, & Tipper, 2003; Richardson & Spivey, 2004). Recent research suggests that visual representation of an environment can facilitate effective scanning (Barsalou, 1999; Brandt & Stark, 1997; Kosslyn, Behrmann, & Jeannerod, 1995; Martin, 2001) as does attention (Findlay & Gilchrist, 1998; Hoffman & Subramanium, 1995; Hodgson & Muller, 1995; Liu & Wickens, 1990).

A pilot, for example, utilizes selective attention to visually monitor multiple information sources simultaneously (Sanders et al., 1977; Schulte & Onken, 1995; Spady, 1987). Visual acquisition becomes more challenging as the number of information sources increases (Findlay et al., 1995; Sanders & McCormick, 1993; Treisman & Gelade, 1980). Extracting information is also affected by display clutter (Neisser et al., 1964; Tullis, 1983).

Assessing pilot eye movement behavior can provide useful information about visual acquisition of data in the cockpit (Comstock et al., 1987; Harris et al., 1986; Kleiss et al., 1988). One potential benefit of integrated cockpit displays is reductions in scan time to acquire essential information (Itoh, Hayashi, Tsukui, & Saito, 1990; Wickens, Gordon et al., 1998). This notion makes sense because people are better at attending to integrated displays (Parasuraman & Mouloua, 1996; Wickens, Fadden, Merwin, & Ververs, 1998). Visual scanning of complex displays tends to be most concentrated toward the center regions of the visual field as opposed to the conventional "T" scan pattern that has been widely demonstrated by pilots (Parasuraman, 1986; Schulte & Onken, 1995). Based on this, a cockpit equipped with integrated displays may promote more effective visual sampling behavior.

Visual Displays

There are several different types of quantitative visual displays. At the most basic level, quantitative visual displays are either analog or digital. Analog displays can have a fixed scale with a moving pointer (e.g., a traditional round dial style altimeter), or a moving scale with a fixed pointer (e.g., a tape display). The type of information conveyed by the display, as well as type of system, dictates which type of display is most appropriate. Digital displays are good for obtaining specific numeric values, as long as the values conveyed remain constant for long enough to read the data (Goolkasian & Bunting, 1985). If the information is continually changing, a fixed scale with a moving pointer is better than a digital display (Helander, 1987). A fixed scale is also beneficial when the entire scale needs to be viewed at all times or to observe trend information (Kantowitz & Sorkin, 1983). With a large scale range, however, a moving scale with a fixed pointer is better, especially if precise data must be extracted from a large scale range.

In complex systems, often information from multiple displays must be integrated to understand the overall status of the system, or of a sub-system. Displays that integrate related information can lessen the cognitive demands placed on the operator. Considerable research has been conducted to examine the effects of display integration (e.g., Abbott & Steinmetz, 1987; Barnett, & Wickens, 1988; Bennett, Payne, Calcaterra, & Nittoli, 2000; Beskenis, Green, Hyer, & Johnson, 1998; Roscoe, 1980; Roscoe, Corl, & Jensen, 1981; Schmidt & Elvers, 1992; Wickens & Andre, 1990). Appropriately integrated displays can have a positive impact on situation awareness (Andre, Wickens, Moorman, & Boschelli, 1991; Endsley, Sollenberger, Nakata, & Stein, 2000). Integrated displays can promote improved monitoring performance (Parasuraman, Mouloua, & Molloy, 1996). As such, any complex environment that includes augmented displays should utilize integrated displays to increase situation awareness (GAMA, 2000; Sarter & Woods, 1991).

An early study by Roscoe (1968) investigated the benefits of different type of altimeters. Roscoe examined three important cockpit display issues: analog versus digital presentation, vertical versus circular scales, and integrated versus non-integrated information. Roscoe found the integrated vertical scale to elicit the best performance, in terms of reduced errors and faster response time. This is congruent with Roscoe, Corl, and Jensen's (1981) Principle of Pictorial Realism.

Roscoe et al. (1981) proposed principles of aircraft position displays to aid in determining the display type best suited to convey different types of information. The Principle of Pictorial Realism suggests that an aircraft position display should provide a visual representation of the real world in which the aircraft's position is viewed three-dimensionally. That is, an aircraft position display should convey altitude along with heading and position to provide a complete representation of the aircraft's location. Roscoe's Principle of Integration asserts that cognitively related data should be integrated. Finally, the Principle of Pursuit Presentation suggests that pursuit displays, as opposed to compensatory displays, should be used in aircraft position displays whenever possible. Pursuit displays facilitate visualization of the aircraft's current and future location and are compatible with human information processing.

Garner's (1970) work on the dimensional organization of visual stimuli distinguished between two categories of visual displays: separable and integral. Separable dimensions are characterized by a lack of interaction between stimulus dimensions (Garner & Felfoldy, 1978). That is, each dimension within a separable display is salient and independent from other dimensions. The height and width of a connecting line segment, for example, constitutes separable displays because the height can be specified without distinguishing the width of the segment. Integral dimensions, on the other hand, are interdependent dimensions such that the unique characteristics of one contributing dimension are not easily identifiable from other contributing dimensions. A rectangle, for example, has integral dimensions in that the height of the rectangle cannot be specified without conveying fundamental information regarding the rectangle's width.

The important concept drawn from dimensional integrality research is that attention is somewhat automatically drawn away from individual components of an integral display. This occurrence may actually be due to an emergent feature that results from the integral display or perceptual grouping (Buttigieg & Sanderson, 1991; Pomerantz, 1981). Separable displays can be arranged such that an emergent feature is apparent but this occurrence is more likely in integral displays. For instance, several individual bar graphs presented in a row can produce an emergent feature if all the bars align to convey higher-order information.

The theoretical underpinnings of Garner’s (1970) as well as classic research on functional grouping (c.f., Bailey, 1989; Bonney & Williams, 1977) provided the fundamental basis for the Proximity Compatibility Principle (Carswell & Wickens, 1987; Wickens & Andre, 1990; Wickens, Sandry, & Vidulich, 1983). The concepts outlined in the Proximity Compatibility Principle are also analogous to recent principles of ecological interface design (Bennett & Flach, 1992). The Proximity Compatibility Principle is a widely researched postulate that addresses the concept of spatial and temporal proximity in display layout (Abbott & Steinmetz, 1987; Beskenis, Green, Hyer, & Johnson, 1998; Theunissen, 1997; Wickens & Andre, 1990).

The Proximity Compatibility Principle

The Proximity Compatibility Principle (Carswell & Wickens, 1988; Wickens & Andre, 1990) suggests that both perceptual proximity and processing proximity must be considered in display design and the layout of multiple displays in a complex environment. Perceptual proximity refers to spatial aspects of two displays (e.g., distance between two displays) as well as physical attributes of two displays such as color, code (e.g., analog or digital), and dimensionality. Processing proximity refers to the temporal factors associated with the display (e.g., degree to which two or more information sources must be used to complete one task). If two data sources must be mentally processed together by the user to generate useful information, the displays have high proximity. Two data sources that must be processed independently have low proximity. Perceptual proximity and processing proximity determine the functional similarity among display components that must be considered to moderate display layout.

Display Characteristics. The Proximity Compatibility Principle suggests that a display's perceptual characteristics should be congruent with the cognitive processes used to derive information from that display (Wickens & Carswell, 1995). For instance, if two sources of information must be compared to make a particular judgment, a display should integrate those two sources. If the two necessary sources of information cannot be integrated, they should be presented in close proximity to one another to facilitate mental integration of the information. On the other hand, information that does not require integration to arrive at a decision should not be integrated or purposely presented in close proximity. An important prediction of the Proximity Compatibility Principle is that appropriately integrated displays facilitate parallel processing so that operators of complex systems do not neglect other crucial information (Carswell & Wickens, 1988; Wickens & Andre, 1990).

Performance Predictions of the Proximity Compatibility Principle. The Proximity Compatibility Principle makes specific performance predictions for both integrated and focus tasks. An integrated task involves combining information from two or more sources to arrive at a decision (e.g., assessing current airspeed, altitude, and heading to determine projected trajectory). A focus task involves information gathering from a single source (e.g., looking at the altimeter to assess current altitude). According to the Proximity Compatibility Principle, integrated displays should facilitate good performance for integrated tasks while focus tasks should suffer from integrated displays. Moreover, performance on multiple focus tasks will excel with separate low proximity displays.

Display proximity has been varied along many dimensions such as display dimensionality (Harwood, Wickens, Kramer, Clay, & Liu, 1986; Merwin & Wickens, 1991, 1996; O'Brien & Wickens, 1997), display orientation (Buttigieg & Sanderson, 1991; Carswell, 1990; Geottl, Kramer & Wickens, 1986; Pomerantz, 1986; Wickens & Carswell, 1995), objectiveness (Carswell & Wickens, 1987; Wickens & Andre, 1990), spatial and temporal display proximity (Hofer, Palen, & Possolo, 1993; Uhlarik & Joseph, 1992; Vincow & Wickens, 1992; Wickens, Fadden et al., 1998).

An experiment by Holahan, Culler, & Wilcox (1978) concurs with the low proximity predictions. Holahan et al., investigated the effects of spatial proximity in a visual search task. Results revealed a positive relationship between spatial proximity of distracters and response time. Similar to the Proximity Compatibility Principle, they suggested that the close mental proximity of distracters interfered with the focused attention task.

O'Brien and Wickens (1997) manipulated integration of air traffic and weather displays to examine the trade offs associated with increased display clutter that is often inherent in complex integrated displays. Consistent with the Proximity Compatibility Principle, they found that an integrated display facilitated superior performance when participants needed to combine information to change the flight path to avoid traffic hazards and adverse weather.

Synthetic Vision System Displays

A synthetic vision system (SVS) display aims to present a view comparable to that of clear, daytime flying conditions (Burgess & Hayes, 1993; Möller & Sachs, 1994; Williams et al., 2001). An SVS display incorporates terrain database information with real time data (e.g., weather and air traffic) to provide the pilot with a head-down synthetically produced VMC-like representation of the environment. The SVS display generates a three-dimensional visual representation of the aircraft within its environment in line with the Principle of Pictorial Realism offered by Roscoe et al., (1981). An SVS display can also provide warnings, alerts, and advisories that can aid in tactical guidance decisions that in turn render safety and operational benefits. The overall goal of an SVS is to improve a pilot's ability to visualize the aircraft relative to the outside environment. Additionally, the system is designed to provide the pilot with a perspective view that is harmonious with the pilot's natural mode of spatial information gathering (Endsley, 2000; Hemm, 2000).

A distinction must be made between an SVS and an augmented reality system such as an enhanced vision system.

An enhanced vision system (EVS) is a near-term design in that it provides a visual representation of the proximal environment (e.g., runway outlines, known airport obstacles, taxiways, flight corridors). An SVS is a longer-term design because it could hypothetically replace the out-the-window view. An enhanced vision system utilizes data and imagery acquired from on-board sensors such as millimeter radar, video cameras, and enhanced weather radar. Complex SVS systems can be coupled with augmented EVS sensory data but the two systems are unique.

Components of Synthetic Vision Systems. An SVS is comprised of three basic components: 1) a synthetic view of the flight environment, 2) hazard/ obstacle detection, and 3) navigational guidance information.

An enhanced intuitive view of the flight environment is intuitive because it replicates what the pilot would see out the window during VMC. An SVS integrates database information with tactical information (e.g., like that found on a traditional Primary Flight Display; PFD) and strategic information (e.g., like that found on navigation displays). This provides the pilot with a display that conveys all pertinent information about the status of the aircraft. Importantly, pilots can also view an accurate rendition of their own aircraft relative to potential obstacles. Synthetic vision displays typically include altitude, indicated, ground and/or true airspeed, vertical airspeed, a velocity vector, and current location relative to navigational fixes (e.g., waypoints).

The second component of SVS is hazard display and detection. An SVS display incorporates information about potential obstacles that could present a hazard. Information such as terrain, ground and air obstacles, and atmospheric information is conveyed by an SVS display. Existing systems such as EVS and Terrain Awareness and Warning System (TAWS) can augment the SVS display to provide additional hazard display and detection. Combining these sources of information with on-board sensor information provides an accurate and timely illustration of the environment, as opposed to current warnings that lack concise, directive information conveyed in a time efficient manner.

The navigational guidance component of an SVS provides pathway guidance and navigation cues. Pilots can receive needed navigational assistance for difficult approaches. One of the most prominent features of SVS is the pathway guidance system. Wiener and Nagel (1988) describe pathway guidance, also commonly referred to as the tunnel-in-the-sky concept, as a three-dimensional pathway guidance system that serves to guide pilots to their destination. Tunnel guidance systems have been shown to improve pilot performance, increase situation awareness, and reduce pilot workload (Alexander, Wickens, & Hardy, 2003; Grunwald, 1996; Regal & Whittington, 1995; Wickens & Hollands, 2000). See Theunissen (1997) for a comprehensive review of research on the tunnel-in-the-sky concept.

Benefits of SVS Displays. There are many potential benefits of SVS displays in terms of aviation safety (Hemm, 2000; Williams et al., 2001). Some of these benefits include generating synthetic visibility comparable to VMC, potentially reducing CFIT and runway incursion incidents, improving situation awareness, and reducing mental workload.

Visibility is especially important during near-ground flight, especially landing approaches. Instrument Landing Systems (ILS) use precision localizer and glide slope radio transmitters located near the runway to provide landing approach guidance. Airports with and without ILS often have weather-related landing and maneuvering restrictions. Meteorological conditions such as fog, rain, and darkness can produce a significantly degraded view. Synthetic vision displays can reduce these restrictions and dangers due to visibility conditions.

The majority of airline incidents resulting in fatalities are attributed to CFIT incidents (Etherington, Vogl, Lapis, & Razo, 2000; Khatwa & Roelen, 1999). Runway incursions are also more common during low visibility. An SVS display provides a clear view of the surrounding terrain and other potential obstacles along with proactive countermeasures to avoid CFIT. The SVS can also produce a visual representation of the airport; this can assist in taxiway navigation to reduce runway incursion incidents.

Endsley (2000) suggests that maintaining situation awareness is one of the most critical aspects of a commercial pilot's job. Moreover, display technologies designed to enhance pilot situation awareness are of prime importance during periods of reduced visibility. Synthetic vision displays are designed to improve pilots' situation awareness by presenting the relative location of objects within the environment (Endsley, 2000; Radke & Ferguson, 1994; Newman, 2001). This type of display conveys information such as the aircraft's position, location of terrain and other ground-based obstacles, positions of other important landmarks (e.g., airports) and may provide information regarding current atmospheric conditions such as turbulence and thunderstorms.

Modern aircraft feature advanced systems designed to prevent CFIT and runway incursion incidents. However, the ongoing occurrence of these types of incidents suggests that current ground proximity warning systems may not be sufficient. For example, the warning provided by enhanced ground proximity warning systems does not always provide an adequate amount of time to successfully avoid terrain (Corwin, 1995). Another serious concern with such warnings is that too often pilots disregard warnings due to high expectations of false alarms (Bliss, Gilson, & Deaton, 1995; Burt, Bartolome-Rull, Burdette, & Comstock, 1999; Beringer, 1997; Noyes, Cresswell, & Rankin, 1999; Noyes, Starr, Frankish, & Rankin, 1995; Selcon, Taylor, & McKenna, 1995; Woods, 1995). This can lead to complacency issues or the "cry-wolf phenomenon" in which pilots develop inappropriately delayed response patterns due to high incidences of false alarms (Bliss, 1993; Freeland & Millard, 1999; Parasuraman & Riley, 1997; Sorkin, 1988).

The Current Study

Inadequate visual displays coupled with high workload can be a dangerous combination in a complex environment such as a commercial aircraft cockpit. Situation awareness can also be adversely affected under these circumstances. Improved visual displays that maximize the benefits of display integrality could mitigate visibility related issues in commercial aviation. Visual displays that integrate information in an appropriate manner should reduce workload, increase situation awareness, and facilitate superior flight performance on integrated tasks. Additionally, an SVS display should promote superior flight performance on all tasks while improving situation awareness and mental workload. Thus, the primary objective of the current study was to explore if the combination of SVS coupled with an integrated display would facilitate performance on an integrative task and if SVS partnered with a less integrated display would facilitate focus task performance. Furthermore, the effect a new visual display has on pilots' oculometric behavior must be explored to provide a comprehensive understanding of the potential ramifications of such a display.

Design. A within-participants design was utilized to investigate pilot performance, subjective workload, and situation awareness as a function of display layout, display view, and workload. Two levels of display integration layout were manipulated within participants: display A (low integration) and display D (high integration). Two display views were manipulated within-participants: a synthetic vision display view and a display with a traditional blue sky over brown ground comparable to an Electronic Attitude Director Indicator display (EADI). Manipulating display integration and display type produced four display conditions: SVS-A, SVS-D, Traditional-A (Trad-A), and Traditional-D (Trad-D). High and low levels of workload were manipulated within participants. Flight performance and eye tracking data served as objective dependent measures. Subjective workload and situation awareness questionnaires provided additional information.

Performance Hypotheses. Lateral and vertical flight path maintenance performance were considered integrative tasks whereas airspeed maintenance was considered a focus task in the current study. Based on Wickens' Proximity Compatibility Principle (Carswell & Wickens, 1987, 1988; Wickens & Carswell, 1995) predictions that an integrated display should facilitate superior performance on integrated tasks, superior lateral and vertical path maintenance was expected with the more integrated display layout. In support of the low proximity predictions of the Proximity Compatibility Principle, better airspeed maintenance performance was expected with the less integrated display. The SVS display and the low workload condition were each expected to promote better performance for all tasks. An interaction was expected between display integration layout and display view. The SVS display coupled with the highly integrated display layout was expected to facilitate the best lateral and vertical flight path maintenance performance. The SVS display partnered with the less integrated display was expected to promote the best airspeed maintenance performance.

Eye Movement Hypotheses. Another objective of the current study was to explore differences in how the experimental display configurations might affect visual acquisition of information in the cockpit. Dwell count, dwell duration, fixation count, fixation duration, were measured to provide a comprehensive assessment of pilots' eye movements. Eye tracking data were expected to reveal differences as a function of display condition and workload level. The more integrated display was expected to facilitate faster data acquisition. Another objective of the current study was to explore eye movement differences produced by the SVS displays. The synthetic vision view was not expected to have an adverse effect on pilot eye scan patterns.

Subjective Measures Hypotheses. Perceived workload was assessed using the NASA-Task Load Index. An interaction between workload level and integration layout was expected; high workload coupled with the less integrated display (A) should induce greater subjective workload than low workload coupled with the more integrated display (D). An interaction between workload and display condition was expected; high workload combined with the less integrated traditional display (Trad-A) was expected to elicit greater subjective workload than the low workload condition combined with the more integrated SVS display (SVS-D). A main effect for display integration layout was also expected for subjective workload; the more integrated display (D) was expected to produce less subjective workload than the less integrated display (A). A main effect was also expected for workload condition such that those experiencing high workload would report greater perceived workload independent of display integration or display view.

Subjective situation awareness was assessed using the Situation Awareness Readiness Technique (SART). An interaction between display integration and display view was expected for subjective situation awareness. Higher situation awareness was expected for the more integrated SVS display (SVS-D) than the less integrated traditional display (Trad-A). Main effects for display integration and display view are also expected. Increased situation awareness was expected from the more integrated display (D) as opposed to the less integrated display (A). Increased situation awareness was also expected for the SVS as opposed to the traditional display.

METHODOLOGY

Experimental Paradigm

A within-participants design was utilized in the current study to investigate pilot performance, eye movements, subjective workload, and situation awareness. Two levels of display integration were manipulated within participants: display A (low integration) and display D (high integration). Two display views were manipulated within participants: a synthetic vision display and a traditional display (a traditional display similar to an Electronic Attitude Director Indicator display; EADI). Manipulating display integration and display view produced four display conditions: SVS-A, SVS-D, Traditional-A (Trad-A), and Traditional-D (Trad-D). High and low levels of workload were manipulated within participants, as described below. Flight performance and eye tracking data served as objective dependent measures. Subjective workload and situation awareness questionnaires provided additional information.

Variable Manipulations

Eight display formats resulted from complete factorial combinations of the within participants variables display condition (SVS-A, SVA-D, Trad-A, Trad-D) and workload (high and low). A data collection session consisted of 16 trials (two replications of each of the eight possible configurations of the three main independent variables), two 15-minute breaks, and a 45-minute lunch break. Presentations of the TLX and SART were presented after each trial. Eye tracking data were collected during one half of the trials, presented in a counter-balanced manner. Two-mile limited visibility due to fog was simulated on the out the window (OTW) scene to prevent pilots from relying on the OTW view in place of the synthetic vision head-down display during the experiment.

Two levels of workload were manipulated by altering 1) the difficulty of the approach (straight-in or curved approach), 2) throttle (manual or automatic), and 3) atmospheric conditions. In the high workload condition, participants experienced a curved approach on manual throttle with 10-knot 160-degree crosswinds. In the low workload condition, participants were presented with a straight-in approach on automatic throttles with no wind. Flight times for the two approaches were comparable.

Participants

Sixteen male pilots ranging in age from 29 - 47 years old (M = 39.48, SD = 5.43) participated in the study. All participants happened to be male because the majority of the qualified people that volunteered for the study were men. All participants had normal or corrected-to-normal vision with nine participants wearing corrective lenses. Pilots were recruited through a NASA contract with Lockheed Martin. Lockheed Martin maintains a database of pilots that have volunteered to participate in research at NASA Langley. Lockheed Martin employees on-site at NASA Langley made all arrangements for the participants, including travel arrangements and stipends. Pilots were compensated $400 plus travel expenses for their participation. Separate Internal Review Boards at Old Dominion University and NASA Langley Research Center approved the use of human subjects.

All participants were current transport-rated pilots; most of the pilots were current First Officers (16 First Officers and 2 Captains). Seven pilots had previous military experience. Piloting experience ranged from 3-23 years (M = 6.32 years, SD = 5.48). As expected, the participants who were current Captains (M = 15.50 years, SD = 7.62) reported more experience than did the First Officers (M = 5.00 years, SD = 3.53). Number of total transport flight hours ranged from 3050 - 16550 (M = 6989.88 hours, SD = 4539.27). Ten of the pilots had experience with an aircraft equipped with a velocity vector. Ten pilots had previous experience with an aircraft with some type of information presented in a tape format as opposed to analog dials; six pilots were currently assigned to an aircraft that presented information in tape format such as a Boeing 777, a 747-400, or many military aircrafts. Most of the participants (N = 13) had at least some glass cockpit experience. Complete participant profiles are presented in Appendix A.

Simulation Facility

The NASA Langley Research Center's Visual Imaging Simulator for Transport Aircraft Systems - Generation III (VISTAS III) was used. The VISTAS III is a piloted fixed-base reconfigurable moderate fidelity part-task flight simulator that emulates a Boeing 700 series aircraft model. The simulator includes a head-down flat panel display, an OTW display, and cockpit configuration with a side stick yoke. Separate IBM™-compatible computers (dual Pentium III™ with 866 MHz, 1.0 GB RAM, 36 GB hard drive) rendered a 25-inch diagonal head-down display with 1280 x 1024 resolution (5:4 aspect ratio). The OTW view was displayed on a multiple screens situated 2.5 meters in front of the participant. Separate IBM™-compatible computers produced a 1024 x 1280 pixel resolution OTW display with a 30-degree vertical field of view and a 24-degree horizontal field of view.

Simulator testing sessions were conducted using the Eagle County, Colorado (FAA airport locator code EGE) database. This airport was chosen from a list of domestic "terrain challenged" airports as a location for which the desired Digital Terrain Elevation Data (DTED) and aerial photography could be obtained for simulation testing. The SVS primary flight display presented the perspective terrain with photo texturing of terrain features around the airport. Photo texturing involves superimposed high altitude photography onto DTED information to produce a realistic perspective scene. The photo-textured area constructed for this simulation was 95 square nautical miles centered around EGE.

Visual Displays

Two display layouts (A and D) and two display views (SVS and traditional, Trad) were manipulated within participants resulting in four display conditions: 1) SVS-A; 2) SVS-D; 3) Trad-A; 4) Trad-D. Both synthetic vision displays superimpose symbology over a visual representation of terrain. The superimposed symbology included a horizon, body axis indicator (waterline symbol), pitch information, roll scale, localizer and glide slope indications, radar altitude (below 500 feel AGL), and flight path vector. An identical conventional navigation display that indicates moving map, track-up, and format waypoints along a programmed path was also presented with each display.

A traditional display comparable to the Electronic Attitude Director Indicator (EADI) display was used in this experiment for comparison purposes. The EADI is a flight instrument that conveys pitch and roll attitude indications as well as flight director commands, localizer and glide slope indications, airspeed, auto throttle modes, radio altitude and decision height. The EADI used for the current study utilized the same pathway guidance vector as the SVS displays.

Display layout A was the approximate size of an EADI (12.9 cm x 12.6 cm) in the current generation Boeing 757 aircraft along with traditional round-dial representations including an airspeed indicator, altimeter, and vertical situation indicator. This display concept represents the case of extracting the current EADI like that currently found in most Boeing 757 and 767 series cockpits and replacing it with an SVS display. See Appendix B for an illustration of display layout A coupled with the SVS view and Appendix C for display layout A coupled with the traditional view. Display D is approximately the size of the CRT primary flight display (16.0 x. 16.0 cm) in the Boeing 747-400 or the flat panel display in the Boeing 777. Display D presents airspeed, altitude, and vertical speed information in a "tape" format integrated into the primary flight display. The same navigational display accompanies display layout D. Display layout D coupled with the SVS view is in Appendix D and display layout D with the traditional view can be seen in Appendix E.

Eye Tracking Apparatus

An Applied Science Laboratories (ASL) Series 4100H head mounted eye tracking system was used to assess eye movements (see Figure 1). The ASL 4100H is designed to measure a freely moving subject's eye line of gaze with respect to the head. The eye tracker and associated optics were affixed to a lightweight band worn around the participant's head. The lightweight band distributes weight evenly and provides a stable platform for the optics. A magnetic head tracker unit (a fixed transmitter) was placed directly behind the pilot's head.

Pupil and corneal reflection was obtained with an infrared LED beam directed coaxially with the viewing axis of a pupil camera. A miniature video camera captured the corneal reflection and pupil images at a rate of 60 Hz. The pupil center and diameter data were used to compute look angle in real time. This angle was corrected for head position and location to provide point of gaze information (x,y,z coordinates) on one or more geometrically described fixation planes.

The ASL 4100H includes an eye camera optics module, visor assembly, scene camera assembly, camera control unit, eye tracking system control unit, control panel, three video monitors, and computer. These components are thoroughly described in Appendix F.

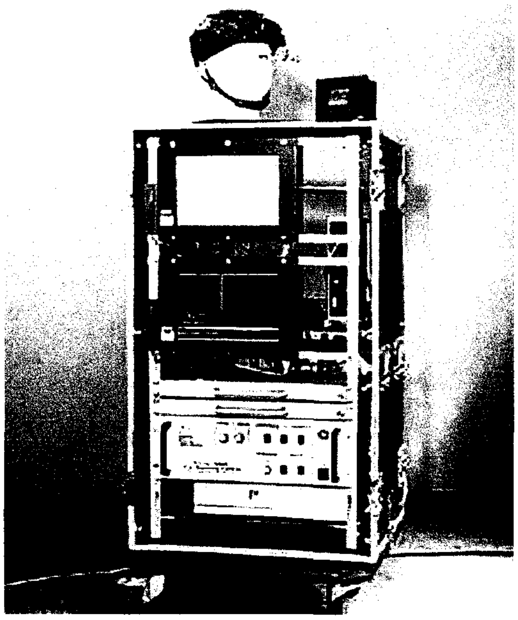

Figure 1. The ASL 4000H eye tracking apparatus.

Subjective Measures

Workload ratings were measured using the NASA Task Load Index (TLX, Hart & Staveland, 1988). The TLX is a widely used, valid and reliable tool to assess participant mental workload (Eggemeier & Wilson, 1991; Hancock & Desmond, 2001; Hancock & Meshkati, 1988). The TLX consists of six scales to assess the relative contributions of task, behavior, and subject related experiences along six dimensions of workload: effort, frustration, performance, mental demand, physical demand, and temporal demand (see Appendix G). Respondents were instructed to make a line on a 100-point scale to respond to each of the six subscales. The cumulative average describes overall workload or the individual subscale averages can be assessed. A higher number indicates greater perceived mental workload.

The TLX has been shown to be significantly correlated with other mental workload measures such as Stein's (1985) Air Traffic Workload Input Technique (r = .89), the Behavior and Event Checklist (r = .39), Redi & Nygren's (1988) Subjective Workload Assessment Technique (SWAT; r =.86), and the Modified Cooper - Harper Scale (r = .86; Bruskiewicz, Hedge, Manning, & Mokilka, 2000; Manning, Mills, Fox, & Pfleiderer, 2001; Hill et al., 1998). The TLX has also been shown to have high factor validity and testretest reliability (*r* = .77; Byers, Bittner, & Hill, 1989; Hill et al., 1992).

The Situational Awareness Rating Technique (SART) was also administered to participants (Taylor, 1989). The SART is a self-report 10-item scale that assesses three areas of situation awareness: 1) demands on attentional resources, 2) supply of attentional resources, and 3) an understanding of the situation (see Appendix H). Participants were instructed to reflect upon the most recent display when responding. Participants responded on 7-point Likert-type scale ranging from 1 (Low) to 7 (High). A higher response indicates greater situation awareness. After accounting for reverse-scored items, an average score was calculated for overall situation awareness.

The SART has been validated within the context of Rasmusen's (1986) Model of Skill-Based, Rule-Based, and Knowledge-Based behavior. The SART has also demonstrated good predictive validity (R^2 = .71) and is thought to be a sensitive measure of situation awareness (Crabtree, Marcelo, McCoy, & Vidulich, 1993; Endsley, 1998; Endsley, Sollenberger, Nakata, & Stein, 2000). The SART has also been show to be correlated with performance (Jones & Endsley, 2000; Selcon & Taylor, 1990).

Procedure

Upon arrival, participants were given a brief study overview before completing an informed consent form (Appendix I) and a demographic questionnaire (Appendix J). Pilots were then asked to read a training manual to become familiar with the VISTAS III facility and EGE approaches 07 and 25 (Appendix K). Pilots received approximately 60 minutes of training that included familiarization with the VISTAS III facility and approach charts for both EGE runways as well as introduction to the TLX and SART. Pilots experienced all possible display configurations during training. The researcher remained in the simulator with the pilots during flight training to ensure complete understanding of the VISTAS III facility and the experimental displays.

Pilots completed 16 trials (two replicates of each of the eight possible combinations of the three variables) originating approximately 15 miles to touchdown at EGE. Pilots were requested to maintain "sterile cockpit rules" Sterile cockpit rules specifically prohibit pilots from performing non-essential activities like unnecessary talking while the aircraft is involved in taxi, takeoff, landing, and all other flight operations conducted below 10,000 feet MSL (FAR 121.542).

Prior to starting each trial, the participant was verbally informed about the exact display configuration that he would be flying (e.g., the experimenter would say "You will be flying a straight-in approach onto EGE25 with automatic throttles and no wind with the large synthetic vision display. Your aircraft is configured for landing. Are you ready? 3, 2, 1, begin." For ease of understanding, the displays were simply referred to as small and large (instead of A and D). The aircraft was configured for landing on all trials (flaps set and gear down). The simulation was stopped immediately at touchdown for all flight scenarios due to abnormal aircraft handling properties on the ground. Pilots completed the TLX and the SART immediately after each trial. Space was provided at the bottom of the SART for pilots to note any comments about the display configuration.

Eye tracking data were collected during eight of the sixteen trials. These eight trials were not presented consecutively to avoid discomfort from the head-mounted eye tracking unit (e.g., eye tracking data were collected from four morning trials and four afternoon sessions). The eye tracking sessions were counterbalanced. The eye tracking apparatus was calibrated for each individual before each use.

The calibration procedure was performed for each participant to ensure that accurate look-point information was collected. To calibrate, a grid of nine points was placed directly in front of the pilot. The pilot was instructed to hold his head still while fixating on each of the nine points. The relative geometric parameters, along with physiological properties of the eye, were computed and compared with the known geometric position of the nine points for each participant. Calibration parameters for each participant were saved for data collection throughout the day. The calibration procedure took approximately 10 minutes. After calibration, the eye tracker accuracy was within approximately one degree of visual angle. Pilots were allowed to move their heads freely after completion of the calibration procedure.

The simulation had to be stopped and reset approximately ten times during the 256 trials because the head mounted unit either slipped or was accidentally moved by the pilot. These stoppages occurred occasionally throughout the data collection sessions (e.g., there was no one pilot that caused a majority of stoppages). When this occurred, the unit was adjusted and recalibrated if necessary then the scenario was presented from the beginning of the trial. Data from these incomplete trials were not used in any analyses.

RESULTS

Flight performance, eye tracking data, and subjective measures were examined with general linear model analyses of variance (GLM-ANOVAs). An *a priori* alpha level of $p <$ .05 was used for all analyses. Levene's test of homogeneity of variance determined that the data were normally distributed.

Data from each of the two approaches (EGE 07 and EGE 25) were separated into five segments that were comparable in approximate distance and flight time. Existing waypoints from each approach were used as start and stop points. All five segments of EGE 25 were straight. Segment 3 of the EGE 07 approach was curved while the remaining segments of EGE 07 were straight (both approaches are included in Appendix K). Hence, segment 3 of the two approaches was markedly different. The precise delineation of each segment for each approach is provided in Appendix L.

Performance within each flight segment and for the total approach was analyzed. A series of 2 (display layout) X 2 (display view) GLM-ANOVAS was conducted to examine performance data from the high workload and low workload trials separately. These analyses were conducted to identify significant differences without the workload manipulation affecting the outcome. This was done because the two workload conditions produced somewhat unique trials. This was due, in part, to the aforementioned differences in segment 3 of EGE 25 and EGE 07. The performance data were then combined and a series of 2 (display layout) X 2 (display view) X 2 (workload) GLM-ANOVAs was conducted.

Pilot Background Data

Initial analyses were conducted to examine potential relationships between participant demographic information and the dependent measures. As one would expect, there was a significant positive correlation between pilot age and years as an airline pilot, r = .48, as well as between pilot age and number of flight hours, r = .62. There were no significant correlations between any of the flight performance measures and pilot characteristics such as education, military experience, years as a pilot, years as a transport pilot, total flight hours, current flight hours, experience with a velocity vector, or current type of aircraft.

There was a positive correlation between age and the overall workload ratings as measured by the TLX, r = .20. This significant correlation prompted an ANOVA to examine how pilot age affected workload reports. The participants were put into four comparable age groups. A 2 (layout: A/D)

X 2 (view: SVS/TRAD) X 2 (workload: high/low) X 4 (age group: group 1 29-33; group 2 34-38; group 3 39-43; group 4 44-47) GLM-ANOVA revealed a significant main effect for age group, F (3, 15) = 15.63, $p < .05$, $eta^2 = .17$. A *post hoc* analysis identified that group 3 (M = 35.56, SD = 18.16) reported significantly more overall mental workload than all other groups. Group 4 (M = 28.21, SD = 15.22) was also significantly higher than group 2 (M = 20.12, SD = 11.57). The youngest group of pilots, group 1 (M = 23.05, SD = 15.57) reported significantly more workload than did group 2. This age-related subjective workload significant difference is even more pronounced when examining the TLX data from only the high workload trials, F (3, 15) = 8.67, $p < .05$, $eta^2 = .25$. A *post hoc* analysis of these data revealed that group 3 (M = 42.75, SD = 16.80) reported significantly more perceived mental workload than did groups 1 (M = 29.30, SD = 17.27), 2 (M = 23.95, SD = 13.31), or 4 (M = 29.99, SD = 16.56). There were no significant interactions between age group and any of the other independent variables.

A series of 2 (display layout) X 2 (display view) X 4 (age groups as described above) ANOVAs was conducted *post hoc* to examine performance differences as a function of pilot age. Age-related performance differences during high workload manifested for total lateral path deviation, F (1, 15) = 4.42, $p < .05$, eta^2 = .10, total vertical path maintenance, F (1, 15) = 4.61, $p < .05$, eta^2 = .13, and airspeed maintenance performance during segment 3, F (1, 15) = 3.71, $p < .05$, eta^2 = .08. *Post hoc* analyses revealed that groups 1 (*M* = 34.42 ft., *SD* = 15.76) and 2 (*M* = 39.69 ft., *SD* = 14.98) demonstrated less lateral path deviation that did groups 3 (*M* = 47.24 ft., *SD* = 15.14) and 4 (*M* = 44.35 ft., *SD* = 9.95). *Post hoc* analysis of the vertical path data identified that group 1 (*M* = 1013.44 ft., *SD* = 23.33) performed significantly worse that either group 2 (*M* = 994.88 ft., *SD* = 24.17), group 3 (*M* = 993.45 ft., *SD* = 44.44), or group 4 (*M* = 985.07 ft., *SD* = 12.71). *Post hoc* analysis revealed that group 4 (*M* = 141.77 kts., *SD* = 1.38) was also significantly better at maintaining airspeed than was group 1 (*M* = 142.98 kts., *SD* = 1.78) or group 3 (*M* = 142.73 kts., *SD* = 1.72); group 2 (*M* = 172.03 kts., *SD* = 1.62) was only significantly different from group 1.

Age-related performance differences were also evident during low workload for both lateral, F (1, 15) = 7.16, $p < .05$, eta^2 = .15, and vertical path maintenance, F (1, 15) = 8.09, $p < .05$, eta^2 = .16. Group 1 (*M* = 49.11 ft., *SD* = 20.49) exhibited significantly more lateral path deviation than did group 2 (*M* = 38.92 ft., *SD* = 14.26), group 3 (*M* =

32.56 ft., *SD* = 9.64), or group 4 (*M* = 33.36 ft., *SD* = 14.19) during low workload. Similarly, an examination of the vertical path maintenance data during low workload identified that Group 1 (*M* = 1880.05 ft., *SD* = 31.79) performed significantly worse than group 2 (*M* = 1846.89 ft., *SD* = 26.55), group 3 (*M* = 1847.14 ft., *SD* = 46.44), or group 4 (*M* = 1830.10 ft., *SD* = 44.19).

Performance Data: High Workload Trials

Flight performance measures included path maintenance (lateral path deviation and vertical path deviation) and airspeed maintenance. The airspeed maintenance measure was available only on the high workload trials because automatic throttle was engaged on all low workload trials.

Lateral Path Maintenance Performance. A 2 (layout) X 2 (view) GLM-ANOVA revealed an interaction between layout and view for lateral path maintenance during segment 2, $F(1, 15) = 4.52$, $p < .05$, $eta^2 = .23$. As seen in Figure 2, significantly more lateral path deviation was demonstrated with the TRAD-A configuration (*M* = 30.74 ft., *SD* = 16.88) than with the TRAD-D (*M* = 25.13 ft., *SD* = 15.53), SVS-A display (*M* = 25.17 ft., *SD* = 10.79), or the SVS-D (*M* = 26.16 ft., *SD* = 12.72).

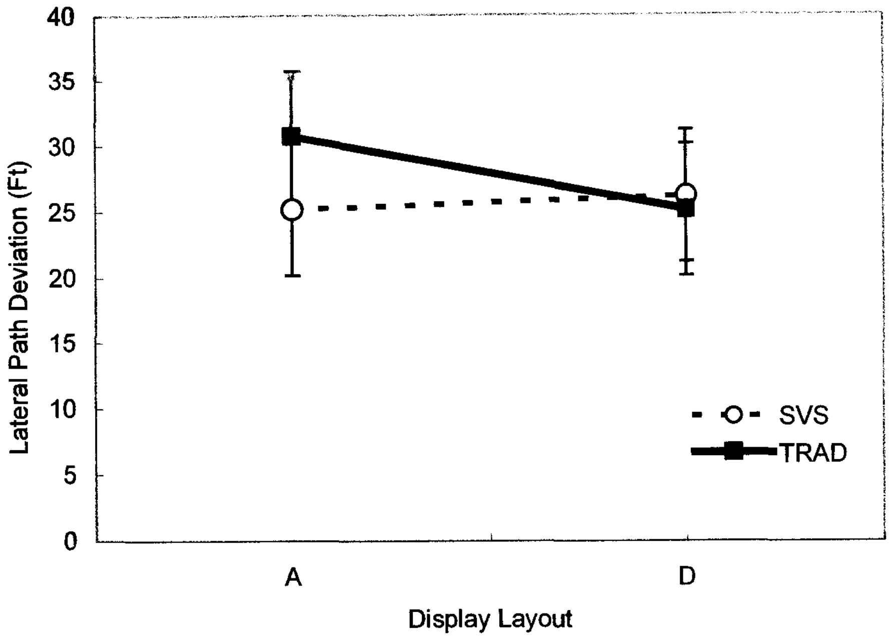

Figure 2. Lateral path maintenance during high workload.

<u>Vertical Path Maintenance Performance</u>. A 2 X 2 GLM-ANOVA revealed an interaction between layout and view for overall vertical path maintenance, F (1, 15) = 8.15, $p <$ .05, eta^2 = .35 (see Figure 3). Significantly less vertical deviation from the path was demonstrated with the TRAD-A configuration (M = 985.83 ft., SD = 22.45) than the SVS-A configuration (M = 1004.32 ft., SD = 29.68), the TRAD-D (M = 998.06 ft., SD = 39.36), or the SVS-D (M = 994.11 ft., SD = 23.51). Vertical path maintenance during segment 3 with layout A (M = 926.09 ft., SD = 24.88) was inferior to performance demonstrated with layout D (M = 914.13 ft., SD = 29.79), F (1, 15) = 6.08, $p <$ .05, eta^2 = .05. The TRAD

view (*M* = 1091.45 ft., *SD* = 25.91) facilitated superior vertical path maintenance during segment 2 than did the SVS view (*M* = 1100.55 ft., *SD* = 27.43), F (1, 15) = 3.73, p < .05, eta^2 =03.

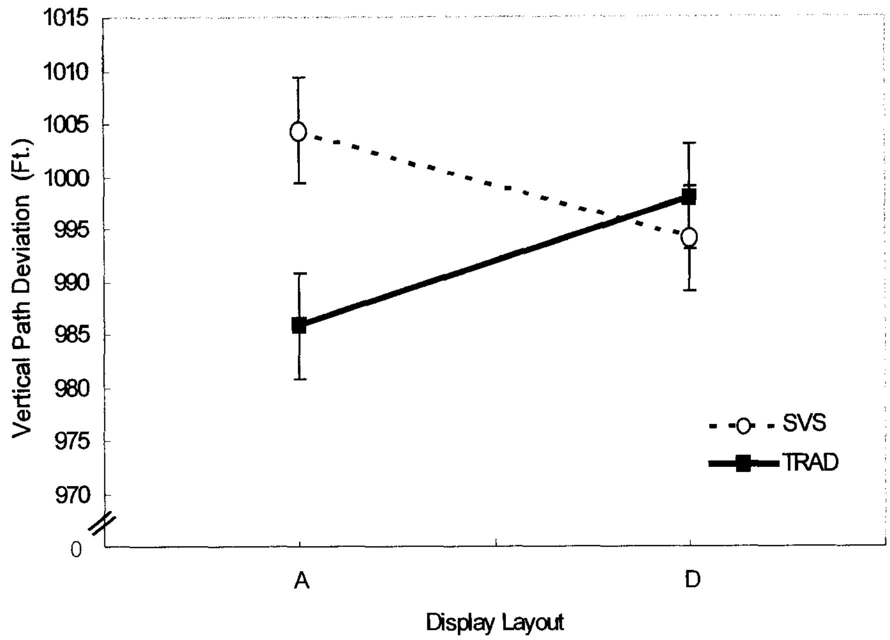

Figure 3. Vertical path maintenance during high workload.

<u>Airspeed Maintenance Performance.</u> Pilots were instructed to maintain 140 knots when on manual throttle trials to touchdown at EGE. A 2 (layout) X 2 (view) GLM-ANOVA revealed a layout by view interaction for airspeed maintenance during segment 2, F (1, 15) = 6.13, p < .05, eta^2 = .29. As seen in Figure 4, pilots were significantly better at maintaining airspeed with the TRAD-A

configuration (*M* = 140.82 kts., *SD* = 1.22) and the SVS-D (*M* = 140.96 kts., *SD* = 1.19) than with TRAD-D (*M* = 141.53 kts., *SD* = 1.29) or the SVS-A (*M* = 141.07 kts., *SD* = 1.16). Layout A (*M* = 140.12 kts., *SD* = 0.99) elicited better total airspeed maintenance performance than did layout D (*M* = 141.46 kts., *SD* = 1.05), F (1, 15) = 4.42, $p < .05$, eta^2 = .03.

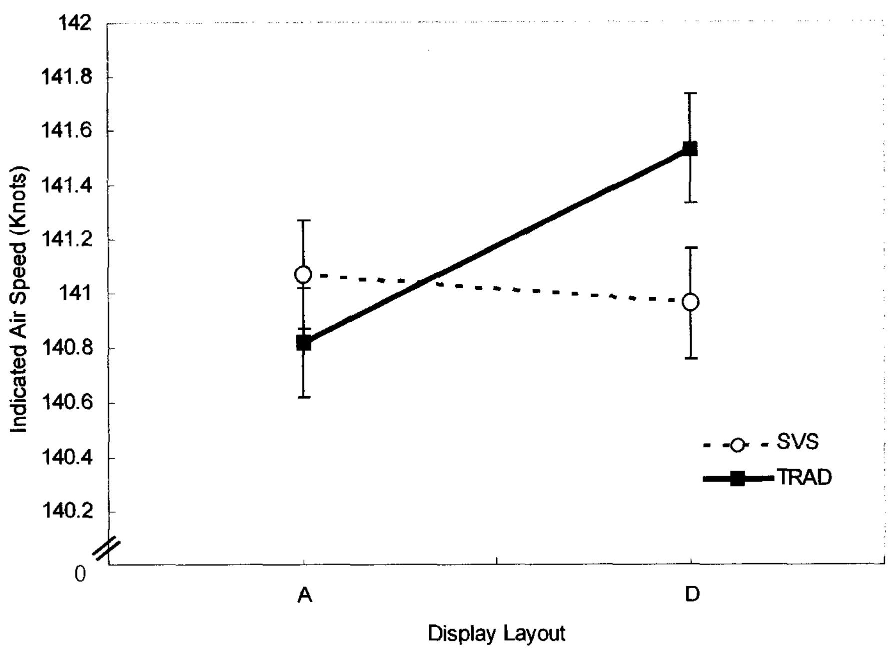

Figure 4. Airspeed maintenance.

Performance Data: Low Workload Trials

Lateral Path Maintenance Performance. A 2 X 2 GLM-ANOVA identified an interaction between layout and view for lateral path maintenance during segment 3 low workload trials, F (1, 15) = 6.57, $p < .05$, $eta^2 = .30$. As seen in Figure 5, lateral path deviation was much larger with the TRAD-A configuration (M = 29.55 ft., SD = 18.93) than with the TRAD-D display layout (M = 19.31 ft., SD = 8.74) while performance with the two SVS configurations was relatively unaffected by the display layout (SVS-A: M = 24.24 ft., SD = 13.02; SVS-D: M = 22.68 ft., SD = 11.25).

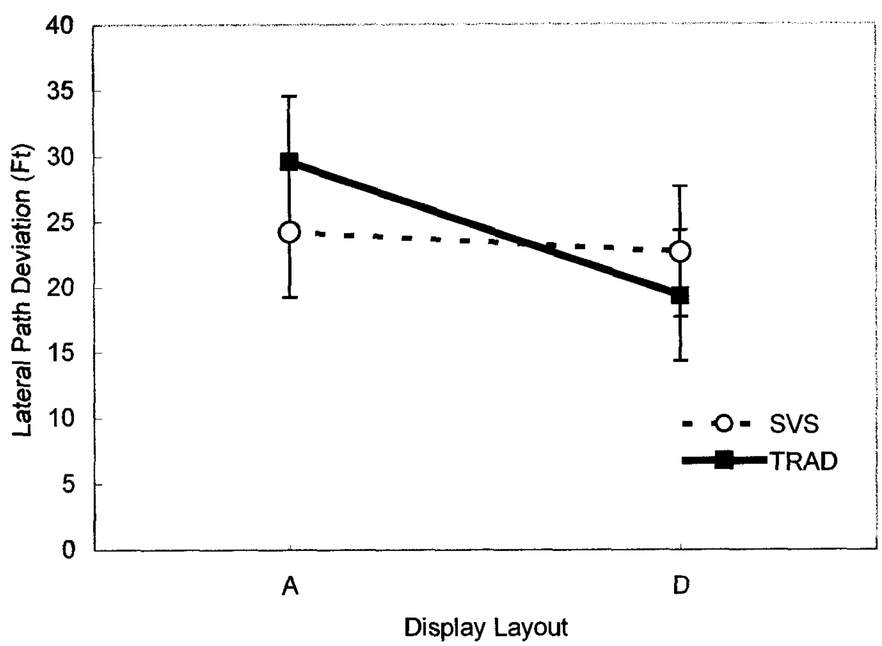

Figure 5. Lateral path maintenance during low workload.

Significantly more path deviation during segment 3 was observed for layout A (M = 26.90 ft., SD = 16.34) than

<.05, eta^2 = 34. Superior lateral path maintenance was

associated with the SVS view (*M* = 35.67 ft., *SD* = 15.69) than the TRAD view (*M* =40.03 ft., *SD* = 15.54), F (1, 15) = 5.24, p <.05, eta^2 = .26.

<u>Vertical Path Maintenance Performance</u>. A 2 X 2 GLM-ANOVA revealed an interaction between layout and view for vertical path maintenance performance during segment 4 low workload trials, F (1, 15) = 4.39, p < .05, eta^2 = .23 (see Figure 6). The best performance was exhibited with the TRAD-D configuration (*M* = 1113.36 ft., *SD* = 21.83) whereas the worst performance was associated with the TRAD-A display (*M* = 1122.81 ft., *SD* = 23.87); again performance with the two SVS displays was not affected by the display layout (SVS-A: *M* = 1118.31 ft., *SD* = 19.96; SVS-D: *M* = 1118.38 ft., *SD* = 14.70). Layout D (*M* = 1842.11 ft., *SD* = 41.75) facilitated better overall vertical path maintenance performance than did layout A (*M* = 1855.83 ft., *SD* = 39.27) under low workload trials, F (1, 15) = 10.48, p < .05, eta^2 = .89. The SVS view (*M* = 1835.75 ft., *SD* = 27.10) promoted better vertical path maintenance performance during segment 2 than did the TRAD view (*M* = 1844.02 ft., *SD* = 25.06), F (1, 15) = 7.01, p < .05, eta^2 =.32.

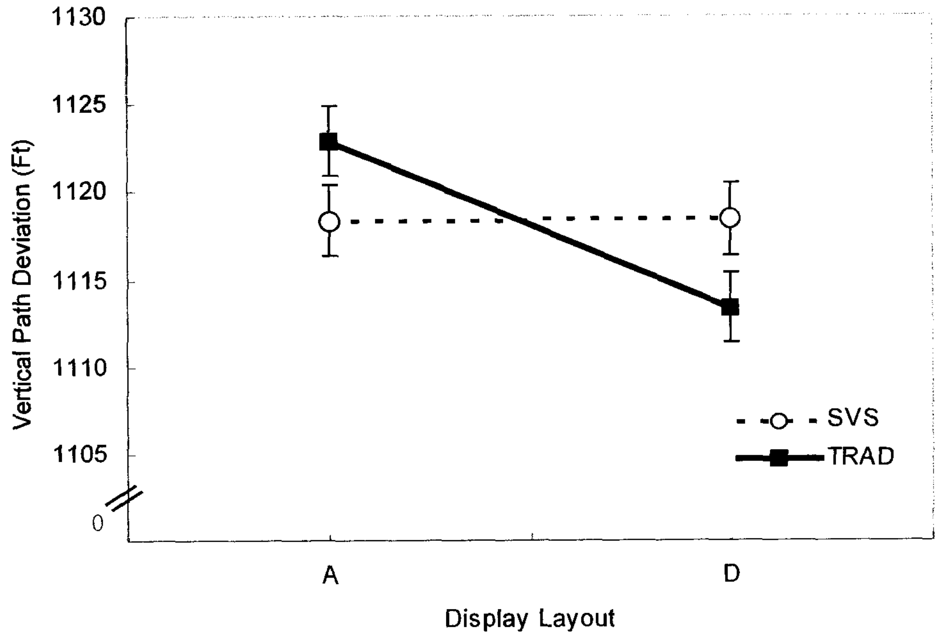

Figure 6. Vertical path maintenance during low workload.

Performance Data: All Trials

Lateral Path Maintenance Performance. A 2 (layout) X 2 (view) X 2 (workload) GLM-ANOVA was conducted. There was a significant interaction between layout and workload for lateral path maintenance during segment 3, F (1, 15) = 3.60, $p < .05$, $eta^2 = .05$ (see Figure 7). Significantly less lateral deviation from the path was exhibited with the more integrated display layout D during low workload (*M* = 20.99 ft., *SD* = 10.14) than layout D during high workload (*M* = 29.28 ft., *SD* = 19.79), layout A during low workload (*M* = 26.89 ft., *SD* = 16.34), or layout A during high workload (*M* =28.16 ft., *SD* = 15.74).

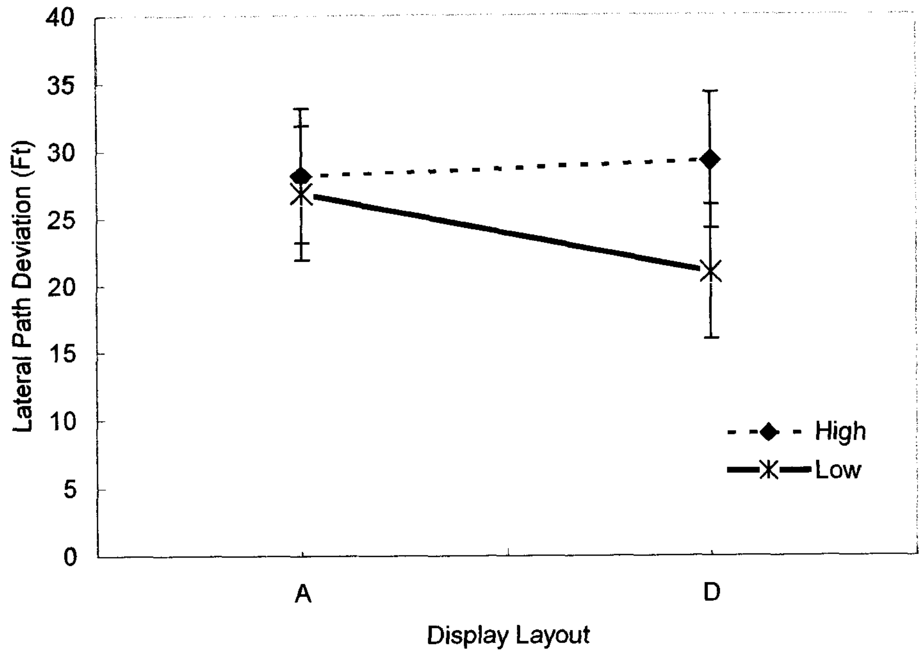

Figure 7. Overall lateral path maintenance.

Pilots were better at maintaining overall lateral path position under low workload (M = 37.85 ft., SD = 15.71) than under high workload (M = 41.92 ft., SD = 16.65), F (1, 15) = 3.60, $p < .05$, eta^2 = .06 (see Figure 8).

Vertical Path Maintenance Performance. A 2 X 2 X 2 GLM-ANOVA revealed an interaction between layout and view for overall vertical path maintenance, F (1, 15) = 5.94, $p < .05$, eta^2 = .24. As seen in Figure 9, superior vertical path maintenance performance was associated with the SVS-D configuration (M = 1415.51 ft., SD = 425.86) than with the TRAD-D (M = 1429.42 ft., SD = 430.07), the TRAD-A (M = 1420.55 ft., SD = 439.64), or the SVS-A displays (M =

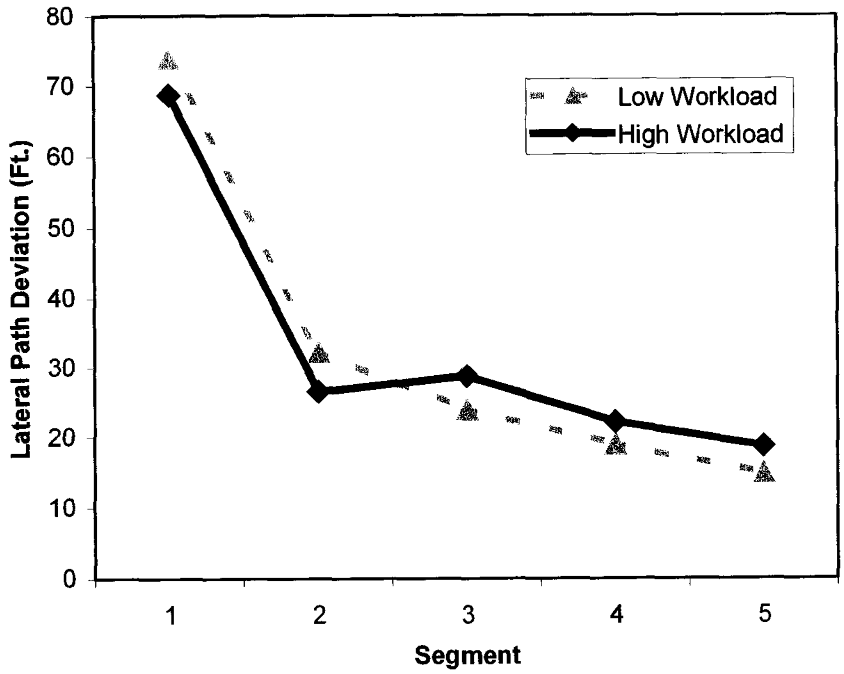

Figure 8. Lateral path deviation across all five segments.

1430.35 ft., *SD* = 430.47). Significantly more overall vertical path error was demonstrated with layout A (*M* = 1452.45 ft., *SD* = 433.39) than layout D (*M* = 1422.41 ft., *SD* = 426.31), F (1, 15) = 5.12, $p < .05$, eta^2 = .09.

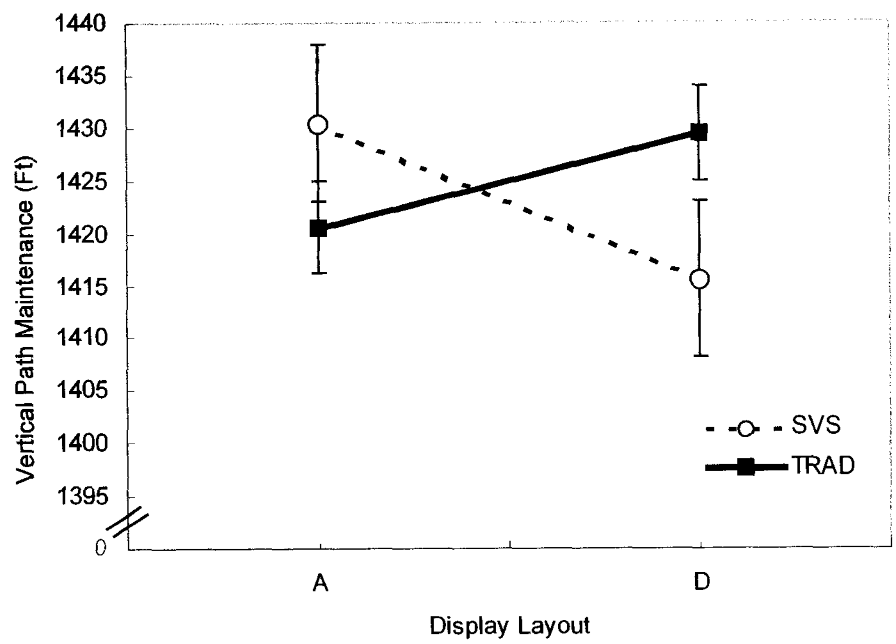

Figure 9. Overall vertical path maintenance.

Oculometric Data

Dwell count, dwell duration, fixation count, and fixation duration within each AOI was measured to provide a comprehensive assessment of pilots' eye movements. Separate AOIs were established for each of the two display layouts. The AOIs were the airspeed indicator, the navigation display, the roll indicator, the primary flight display, the localizer, the glideslope indicator, the altimeter, the vertical speed indicator, and the OTW view. Eye movement activity in each of these AOIs was recorded. Raw eye movement data were condensed using EyeNal™ software prior to export to SPSS™. A series of 2 (display layout) X 2 (display view) X 2 (workload) GLM ANOVAs were conducted to explore differences in visual activity in the predetermined AOIs. Only the trials in which eye tracking data were collected were used in these analyses.

Airspeed Indicator. There were significantly more dwells on the airspeed indicator when pilots were operating under high workload (M = 49.28, SD = 30.11) than when the pilots were under low workload (M = 20.23, SD = 14.93), F (1, 15) = 6.57, $p < .05$, $eta^2 = .66$. Likewise, mean fixation duration during high workload (M = 25.38 s, SD = 21.67) was significantly longer than fixation duration during low workload (M = 6.91 s, SD = 4.16), F (1, 15) = 44.53, $p <$ .05, $eta^2 = .74$. There were also significantly more fixations on the airspeed indicator when pilots were operating under high workload conditions (M = 61.29, SD = 34.29) than when they operated under low workload conditions (M = 23.31, SD = 19.10), F (1, 15) = 59.42, $p <$ .05, $eta^2 = .61$.

Glideslope and Localizer. Mean fixation duration on the glideslope indicator was significantly longer with layout D (M = 8.21 s, SD = 15.45) than with layout A (M = 2.47 s, SD = 6.04), F (1, 15) = 7.64, $p < .05$, $eta^2 = .35$. There were also layout, F (1, 15) = 13.96, $p < .05$, eta^2 = .64, and view, F (1, 15) = 4.24, $p < .05$, $eta^2 = .29$ main effects for the number of fixations on the glideslope. There were more fixations on the glideslope with layout D (*M* = 21.50, *SD* = 22.75) and the TRAD view (*M* = 18.48, *SD* = 26.06) than with layout A (*M* = 7.83, *SD* = 18.31) and the SVS view (*M* = 10.67, *SD* = 15.25), respectively. Conversely, there were significantly more fixations on the localizer during trials with layout A (*M* = 15.63, *SD* = 25.32) than with layout D (*M* = 6.79, *SD* = 10.70), F (1, 15) = 4.24, $p < .05$, eta^2 = .40.

Altimeter. Mean fixation duration on the altimeter was significantly longer with layout A (*M* = 13.16 s, *SD* = 14.59) than with layout D (*M* = 10.29 s, *SD* =8.90), F (1, 15) = 10.29, $p < .05$, eta^2 = .66. There were also layout, F (1, 15) = 8.53, $p < .05$, eta^2 = .43 and view, F (1, 15) = 4.90, $p < .05$, eta^2 = .22 main effects for number of fixations on the altimeter. There were significantly more fixations on the altimeter with layout D (*M* = 36.10, *SD* = 28.23) than layout A (*M* = 22.54, *SD* = 23.94). There were also more fixations on the altimeter during trials with the TRAD view (*M* = 34.44, *SD* = 32.03) than with the SVS view (*M* = 24.02, *SD* = 19.38).

Primary Flight Display. Surprisingly the planned analyses did not reveal eye movement differences in the primary flight display as a function of layout, view, or workload. Correlations were computed to explore how other variables might be related to visual scanning of the primary flight display (see Table 2). Participant age was significantly correlated with mean dwell time (r = .21), dwell count (r = -.24), and fixation count (r = -.19) on the primary flight display.

To better understand these correlations a series of 2 (layout: A/D) X 2 (view: SVS/TRAD) X 2 (workload: high/low) X 4 (participant age group: group 1: 29-33; group 2: 34-38; group 3: 39-43; group 4: 44-47) ANOVAs were conducted. Several age group main effects were identified for indices of visual acquisition of the primary flight display. A *post hoc* analysis of an age group main effect identified that group 4 (M = 2.18 s, SD = .80) demonstrated significantly longer average dwell times on the primary flight display than did group 1 (M = 1.64 s, SD = .46), group 2 (M = 1.45 s, SD = .88), or group 3 (M = 1.70 s, SD = 1.1), F (3, 15) = 3.94, $p < .05$, $\text{eta}^2 = .11$.

Age group main effects were also found for dwell count and fixation count on the primary flight display. A *post hoc* analysis revealed that group 2 (M = 135.41, SD = 56.30) exhibited the most number of dwells on the primary flight display followed by group 1 (M = 110.69, SD = 19.39), group 3 (M = 107.72, SD = 33.62), with group 4 (M = 96.18, SD =

25.65) having the least amount of dwells on the primary flight display, F (3, 15) = 8.53, $p < .05$, $\text{eta}^2 = .16$. Another *post hoc* analysis identified that significantly more fixations on the primary flight display were made by group 1 (M = 281.92, SD = 56.09), than group 2 (M = 230.33, SD = 71.34), group 3 (M = 214.88, SD = 104.96), or group 4 (M = 241.01, SD = 64.91), F (3, 15) = 3.66, $p < .05$, $\text{eta}^2 = .08$.

There were a number of significant correlations among the various eye tracking measures (see Table 2). Mean dwell duration on the airspeed indicator was inversely correlated with mean fixation duration of the airspeed indicator (r = -.20), the primary flight display (r = -.23), the navigation display (r = -.19), and the OTW area (r = -.18). Mean dwell count on the airspeed indicator was positively correlated with mean fixation duration on the airspeed indicator (r = .43), the primary flight display (r = .44), the navigation display (r = .34), and the OTW area (r = .24).

Fixation count on the primary flight display was negatively correlated with mean fixation duration on the airspeed indicator (r = -.32), the primary flight display (r = -.33), the navigation display (r = -.37), and the OTW area (r = -.45). Mean dwell duration on the primary flight display was inversely related to fixation count on the airspeed indicator (r = -.25), the navigation display (r = -.32), and the out-the-window area (r = -.23).

Table 1

Correlational Analyses of Oculometric Data

		Fixation Count				Fixation Duration				Dwell Count				Dwell Duration			
		AS	PFD	NAV	OTW	AS	PFD	NAV	OTW	AS	PFD	NAV	OTW	AS	PFD	NAV	OTW
FC	AS	--	.25*	.18*	.13	-.05	-.01	-.07	-.11	.68*	.24*	.07	.04	.33*	-.25*	-.12	-.23*
	PFD		--	.10	.24*	-.32*	-.33*	-.37*	-.45*	-.13	-.14	-.08	-.07	-.05	.00	-.22*	-.12
	NAV			--	.29*	-.10	-.08	-.11	-.13	.03	.24*	.81*	.10	.06	-.32*	.38*	.17
	OTW				--	-.14	-.11	-.14	-.17	-.05	.04	.16	.72*	-.05	-.23*	-.01	-.19*
FD	AS					--	.94*	.95*	.82*	.43*	.44*	.09	.11	-.20*	-.20*	-.03	-.11
	PFD						--	.82*	.68*	.44*	.52*	.12	.13	-.23*	-.22*	-.04	-.12
	NAV							--	.93*	.34*	.40*	.07	.13	-.19*	-.19*	-.02	-.11
	OTW								--	.24*	.33*	.05	.20*	-.18*	-.20*	-.03	-.10
DC	AS									--	.69*	.24*	.18*	-.04	-.44*	-.15	-.31*
	PFD										--	.48*	.35*	-.34*	-.76*	-.15	-.27*
	NAV											--	.22*	-.04	-.47*	.24*	.09
	OTW												--	-.23*	-.46*	-.17	-.48*
DD	AS													--	.18	.26*	.17
	PFD														--	.10	.25*
	NAV															--	.27*
	OTW																--

*$p < .05$

Mental Workload

A 2 (display layout) X 2 (display view) X 2 (workload) GLM-ANOVA was conducted to examine subjective workload differences as measured by the NASA-TLX. The only significant interaction was found between layout and workload for the physical demand subscale of the TLX, F (1,

15) = 5.12, $p < .05$, $eta^2 = .31$. As seen in Figure 10, significantly greater perceived physical demand was reported for layout A under high workload conditions (M = 33.33, SD = 23.86) whereas the lowest report was for layout D under low workload conditions (M = 18.95, SD = 18.36).

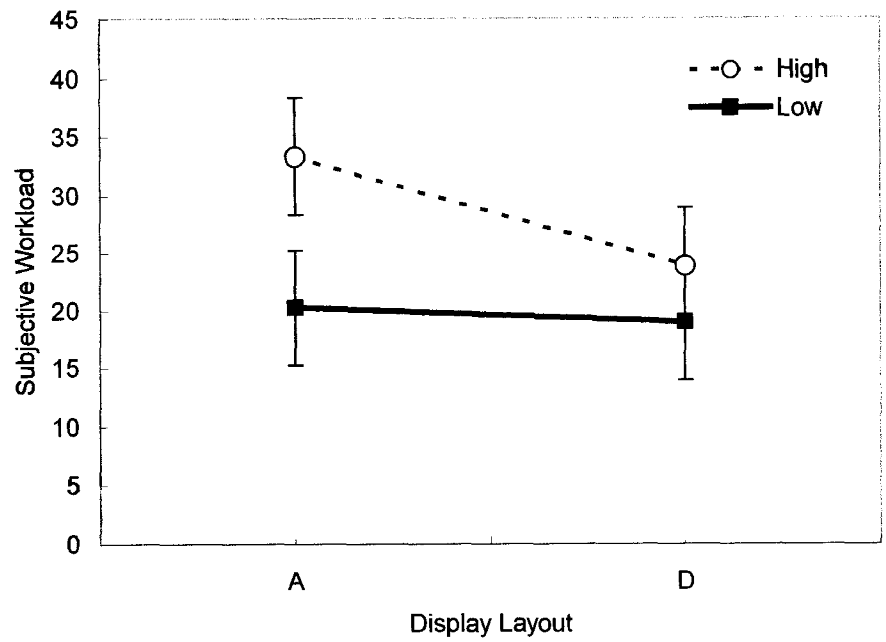

Figure 10. Subjective workload.

Mental workload reported on the overall TLX revealed layout, F (1, 15) = 12.51, $p < .05$, $eta^2 = .45$, view F (1, 15) = 8.93, $p < .05$, $eta^2 = .56$, and workload F (1, 15) = 16.21, $p < .05$, $eta^2 = .52$ main effects. Lower mental workload was reported for layout D (M = 23.84, SD = 15.30) than layout A (M = 29.27, SD = 16.54), the SVS view (M =

22.33, *SD* = 15.20) than the TRAD view (*M* = 29.44, *SD* = 26.52), and the low workload condition (*M* = 24.86, *SD* = 13.58) than the high workload condition (*M* = 31.24, *SD* = 17.19).

Situation Awareness

A 2 (display layout) X 2 (display view) X 2 (workload) GLM ANOVA was conducted to examine situation awareness as measured by the Situational Awareness Rating Technique (SART). The only significant interaction was found between layout and view for the information quality item of the SART, F (1, 15) = 11.57, $p < .05$, $\text{eta}^2 = .43$ (see Figure 11). Information quality for the SVS layout D configuration (*M* = 6.25, *SD* = .56) was rated significantly better than the SVS-A display (*M* = 6.10, *SD* = .73) or the TRAD-D display (*M* = 6.08, *SD* = .58) while the worst information quality was reported for the TRAD-A configuration (*M* = 5.52, *SD* = 1.33).

Layout main effects for situation awareness were found for item 9 which assesses situation awareness in terms of information quality, F (1, 15) = 10.62, $p < .05$, $\text{eta}^2 = .04$ and item 10 about information familiarity, F (1, 15) = 6.72, $p < .05$, $\text{eta}^2 = .03$. Data from both item 9 (layout A: *M* = 5.80, *SD* = 1.01; layout D: *M* = 6.17, *SD* = .57) and item 10 (layout A: *M* = 5.83, *SD* = 1.20; layout D: *M* = 6.21, *SD* =

.94) indicate that greater situation awareness was reported for the more integrated display layout. Greater average situation awareness was reported for the SVS view (*M* = 4.95, *SD* = .55) than the TRAD view (*M* = 4.73, *SD* = .63), $F\ (1, 15) = 8.84$, $p < .05$, $eta^2 = .54$. Better situation awareness was also reported for low workload trials (*M* = 5.06, *SD* = .55) than high workload trials (*M* = 4.63, *SD* = .57), $F\ (1, 15) = 25.88$, $p < .05$, $eta^2 = .63$.

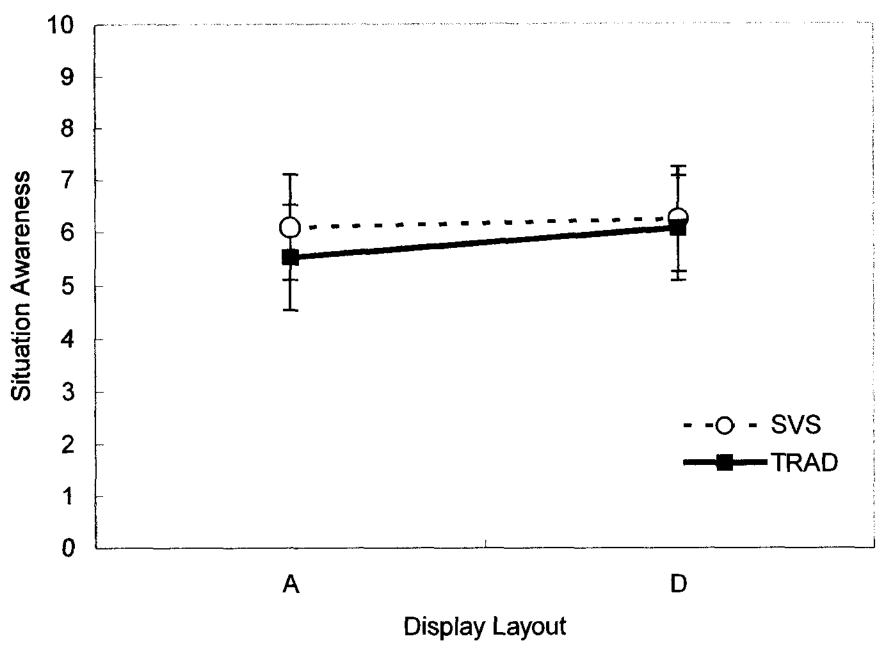

Figure 11. Situation awareness.

<u>Correlations Among Subjective Measures</u>. There was a significant correlation between subjective workload and situation awareness, $r = -.61$; pilots reporting greater situation awareness experienced less subjective workload.

Furthermore, overall situation awareness was correlated with lateral path maintenance performance. Increased situation awareness was associated with reduced lateral path deviation (r = -.20). More experienced pilots reported increased situation awareness (r = .19).

Results Summary

Integrated Task Performance. During segment 3, the worst lateral path maintenance performance was exhibited with the TRAD-A configuration during both high and low workload trials. Layout D combined with low workload produced the best lateral path maintenance performance during segment 3. Layout D and the SVS view produced the best performance during segment 3 of the low workload trials. The low workload condition produced the best overall lateral path maintenance. An age group main effect during indicated that the oldest group of participants demonstrated significantly worse overall lateral path maintenance performance than the youngest group of pilots during high workload.

Vertical path maintenance data provide varied results. Under high workload conditions, the TRAD-A configuration facilitated the best overall vertical path maintenance performance while the SVS-A condition was noticeably the worst combination of display layout and view for this measure. However, under low workload the TRAD-D configuration produced the best performance whereas the worst performance was exhibited with the TRAD-A configuration; notably the SVS view was relatively unaffected by layout during low workload. Finally, when the data were combined the SVS-D configuration facilitated the best overall vertical path maintenance. Also across workload conditions, the best vertical path maintenance was demonstrated with the more integrated layout. During segment 2, the TRAD view produced the best vertical path maintenance performance during high workload whereas the SVS view produced the best performance during low workload trials. The oldest group of participants out performed their younger colleagues during low and high workload conditions.

Focus Task Performance. Airspeed maintenance served as the focus task in the current study. The TRAD-A and SVS-D configurations facilitated better airspeed maintenance than the TRAD-D or the SVS-A conditions. The less integrated layout facilitated significantly better airspeed maintenance control than did the more integrated layout. The oldest group of participants demonstrated superior airspeed maintenance performance than did the youngest group during the most challenging portion of the high workload condition.

Eye Movements. There were significantly more dwells and fixations as well as longer fixations on the airspeed indicator during high workload trials than during low workload trials. Fixation time on the glideslope indicator was longer with layout D than layout A. There were also more fixations on the glideslope indicator with layout D and the TRAD view than layout A and the SVS view, respectively. Conversely, there were more fixations on the localizer with layout A than with layout D. Fixation time on the altimeter was greater with layout A than D. However, there were more fixations on layout D and the TRAD view than layout A and the SVS view. There were many correlations with various oculometric activities on the PFD. Pilot age had an unexpected effect on eye movement behavior. The group of the oldest pilots exhibited longer dwell time on the PFD, but looked at it significantly less than did all other age groups. The youngest group of pilots had significantly more fixations on the PFD than did all other age groups.

Subjective Measures. Layout A during high workload produced the highest subjective workload ratings. Layout A, the TRAD view, and the high workload condition produced the highest workload ratings. The SVS-D configuration produced the best situation awareness. Layout D and the SVS view produced superior SA than did layout A and the TRAD view, respectively. The low workload condition also increased situation awareness ratings.

DISCUSSION

Objectives of the Current Study

The primary goal of the current study was to investigate flight performance and eye movement activity of pilots experiencing two arrangements of SVS displays and two baseline displays without SVS. Measuring mental workload and situation awareness was also of prime importance. One objective was to test the predictions of the Proximity Compatibility Principle in a synthetic vision environment. The second objective was to conduct an empirical examination of two SVS displays and assess effects on performance, subjective workload, and self-reported situation awareness in a simulated commercial cockpit. The third objective was to assess differences in eye movements stimulated by the individual and joint effects of display integration and synthetic vision displays.

Proximity Compatibility Principle Predictions

Supporting the high proximity predictions of the Proximity Compatibility Principle, the more integrated layout produced superior integrated task performance than did the less integrated layout. This agrees with a large body of research that has demonstrated that integrative displays facilitate performance on integrative tasks (e.g., Carswell & Wickens, 1987; Gillie & Berry, 1994; Geottl, Wickens, & Kramer, 1991; Hofer et al., 1993; Kroft & Wickens, 2001; O'Brien & Wickens, 1997; Wickens & Helleberg, 1999). Increased workload was expected to exaggerate effects between display type and task type. However, lateral path maintenance performance improvements with the more integrated display layout were evident only during low workload whereas vertical path maintenance improvements occurred during all workload conditions.

The low proximity predictions for the interaction between display type and task type were also confirmed. However, the traditional view coupled with the less integrated display layout facilitated superior performance over the SVS view coupled with the same display layout. Perhaps the traditional blue sky over brown ground coupled with the more familiar layout of the less integrated display can explain the performance improvement associated with the traditional display, even though pilot experience with these types of displays was not indicative of observable performance differences.

There have been studies that do not support the predictions of the Proximity Compatibility Principle. Many of these studies contend that emergent features have the largest impact on visual attention and performance (Coury &

Boulette, 1992; Sanderson, Flach, Buttigieg, & Casey, 1989). Coury, Boulette, & Smith (1989) found mixed support for the expected interaction between display type and task type predicted by the Proximity Compatibility Principle. They suggest that extraneous variables moderate performance and can interfere with the expected interaction.

Sanderson et al., (1989) suggests that the interaction predicted by the Proximity Compatibility Principle is a result of emergent features more than display proximity. To test the purported effect of emergent features, Wickens and Andre (1990) developed a study to investigate the role of emergent features within the Proximity Compatibility Principle predictions; the interaction between display type and task type was corroborated. Buttigieg and Sanderson's (1991) innovative paradigm that controlled for emergent features did not support the Proximity Compatibility Principle. In fact, Buttigieg and Sanderson suggested that the presence of a strong emergent feature is more useful. However, their emergent features approach does not explain performance differences as a function of display *type* as does the Proximity Compatibility Principle. The current study supports Proximity Compatibility Principle because the expected interaction between display type and task type manifested *without* differing emergent features on any of the four possible display configurations.

Opposition to the Proximity Compatibility Principle has also been introduced by Uhlarik and Joseph (1992). They assessed communication performance differences between temporal and spatial proximity differences. They found that the Proximity Compatibility Principle predicted integrated task performance with temporal displays, but not for displays that were considered high proximity based only on their proximity. They argue that "proximity" cannot be defined merely by physical metrics (e.g., relative location), but rather on the cognitive inputs required to extract information from a display. This opposes Wickens contention that display proximity can be defined in terms of either physical metrics or objectiveness (Wickens & Andre, 1990). This would suggest that placing important displays close together should facilitate easier information extraction.

Merely presenting the analog dials along side the somewhat integrated display did not facilitate the best performance. As such, these data agree with previous research that proximity cannot be determined primarily on physical attributes (Bennett, Toms, & Woods, 1993; Edgell & Morrissey, 1992; Hayward & Lowe, 1998). Rather, several types of display relatedness must be contemplated. Vincow and Wickens (1992) built upon the Proximity Compatibility Principle to identify "Types of Display Relatedness" that must be considered in display layout. Task relatedness (how much information for multiple displays must be mentally combined to complete a task), correlational relatedness (changes in one display are consistently related to changes in another display), system relatedness (multiple displays with similar fundamental systems), and integration relatedness (multiple displays that convey data that must be integrated by the user to extract viable information) must all be considered in display layout. Wickens and Carswell (1995) clarify that the Proximity Compatibility Principle predictions depend upon both perceptual proximity and processing proximity.

One issue that must be addressed is that the two display layouts utilized in the current study had qualitatively unique features. The more integrated display utilized tapes whereas the less integrated display utilized round dials. Both of these are analog displays with redundant digital presentation. However, the tape display has a fixed pointer with a moving scale whereas the dials in the less integrated display are traditional altimeter dials with a fixed scale and moving pointer. The advantages and disadvantages of the specific type of visual display that is best suited for a given situation has been explored since the birth of human factors research (Helander, 1987; Hutchins, 2000; Roscoe, 1968, 1980). Tape displays are becoming increasingly prominent in aviation. They facilitate extraction of detailed information from a large scale range. Circular displays, however, have also been shown to elicit better performance than vertical and horizontal displays in complex environments (see Sanders & McCormick, 1993 for a summary).

Synthetic Vision System Predictions

Congruent with recent research (e.g., Kramer, Prinzel, Bailey, & Arthur, 2003; Prinzel et al., 2004; Schnell, Kwon, Merchant, & Etherington, 2004), these data suggest that using an SVS display may facilitate superior flight performance. The finding that SVS did improve lateral performance in the current study, even if only during low workload, is an important one that warrants further study. Data have indicated that CFITs are routinely attributed to lateral path error (Corwin, 1995; Graeber, 1996). The slight improvement indicated by these data provides optimism that developing SVS displays may reduce lateral path error.

The SVS display complements the user's mental model. Recent research suggests that SVS technologies may reduce low visibility incidents (Comstock, Glaab, Prinzel, & Elliott, 2001; Kramer, Prinzel, Bailey, & Arthur, 2003; Stark, 2003). Endsley (2000) indicates that SVS displays have a promising future in commercial aviation. A display that is congruent with the user's mental model of the system will facilitate performance and improve situation awareness (Endsley, 1988; Roske-Hofstand & Paap, 1986; Hancock & Desmond, 2001).

Eye Tracking Predictions

Another objective of the current study was to assess eye movement as a function of display integration and display view. Because the aircraft was on automatic throttle during low workload trials, there was more eye activity on the airspeed indicator than when pilots utilized manual throttle. There were more dwells, more fixations, and longer fixations on the airspeed indicator when pilots experienced high workload approaches as opposed to low workload approaches.

Pilots were able to ascertain vertical position with fewer fixations on the glideslope with the synthetic vision display than with the traditional display. The synthetic view of the environment may have reduced reliance on the glideslope indicator to maintain vertical position along the programmed path. Pilots were able to maintain vertical path position with fewer fixations on the SVS display glideslope. Pilots fixated on the localizer more often when using the less integrated display. This makes sense, because the synthetic vision display did not identify differences in visual sampling of the localizer. This may indicate that a synthetic vision display is more useful to convey vertical position information than to convey lateral position information, as a localizer does.

Pilots also fixated on the altimeter more often while using the more integrated display. However, fixation duration on the altimeter in the less integrated display was longer than fixations on the altimeter in the more integrated display layout. There were also more fixations on the altimeter with the traditional view than with the synthetic vision view. Again, it appears as though pilots were able to derive more vertical position information from the synthetic vision display than from the traditional information.

Age group was found to be predictive of visual activity within the primary flight display. The group of the oldest pilots looked at the primary flight display fewer times, but looked at it for a longer period of time.

The youngest group of pilots exhibited significantly more fixations on the primary flight display than did all other groups. These differences are evidence of different eye scan patterns as a function of pilot age.

Age and experience have been shown to have an effect on eye movements between novice and experienced drivers (Dishart & Land, 1998; Underwood et al., 2003), between graduate students and professors (Dixon, 1948), between professional and amateur athletes (Harbin, Durst, & Harbin, 1989; Land & McLeod, 2000; Lenoir, Crevits, Goethals, Wildenbeest, & Musch, 2000). Some suggest that professional athletes' visualization abilities may be the reason for their effective eye movement techniques (Vickers, 1992). Perhaps the age differences reported in the current study could be analogous to apparent differences between amateur and professional athletes. These data indicate that the older pilots may demonstrate more effective visual sampling techniques. The older pilots also outperformed their younger colleagues, especially during high workload. It is unclear if the visual sampling technique *caused* these performance improvements or if these differences simply co-existed.

Recent research suggests that visualization can induce effective visual sampling techniques (Barsalou, 1999;

Kosslyn et al., 1995; Martin, 2001; Brandt & Stark, 1997). So, a display that enables the user to visualize his environment should facilitate effective visual sampling. The SVS displays examined in the current study promote visualization of one's own aircraft relative to the immediate and future environment (Koczo, Klein, Both, & Lamb, 1998; Regal & Whittington, 1994). Other research suggests that scene quality will promote effective scanning (Henderson, 2003). The realistic scene utilized in an SVS display should also facilitate effective visual sampling activity.

These data offer partial support for Zelinsky and Sheinberg's (1995) Variable Number Model. There were more fixations on the glideslope indicator and the altimeter with the more complex integrated display, as predicted by the Variable Number Model. However, contrary to the predictions of this model increased fixation duration on the glideslope was also observed with the more complex display. The predictions of the Variable Duration Model were not supported because increased fixation duration was not consistently attributed to the more complex displays. Both of these models, as well as research by Demarais and Cohen (1998), predict that the synthetic vision display should elicit more fixations than the traditional display due to the increased complexity inherent in an SVS display. However, the only significant differences as a function of display view indicated more fixations on the glideslope indicator and the altimeter with the traditional display.

These data support the SEEV model of attention (Wickens, Helleberg, Goh et al., 2001) as a framework to predict and understand eye scan behavior *and* situation awareness in a complex environment. The person's experiences, knowledge, and mental model produce expectancy of the situation, moderates the value the person puts on the information which in turn dictates the amount of effort the person is willing to put forth. If expectancy is accurate, the person will have adequate situation awareness. Good situation awareness will in turn allow the person to make a good assessment about the value he places on the information and the amount of effort, in this case visual effort, he can "spend" to obtain the information.

For example, the participants placed little value on the airspeed indicator during auto-throttle trials because they expected it to be relatively constant. They monitored it, but did not devote nearly as much visual attention to this indicator as when they were on manual throttle. Likewise, the separable airspeed indicator in the less integrated display was more salient than the integrated airspeed tape in the high-proximity display layout. This increased salience helps to explain performance improvements with the less integrated layout.

Strengths, Limitations, and Future Research

Unlike many aviation studies that rely on participation from non-pilot college students, the current study was conducted with a highly representative participant pool in a moderate fidelity simulator capable of presenting high resolution head-down and OTW displays. This paradigm improves generalizability. Moreover, having the actual end users is important in the design process of any complex system (O'Brien & Charlton, 1996; Parasuraman, Hansman, & Bussolari, 2002; Shneiderman, 1998).

Assessing eye movements provided an objective measure of visual attention. Without objective data, researchers must make considerable inferences about the operator's attention. Eye movement data provide a means for researchers to identify allocation of visual attention. For example, a pilot may visually neglect the vertical speed indicator but unless there is an observable error relating to vertical speed information, the researcher may not even recognize that the pilot is not scanning this display. Using an eye movement analysis in this same scenario, the researcher can identify where the pilot is devoting his visual attention. Measuring eye movement activity also provides an excellent method to assess when and where a person visually acquires an emergent feature in a display.

The focus of this study was to assess performance and behavior on approach. These 5-7 minute trials were obviously not comparable to actual flight time for a commercial aircraft. These data may not accurately represent performance and behavior exhibited over a longer flight. A paradigm designed for cross-country flight should be conducted to assess changes that occur during different phases of flight (e.g., takeoff, cruise, on autopilot, or during unexpected events).

Along this line, the workload requirements were not comparable to aviating a commercial aircraft. Pilots performed only a fraction of the tasks that are actually required to operate a commercial aircraft. The simulator was "configured for landing" from the start of the approach, and there were no communication requirements or air traffic. Subject matter experts like highly trained commercial pilots may not be subject to huge performance deficits under typical "high" workload situations.

The workload manipulation in the current study created two unique approaches. The hardest segment was notably segment 3 of the high workload approach. During this segment pilots had to aviate a sharp turn on manual throttle with cross winds. It would make sense that this increased workload level would elucidate performance differences. However, here was only one performance difference that was unique to segment 3 high workload trials (better performance for the more integrated display layout). It is possible that pilots performed better during this segment because it was more comparable to the workload they are used to experiencing during actual flight.

Perhaps pilot performance may be partially explained by the Yerkes Dodson Law. This principle proposes an optimal arousal level during which people perform best. Perhaps this same curvilinear relationship was demonstrated in the current study. This would explain some of the performance differences between the low and high workload groups. In normal populations, increasing workload generally has a deleterious affect on performance. With this group, however, the highest workload condition did not bring out the worst performance. The current study was not designed to test this supposition. Future research could examine if an optimal arousal level may facilitate pilot performance.

In any case, it would be interesting to investigate if these data would be replicated in a full-task simulator study designed to produce mental demands typical of piloting a commercial aircraft. Future research along this line must also incorporate traffic to investigate if integrated SVS displays can enable better detection of air traffic under VFR and IFR. There are still a relatively high number of midair collisions per year. The FAA estimates that there have been 10-15 collisions per year over the last ten years resulting in serious casualty, loss of human life, or loss of aircraft (Prinzo, 2001). A study in a full task simulator that introduces traffic could also examine how an integrated SVS display might interact with the "see and avoid" method suggested by the FAA.

Another avenue for future research should be to provide an objective assessment of how integrated synthetic vision displays impact situation awareness. One objective tool for measuring situation awareness in simulation studies is the query technique (Adams, Tenney, & Pew, 1995; Endsley, 1995b; Gronlund, Ohrt, Dougherty, Perry, & Manning, 1998; Marshak, Kuperman, Ramsey, & Wilson, 1987; Tenney, Adams, Pew, Huggins, & Rogers, 2002). In this approach, the simulation is suspended briefly blocking all visual cues to the current display status. The participant then answers a series of brief, task-specific questions about the situation. The responses are compared with the correct information to determine the person's knowledge of the situation. Endsley (1995a) and Wickens (1996) contend that an operator with adequate situation awareness should be able to recall highly relevant, attended to, and processed information. This type of technique should be used with the current paradigm to provide an objective assessment of situation awareness.

Design Implications

Integrating multiple components or adding a perspective 3-D scene to an already complex display can contribute to display clutter (Garner, 1970; Buttigieg & Sanderson, 1991; Tullis, 1983; Ververs & Wickens, 1998). Display clutter can inflict added processing requirements on the pilot (Neisser & Becklen, 1975) such as causing a disruption in visual acquisition of targeting information (Schons & Wickens, 1993). Display complexity can also alter scan patterns (Demarais & Cohen, 1998; Ehrlichman, Weiner, & Baker, 1974; Weber & Malmstrom, 1979).

The potential cost of imposing additional cognitive requirements in an already high workload situation must be weighed against the potential benefits results from utilizing an integrated SVS display. Results of the current study indicate that the benefits resulting from utilizing an integrated SVS display may outweigh the potential cost of adding additional clutter. Furthermore, this concurs with Bennett and Flach's (1992) suggestion that the benefits of high-proximity displays for integrative tasks prevail over the potential costs.

The pragmatic design implication that must be addressed concerns the viability of retrofitting existing cockpits with integrated SVS displays. A safety and cost benefit analysis is required to answer this question. Realistically, the operational benefits must be apparent for any airline to willingly retrofit aircraft with a new system. Providing a HUD synthetic vision display may be a more economically feasible alternative to a complete retrofit. If ongoing research continues to provide support for integrated synthetic vision displays, the FAA could eventually mandate the use of integrated synthetic vision displays in commercial or general aviation. Perhaps the less complicated solution may be to focus government and industry efforts to incorporate integrated primary flight displays augmented with synthetic vision on the next generation of commercial aircraft.

The notion that augmenting a cockpit with synthetic vision may increase situation awareness also has pivotal design implications. These data support previous research findings that appropriately integrated displays can foster situation awareness in a complex environment (Endsley et al., 2000; GAMA, 2000; Wickens, Fadden et al., 1998). These data suggest that spatial situation awareness may be improved by display integration and the use of the synthetic vision view. Maintaining ample situation awareness is crucial to overall flight performance and more importantly to avoid CFITs (Endlsey, 2000; Fracker, 1989).

Conclusions

Every effort must be made to mitigate the competing multidimensional demands on a commercial pilot. One way to accomplish this is to provide displays that integrate information. The display layout guidelines provided by the Proximity Compatibility Principle should be utilized in future research and development of integrated synthetic vision system displays for commercial cockpits. Further, these data advocate the SEEV model of attention as a framework to predict and understand eye movement behavior *and* situation awareness in a complex environment.

In addition to situation awareness self-report data indicating that the integrated SVS display produced the best situation awareness, anecdotal comments from pilots indicated that they experienced greater geographical situation awareness with the SVS displays. For instance, pilots made comments like "I feel like I know right where the mountains are with this SVS display". Comments like this suggest that the SVS display promotes geographical situation awareness. This offers promising support for the SVS displays because pilots that think they have good situation awareness usually *do have* good situation awareness (Garland & Endsley, 2000).

The predicament that designers of complex systems must face is to produce displays that can facilitate improved performance and situation awareness to the masses - accommodating a wide range of individual experience, knowledge, and mental models. Accomplishing this feat will no doubt reduce commercial aviation accidents such as CFITs worldwide, especially during low visibility situations. Equipping commercial cockpits with integrated SVS displays may be one solution to this quandary.

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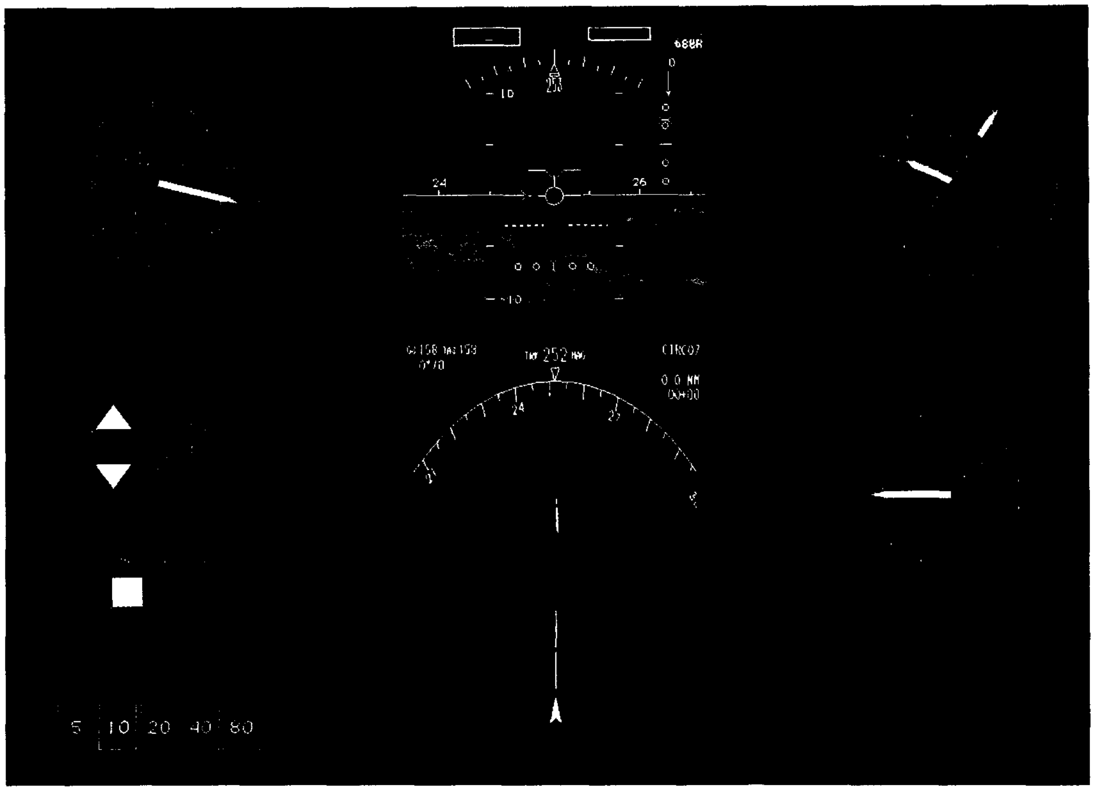
APPENDIX A

Pilot Demographic Data

Ss #	Age	Years Education	Vision Corrected	Years Transport Pilot	Transport Flight Hours	Current Aircraft	Current Position	Years Military	Pilot Years	Experience with			
										Glass Cockpit	Tape Display	HUD	Velocity Vector
1	47	16	Y	15	16658	737	FO	0	25	N	N	N	N
2	47	16	Y	23	19000	747	Capt	0	32	Y	Y	Y	Y
3	41	16	Y	3	3800	737	FO	16	16	Y	N	Y	Y
4	41	16	Y	3	3800	737	FO	16	16	Y	N	Y	Y
5	35	16	N	3	4500	RJ	FO	0	12	N	N	N	N
6	45	14	Y	3	5500	320	FO	20	12	Y	Y	N	N
7	43	18	Y	3	4600	320	FO	14	18	Y	Y	Y	Y
8	38	17	Y	8	5000	RJ	Capt	0	17	Y	N	N	Y
9	32	16	Y	7	5700	737	FO	0	12	Y	N	N	Y
10	38	18	N	4	5000	320	FO	14	16	Y	Y	Y	Y
11	38	16	N	2	3000	767	FO	13	12	Y	N	Y	N
12	43	16	N	10	9000	777	FO	17	17	Y	Y	N	Y
13	47	16	N	6	9200	320	FO	0	22	Y	Y	N	Y
14	33	16	N	6	5200	737	FO	0	15	N	N	N	N
15	37	17	N	2	8800	737	FO	0	18	Y	N	N	Y
16	29	16	Y	3	3080	RJ	FO	0	9	Y	N	N	N

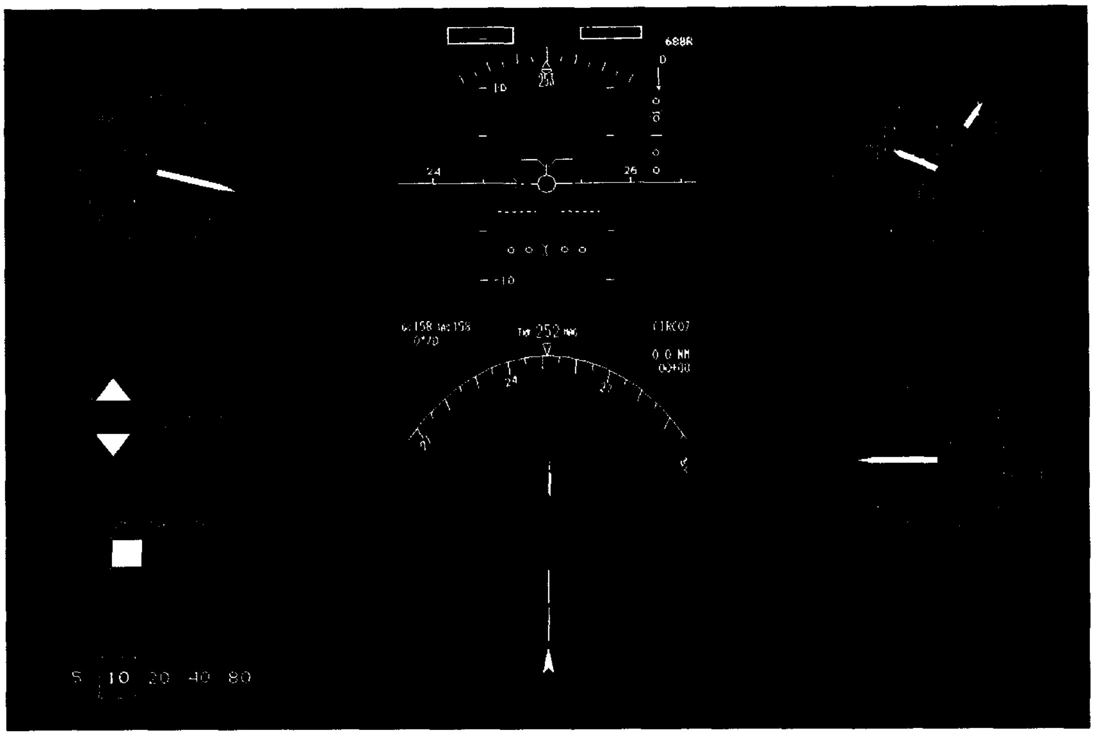
APPENDIX B

Layout A With Synthetic Vision View



APPENDIX C

Layout A With Traditional View

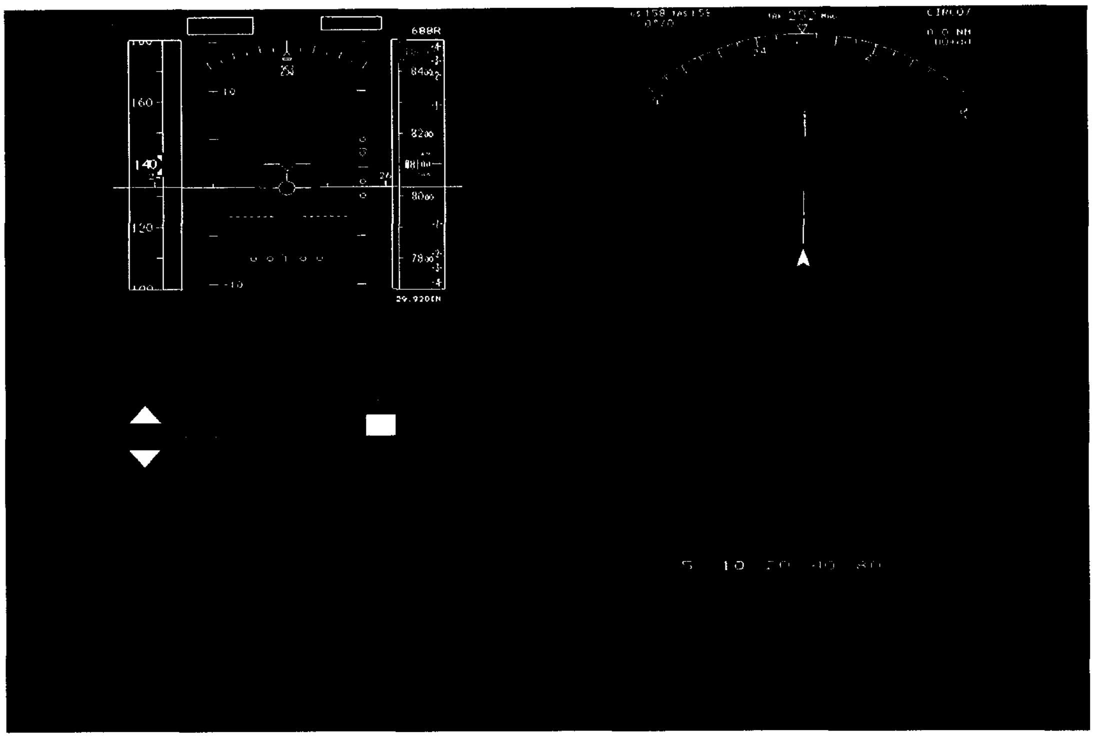


APPENDIX D

Layout D With Synthetic Vision View

APPENDIX E

Layout D With Traditional View



APPENDIX F

Components of the ASL 4100H Eye Tracker

Eye Camera Optics Module. The eye camera optics module focuses an image of the eye onto a solid-state camera sensor. The focusing tube was used to adjust the camera focus. A mirror inside the prism housing redirects the camera optical path through the camera lens. Beam splitter adjustment screws were used to optimize the alignment of the illumination beam on the optical axis. The eye camera optics module was clamped to the front of the helmet.

Visor Assembly. The visor assembly reflects the eye image towards the eye camera. This assembly was essentially transparent to the wearer. The left half of the visor was reflective to near infrared and transmissive in the visible spectrum. The visor was mounted on two telescoping arms with hinges that allow for flexible positioning.

Scene Camera Assembly. The scene camera provides a frame of reference for the eye line-of-gaze measurements. The scene camera lens allows for a 50-degree field of view.

Camera Control Unit. The pupil and scene cameras are connected to a camera control unit that houses the camera electronics. Video and power cables extend from each camera control unit to the eye tracker control unit rear panel.

Eye Tracking System Control Unit. The ASL 4100H control unit was housed in an 18 x 18 x 19.5 inch cabinet that contains the electronics unit, three video monitors, a control panel, a connector panel, and all power supplies. This cabinet was located behind the VISTAS III facility and was completely out of the pilot's view while he or she was flying the simulator.

Control Panel. The control panel includes a main system power switch, camera and illuminator power switches, and an illuminator level adjustment. Discrimination controls are available to adjust the video threshold levels for pupil and corneal reflection edge detection. A cursor or a set of cross bars was used to designate line-of-gaze on the scene monitor.

Monitors. The control panel has three video monitors. On the left was the scene monitor that presents a video image of the scene being viewed. A set of cross bars was superimposed to indicate the gaze point. The scene monitor automatically reverses the image from the helmet mounted scene camera to produce a conventional image. The image from the eye camera was displayed on the center monitor (the eye monitor). In this monitor, a white outline was superimposed over the pupil image and a black outline was superimposed on the corneal reflection. A white cross bar designates the pupil centroid and a black cross bar designates the corneal reflection centroid. The third monitor was not used in this study.

Computer. A desktop PC computer (hard drive, RAM, and processor) was responsible for pattern recognition, eye position computations, and user interface.

APPENDIX G

NASA-Task Load Index

Rating Scale Definitions

Title	Descriptions
MENTAL DEMAND	How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?
PHYSICAL DEMAND	How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
TEMPORAL DEMAND	How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?
PERFORMANCE	How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?
EFFORT	How hard did you have to work (mentally and physically) to accomplish your level of performance?
FRUSTRATION LEVEL	How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

NASA TLX

Place a mark at the desired point on each scale:

MENTAL DEMAND

Low High

PHYSICAL DEMAND

Low High

TEMPORAL DEMAND

Low High

PERFORMANCE

Good Poor

EFFORT

Low High

FRUSTRATION

Low High

APPENDIX H

Situational Awareness Rating Technique

Please circle the number that best describe your response to each question. Please consider only the most recent display when responding.

			Low						High
1	Situation Instability	To what extent was the situation unpredictable?	1	2	3	4	5	6	7
2	Situation Variability	Rate the number of variables influencing the situation.	1	2	3	4	5	6	7
3	Situation Complexity	Rate the amount of mental resources being demanded.	1	2	3	4	5	6	7
4	Readiness	Rate your readiness to handle the scenario.	1	2	3	4	5	6	7
5	Spare Mental Capacity	Rate how much space mental resources were available to deal with additional tasks.	1	2	3	4	5	6	7
6	Concentration	Rate the amount of mental effort required to deal with the scenario.	1	2	3	4	5	6	7
7	Division of Attention	Rate the percentage of time devoted to dealing with the scenario.	1	2	3	4	5	6	7
8	Information Quantity	Rate the amount of the content that you did understand.	1	2	3	4	5	6	7
9	Information Quality	Rate the goodness of information that you received.	1	2	3	4	5	6	7
10	Information Familiarity	Rate your familiarity with the situation.	1	2	3	4	5	6	7

Please provide any comments about the previous display layout:

APPENDIX I

INFORMED CONSENT DOCUMENT

PROJECT TITLE: EYESPY

INTRODUCTION
The purposes of this form are to give you information that may affect your decision whether to say YES or NO to participation in this research, and to record the consent of those who say YES. This project will be conducted at NASA Langley Research Center in the Visual Imaging Simulator for Transport Aircraft Systems - Generation III (VISTAS III).

RESEARCHERS:

Julie M. Stark, ODU/ NASA LaRC	J. R. Comstock NASA LaRC	James P. Bliss, Old Dominion University

DESCRIPTION OF RESEARCH STUDY:
Several studies have been conducted looking into the subject of advanced aviation displays. The focus of this study is to examine different candidate synthetic vision displays for commercial aviation. Differences in eye scan patterns will also be investigated.

If you decide to participate, then you will join a study involving research of different candidate synthetic vision displays for commercial aviation. You will be wearing a head mounted eye tracking unit throughout the duration of the experiment. This unit will collect data on your eye scan patterns while you fly multiple short approaches to the Eagle Vail, CO airport in the VISTAS-III flight simulator.

Your participation will last for approximately six hours. You will be given breaks throughout the day including a 45-minute lunch break.

Approximately 16 commercial airline pilots will be participating in this study.

EXCLUSIONARY CRITERIA:
You should be a current transport-rated commercial airline pilot to be eligible to participate in this study. You must have normal or corrected-to-normal vision to participate in this study. You should be at least 18 years old.

RISKS AND BENEFITS:
RISKS: There are no foreseeable risks associated with participation in this study. However, as with any research, there is some possibility that you may be subject to risks that have not yet been identified. You have been briefed on how to properly egress the VISTAS-III simulator facility in the event of an emergency.

BENEFITS: There are no direct benefits to you, however, you may benefit by participating in this study from experience with new aviation display technologies. Your inputs today may affect future commercial aviation cockpit displays.

COSTS AND PAYMENTS:

The researchers want your decision about participating in this study to be absolutely voluntary. Yet they recognize that your participation may pose some inconvenience. In order to compensate you, you will receive $400 to help defray incidental expenses associated with participation.

NEW INFORMATION:
If new information is discovered during this study that may reasonably change your decision to participate, this information will be provided to you.

CONFIDENTIALITY:
The researchers will take all reasonable precautions to maintain your anonymity. No identifying information will be recording on questionnaires or performance data. All questionnaires and performance data will be analyzed to assess group trends, not individual information.

The results of this study may be used in reports, presentations, and publications. You will not be identified in any subsequent reports, presentation, or publications. Of course, your records may be subpoenaed by court order or inspected by government bodies with oversight authority.

WITHDRAWAL PRIVILEGE:
It is OK for you to say NO. Even if you say YES now, you are free to say NO later, and walk away or withdraw from the study -- at any time. Your decision will not affect your relationship with NASA LaRC, or otherwise cause a loss of benefits to which you might otherwise be entitled. The researchers reserve the right to withdraw your participation in this study, at any time, if they observe potential problems with your continued participation.

COMPENSATION FOR ILLNESS AND INJURY:
If you say YES, then your consent in this document does not waive any of your legal rights. However, in the event of harm, injury, or illness arising from this study, neither Old Dominion University, NASA LaRC, nor the researchers are able to give you any money, insurance coverage, free medical care, or any other compensation for such injury. In the event that you suffer injury as a result of participation in any research project, you may contact Julie Stark, J. R. Comstock, or Dr. David Swain the current IRB chair at 683-6028 at Old Dominion University, who will be glad to review the matter with you.

VOLUNTARY CONSENT:
By signing this form, you are saying several things. You are saying that you have read this form or have had it read to you, that you are satisfied that you understand this form, the research study, and its risks and benefits. The researchers should have answered any questions you may have had about the research. The researchers can address any questions you may have.

By signing below, you are indicating that you agree to participate in this study.

Participant's Printed Name & Signature	**Date**
Witness' Printed Name & Signature	**Date**

INVESTIGATOR'S STATEMENT
I certify that I have explained to this subject the nature and purpose of this research, including benefits, risks, costs, and any experimental procedures. I have described the rights and protections afforded to human subjects and have done nothing to pressure, coerce, or falsely entice this subject into participating. I am aware of my obligations under state and federal laws, and promise compliance. I have answered the subject's questions and have encouraged him/her to ask additional questions at any time during the course of this study. I have witnessed the above signature(s) on this consent form.

J. R. Comstock/ J. M. Stark **Investigator's Printed Name & Signature**	**Date**

APPENDIX J

Demographic Questionnaire

ID: ____________________ Date: __________________

1. Please circle your gender: Male Female

2. Please indicate your age: _____

3. Please list any pilot's licenses that you currently maintain:

4. Please list any pilot's licenses that you have previously held:

5. Please list your number of years experience with military aircraft?
____ years

6. Please list type (s) of military aircraft flown:

7. Please list your number of years experience with civilian aircraft?
____ years

8. Please list type (s) of civilian aircraft flown:

9. Do you have previous flight simulator experience? Yes No

10. Are You familiar with the Eagle Vail, Co airport? Yes No
If yes, please describe your familiarity with the Eagle Vail airport:

11. Are you familiar with the concept of synthetic vision? Yes No

12. Do you know what a velocity vector is? Yes No

APPENDIX K

Pilot Training Manual

WELCOME

Thank you for your interest in this research project. This statement describes the general purpose of this investigation, your role in the investigation, and the expected duration of your participation. While reviewing this information, please consult the experimenters if you have any questions.

We are not interested in how your individual performance while flying with these displays. Rather, your participation in addition to other participants will be used to understand how pilot performance in general is affected by different cockpit display concepts. You will be asked to fly several approaches to landing scenarios. In order to compare performance in these varied situations, we will be collecting performance data as well as asking about your impressions of workload and situation awareness. Your participation may be videotaped so that we may review the strategies you employ in performing the tasks. All data will be held confidential by the experimenters. Data resulting from your performance will be identified with only a subject number to protect your anonymity.

This research project concerns issues important to display concepts for Synthetic Vision System (SVS) displays. This experiment explores several display concepts for providing a clear view of the outside world while flying in both clear and IMC conditions. Performance and subjective data will be collected and your eye scan patterns will be assessed during some portions of this experiment.

There are no costs to you for your participation in this study. There are no known risks associated with participating in this study. If you wish to withdraw from this experiment, you may do so at any time without penalty. You may retain this description of the experiment. If you have any questions regarding the experiment, you may contact the researchers at any time.

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Flight Simulation Facility and Experiment Information

The experiment will be conducted using the NASA Langley Visual Imaging Simulator for Transport Aircraft Systems - Generation III (VISTAS-III) facility. This simulator is an engineering workstation used for concept development. You will be familiarized with the interface and functionality of the simulator as well as emergency egress procedures as part of the training for this experiment. You will be provided with rest breaks during the experiment. The entire experimental period (including training and debriefing) should last approximately 6 hours.

VISTAS-III is designed to emulate a Boeing 757 aircraft. This simulator allows us to compare conventional flight displays with wide field-of-view, integrated, pictorial display concepts. You will be evaluating two different synthetic vision displays and two conventional displays. All displays have a velocity vector and guidance beacon. You will fly short approaches into the Eagle Vail, CO airport (EGE runways 07 and 25). Field elevation at EGE is 6530.

The Synthetic Vision System can provide a clear view of the outside world through the application of computer-generated imagery derived from an onboard database of terrain that includes obstacle and airport information including. This database information is superimposed with high-resolution aerial photography to provide a very realistic view surrounding EGE.

Eye tracking data will be collected throughout the experiment. You will be wearing a non-obtrusive headband that contains the pupil camera optics module, an adjustable visor assembly, and a scene camera assembly.

There may be approaches throughout the day in which the one or more of the displays convey erroneous information. This could be in the form of two displays that present incongruent information or a heads down display that is incompatible with the out the window scene. Please verbally report any inaccuracies that you notice to the researchers immediately.

DISPLAYS

The following four different displays layouts will be used today:

Synthetic Vision System Display A - SVS A
Synthetic Vision System Display D - SVS D
Traditional Display A - TRAD A
Traditional Display D - TRAD D

Each of the displays is described in detail in this manual.

SVS - A

This is an example of the SVS - A display layout that includes:

1. Analog radial airspeed indicator
2. Analog radar altimeter
3. Analog vertical airspeed indicator
4. Photo-realistic SVS equipped PFD with "HUD like" symbology displaying the horizon, body axis indicator (waterline symbol), pitch information, roll scale with:
   a. magnetic heading
   b. wind indicator
   c. velocity vector (with acceleration cue and airspeed deviation bar)
   d. guidance beacon
   e. 3 degree reference line
   f. glideslope indicator (no ILS input)
   g. localizer with ILS
   h. radar altitude (below 500 ft AGL)
5. A conventional navigation display situated below the PFD

SVS - D

This is an example of the SVS - D display that includes:

1. Photo-realistic SVS equipped PFD with "HUD like" symbology displaying the horizon, body axis indicator (waterline symbol), pitch information, roll scale with:
   a. integrated airspeed, altimeter, and VSI in a tape format
   b. magnetic heading
   c. wind indicator
   d. velocity vector (with acceleration cue and airspeed deviation bar)
   e. guidance beacon
   f. 3 degree reference line
   g. glideslope indicator (no ILS input)
   h. ILS localizer
   i. radar altitude (below 500 ft AGL)
2. A conventional navigation display alongside the PFD

TRAD - A

This is an example of the basic instrument package found in early generation cockpits that feature:

- Electronic Attitude Director Indicator (EADI) with "HUD like" symbology displaying the horizon, body axis indicator (waterline symbol), pitch information, roll scale
- Conventional navigation display under the PFD
- Has same velocity vector and guidance beacon as SVS displays
- 3 degree reference line
- Analog altitude, airspeed, and vertical airspeed indicators

TRAD - D

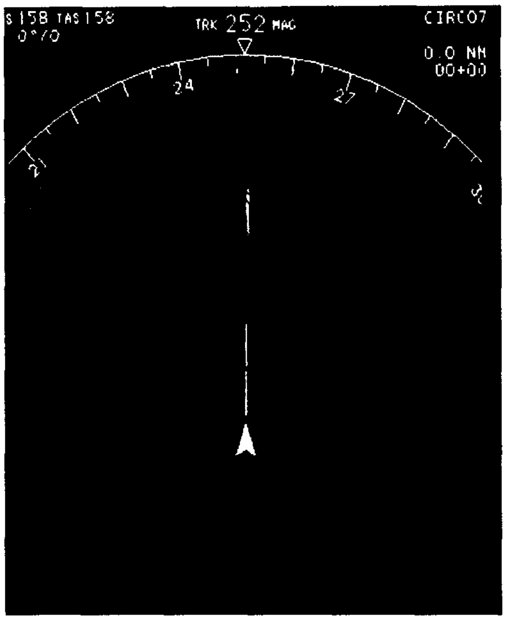
This is an example of the traditional display D layout that includes:

- EADI with integrated airspeed, altitude, and vertical rate information represented in tape format with "HUD like" symbology displaying the horizon, body axis indicator (waterline symbol), pitch information, roll scale
- Same velocity vector and guidance beacon found on SVS displays
- 3 degree reference line
- Conventional navigation display beside PFD

Navigational Display

This is an example of the navigation display (ND) that accompanies each display layout. The ND indicates moving map format waypoints (track-up) along a programmed path with a Terrain Avoidance Warning System (TAWS). The TAWS color coding is reviewed on the next page of this manual. The ND includes:

1. wind indicator
2. magnetic heading indicator
3. runway approach



Terrain Avoidance Warning System (TAWS) Color Coding

- Terrain background information is displayed in terms of predetermined dot patterns whose density varies as a function of the elevation of the terrain relative to the aircraft.
- Terrain background information as well as terrain advisory and warning indications may be displayed on a navigational display.
- Terrain threat indications are displayed along the groundtrack while background terrain is displayed relative to the heading of the aircraft.
- Terrain threat algorithms are based upon an array of vectors instead of a single vector along the groundtrack that takes into account errors due to the terrain database, GPS lat/long errors as well as the published track angle accuracy.
- No terrain data is indicated on the display using medium dot density magenta and is referred to as "purple haze".
- Terrain not shown if more than 2000 feet below reference altitude or below 400 feet above runway elevation except when low on approach.
- Reference altitude is projected down from actual aircraft altitude to provide a 30 second advance display of terrain when descending more than 1000 feet per minute (not when climbing or during level flight).

Approaches to EGE 25 and EGE 07

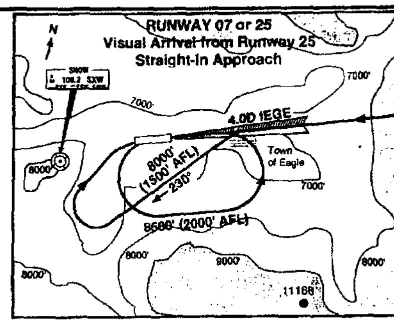
AMERICAN AIRLINES

EAGLE, COLORADO
EAGLE CO. REGIONAL
EGE

10-7T 22 JAN 99 [redacted]

FLIGHT MANUAL PART II
DOMESTIC COVERAGE

AA



CAUTION

All visual maneuvering must be done south of the runway due to terrain. Maintain visual contact with airport at all times.

Runway 07

- At 4.0 D IEGE make a left turn to approximately 230° and fly toward the lower terrain south of the runway not below 8035' MSL (1500'AFL).
- When abeam the runway end begin descending right turn with 30° bank angle.

CAUTION

Very high terrain exists 2 NM west of runway end.

- This pattern requires a short tight turn to final thus the aircraft must be slowed and configured prior to the turn-in.

Runway 25

- If, upon visual contact with the runway, the aircraft is too high for a normal descent to landing, continue visually over mid field at 8535' MSL (2000' AFL).
- Begin a left turn at 25°-30° bank angle to enter a left downwind pattern at 8535' MSL (2000' AFL).
- When abeam the town of Eagle start a descending turn to base and final.

REJECTED LANDING RWY 07 or RWY 25

- If able to maintain visual contact remain in landing pattern or contact EGE Tower / DEN Center for departure clearance.
- If visual contact is lost with the runway immediately execute a go-around and climb to 14,500'. Consider eastbound climb out on Runway 25 localizer.
- If terrain can not be avoided visually, **DO NOT** execute the published missed approach via SXW VOR.
- FMS COTND2 departure offers terrain avoidance guidance.

Change: Departure name

Supplied by Jeppesen Sanderson, Inc.

ARRIVAL continued

SECONDARY APPROACHES

LOC DME-C and LOC-B

- LOC approaches authorized DAY ONLY.
- Both IEGE DME and SXW VOR must be operative for LOC DME-C. If not, use LOC-B.
- Cross VAILE or TALIA in landing configuration and at approach speed.
- When runway is visually acquired, if conditions do not permit a straight-in landing, consider entering left traffic pattern for Runway 25 or right traffic pattern for Runway 07 (see page 10-7T). All maneuvering must be done south of the runway.
- If below MDA and conditions do not permit a landing, climb visually to 14,500' or execute the Cottonwood Two LNAV departure.

DEPARTURE

Ramp Coordinates - N39 38.5 W106 54.8

Runway 25 Hold Short Coordinates N39 38.6 W106 54.2

Clearance Request

- Put clearance on request with Ground as soon as possible prior to departure.
- Departure routing originates with EGE Tower. If questions arise about the filed IFR flight plan, contact DEN Center on 124.75.
- SHORT RANGE IFR Clearance:
  Clearance limit will be JESIE intersection. Expect further clearance from DEN Center on Frequency 128.65.
  VFR DEPARTURE on IFR flight plan:
  To minimize delays due to other IFR traffic you may request a VFR Departure Climb.
  - Captain must request VFR Departure (ATC will not initiate).
  - The IFR clearance will state a fix and altitude to proceed to VFR.
  - Captain is responsible for terrain clearance and separation from other aircraft.
  - Aircraft must remain on assigned ATC route. If deviations are necessary to maintain VFR, contact ATC and obtain amended routing.

AMERICAN AIRLINES

19 JAN 01 (10-7S)

FLIGHT MANUAL PART II
DOMESTIC COVERAGE

EAGLE, COLORADO
EAGLE CO. REGIONAL
EGE

ARRIVAL

CAUTION

Taxiway C-2 ramp entry offers minimum clearance. Follow taxi lines very closely.

Anticipate Turbulence on Approach
- Seat Flight Attendants prior to departing RLG.

Special Procedures
- Expect holding at RLG until airspace is clear. DEN Center will attempt to approve requests for holding pattern north of RLG.
- Consider canceling IFR to facilitate traffic flow. To cancel IFR you must:
  - be below 18,000' MSL.
  - be able to maintain VFR to the airport.
  - be in contact with EGE Tower.
  - have the runway in sight.

LANDING

Use 30° flaps.
Plan touchdown 1000' from approach end.
- Tailwind limits: (Braking action must be GOOD or better)
  - *Runway 25:10 kts maximum*
  - Runway 07:5 kts maximum (DAY ONLY)

Once firmly on the ground. **DO NOT** attempt a go-around.
Last 1500' of runway may be slick.
- *Runway slope: Runway 25 is -1% Runway 07 is +1%*

PRIMARY APPROACH

LOC/DME (FMS) Rwy 25 "LDA25 / RLG Transition"
See technique guide on page 11-6A.

APPENDIX L

Segment Information

EGE25

	Start Waypoint	Stop Waypoint	Distance (ft)	Approx Time (s)
Segment 1	Startrun	DME11.5	12075	41
Segment 2	DME11.5	DME8.5	18215	67
Segment 3	DME8.5	DME6.0	15179	57
Segment 4	DME6.0	F070D	11258	43
Segment 5	F070D	TH25	19072	73

EGE07

	Start Waypoint	Stop Waypoint	Distance (ft)	Approx Time (s)
Segment 1	DME5.32	FOX	14199	56
Segment 2	FOX	ECHO	23081	87
Segment 3	ECHO	VICTOR	14327	54
Segment 4	VICTOR	FINAL07	15123	57
Segment 5	FINAL07	TH07	3184	12

VITA

Julie Stark resides in Virginia Beach, Virginia. She received her Ph.D. in 2004 in Human Factors and Engineering Management from Old Dominion University under the direction of Dr. James P. Bliss.

Julie recently presented a portion of this study at the Human Factors and Ergonomics Society 47th Annual Meeting in Denver, Colorado. She was honored with the Alphonse Chapanis Award for the Best Student Paper at the conference.

Julie will continue her research in aviation psychology with a National Research Council Post Doctoral Associateship at NASA Langley Research Center located in Hampton, Virginia.

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