Quantifying Pilot Visual Attention in Low Visibility Terminal Operations

Ellis, Kyle K.E., Arthur III, J.J. (Trey), Latorella, Kara A., Kramer, Lynda J., Shelton, Kevin J., Norman, Robert M., and Prinzel, Lance J.
National Aeronautics and Space Administration
Langley Research Center
Hampton, VA
USA
Kyle.Ellis@NASA.GOV

ABSTRACT

Quantifying pilot visual behavior allows researchers to determine not only where a pilot is looking and when, but holds implications for specific behavioral tracking when these data are coupled with flight technical performance. Remote eye tracking systems have been integrated into simulators at NASA Langley with effectively no impact on the pilot environment. This paper discusses the installation and use of a remote eye tracking system. The data collection techniques from a complex human-in-the-loop (HITL) research experiment are discussed; especially, the data reduction algorithms and logic to transform raw eye tracking data into quantified visual behavior metrics, and analysis methods to interpret visual behavior. The findings suggest superior performance for Head-Up Display (HUD) and improved attentional behavior for Head-Down Display (HDD) implementations of Synthetic Vision System (SVS) technologies for low visibility terminal area operations.

Keywords: eye tracking, flight deck, NextGen, human machine interface, aviation

1 INTRODUCTION

Since its inception, NASA Langley Research Center (NASA LaRC) has conducted research in the field of Aeronautics, with an ever increasing interest in the human factors associated with aviation safety and the pilot/ flight deck interface. With this research scope, LaRC conducts research in flight deck interface design, employing various approaches to quantify pilot visual behavior (Comstock, Coates, & Kirby, 1985); (Spady & Waller, 1973).

Today, NASA LaRC is working with state-of-the-art technology including the integration of remote eye tracking systems inside its commercial aviation simulators with minimal impact on the flight deck environment (Latorella and Ellis, 2010). An important aspect of eye tracking is to quantify visual behavior and to associate this behavior with quantitative metrics related to a pilot's visual attention, cognitive processing, workload, and awareness or saliency of visual information (e.g., traffic awareness, prominence and importance of outside visual cues and references, effectiveness of visual alerts). Differences in pilot behavior across display variations can lead to significant findings in regard to the utility of various display types, location of display, complexity in usability, and operational comparisons in various flight environments.

The development of quantitative behavioral metrics using eye tracking is explored by comparing eye tracking indicators to the behavioral indicators of display use and flight technical data. A review of the metrics developed for NASA's NextSafe-2 experiment is presented to highlight the capabilities of NASA LaRC's eye tracking installation and associated analytical methodologies.

The NextSafe-2 experiment was a fixed-base simulation experiment investigating whether a lower decision height or reduced visibility minima is supported by the use of Synthetic Vision Systems (SVS). A SVS display was compared to a baseline blue-over-brown primary flight display in approach and landing operations (Ellis, Kramer, Shelton, Arthur III, & Prinzel, 2011). Along with flight technical analysis, eye tracking results were utilized, contrasting these display technologies with flight technical performance and human behavioral differences. The approach to oculometer hardware integration, methodologies for data reduction, and the impact of results are discussed. Further, this work points out future research needs to fulfill the development of quantitative behavioral metrics.

1.2 Background

Remote eye tracking systems first determine head position in all six degrees of freedom. This is done by two dimensional image recognition using several key facial characteristics. Points such as the eye corners, nostrils, corners of the mouth, ears, etc are identified and measured in relative pixel distance. Combining the located image points using two cameras of known position allows for 3D image processing, producing 6 degree of freedom head position values. Eye tracking is then measured by determining the center of the pupil through contrast image processing, relative to a glint reflection, provided by infra-red light sources of known location on the iris that indicates the center of the eye itself. By calculating the known distance between these two points, trigonometry is used to calculate a vector between the two points. A three dimensional eye gaze vector can be calculated in reference to a world coordinate system, such as a flight deck. A minimum of two cameras are required to perform 3 dimensional calculations (Ellis & Schnell, 2009).

Reducing the data has historically been done with some scientific variance. Lookpoints from the gaze vector calculation are determined by the intersection point of the gaze vector with a predefined area of interest (AOI) where an AOI is within the subject's visual environment, such as the primary flight display, or navigation display. Sub-AOIs may also be defined (e.g., the attitude indicator or airspeed read-out). Lookpoints may also be used in the determination of fixations and saccadic movement. There are no standard definitions of fixations and saccades, however, most research loosely defines a fixation as "a relatively stable eye-in-head position within some threshold of dispersion (~2 deg) over some minimum duration (200ms), and with a velocity threshold of 15-100 degrees per second" (Jacob & Karn, 2003). For our research, fixations are defined as spatial and time dependent, characterized by occupying a spatial radius of 2 degrees for a minimum of 200ms. Saccade movements are defined as the movement from one fixation to the next, measured in both angular distance and velocity.

2 METHOD

The Smart Eye remote eye tracking oculometers have been integrated into two of the simulation cabs in NASA Langley's Cockpit Motion Facility. (Latorella, et al., 2010)describes the initial Integrated Flight Deck installation, which collected both crew members' synchronized eye movement data. The following describes a similar installation in the Research Flight Deck (RFD) simulator for the left pilot seat. Each system is capable of using anywhere from 2 to 8 cameras, outputting real-time eye gaze data across a 100^{+} degree visual tracking range. The Smart Eye system was selected due to its superior performance, coupled with the flexibility in the placement of cameras and illuminators. This flexibility was crucial for nearly seamless integration into the flight deck, minimizing intrusion to the flight deck environment, thus, maintaining a high level of simulator fidelity.

2.2 Flight Deck Integration

The cameras provided the desired level of eye gaze accuracy (approximately 2-3 degrees), without compromising simulation fidelity during the NextSafe-2 experiment. Figure 1 shows the locations of the cameras and illuminators installed in the RFD simulator. Data was collected for the left seat pilot in the NextSafe-2 experiment; however, synchronized collection of a dual crew flight deck has been installed and successfully utilized in NASA Langley's Integrated Flight Deck (IFD) for another HITL experiment investigating Data Comm interaction on the flight deck (Norman, et al., 2010).

Validation and verification of system output was performed, assessing data collection quality and accuracy commensurate with previous experiments (Latorella, et al., 2010). The functional head box - the tracking region of the subject, centered on the designed eye point of the flight deck - was approximately one cubic foot. Trade-offs in eye tracking camera placement and lens size were made to create a head box capable of capturing all pilot head movements (as dictated by the experiment tasks) yet maintain sufficient resolution for the image processing.

Figure 1. Camera and Illuminator Locations in RFD

2.3 Data Collection

The raw data stream output of the two Smart Eye computers was recorded when the simulator was operating and was combined with simulator state data. The data were synchronized and time stamped for each trial.

The collected eye tracking data for the NextSafe-2 experiment is shown in Table 1. AOIs were explicitly outlined by defining a world coordinate model of the interior flight deck and out-the-window (OTW) scene. The eye gaze vector information, especially when coupled with AOI information, provides explicit insight into which displays the pilots focused their attention, as well as visitation frequency and when the attention occurred.

Table 1. Eye Tracker Output Parameters for NextSafe-2

Frame Rate	Eye Position X
Frame Number	Eye Position Y
Head Position X	Eye Position Z
Head Position Y	Gaze Direction A
Head Position Z	Gaze Direction B
Head Position Quality	Gaze Direction C
Head Heading	Gaze Heading
Head Pitch	Gaze Pitch
Head Roll	Gaze Direction Quality
Time Stamp	Pupil Diameter
User Time Stamp	Pupil Diameter Quality
Closest World Intersection	

2.4 Data Reduction

The data were reduced to support specific research objectives. Aviation research often uses specific windows of time or "snapshot data" (i.e., data collected at operationally significant points in time or space) to parse out the data and answer meaningful experimental questions and hypotheses. Specific to eye tracking applications, it is important to also define the data reduction parameters based upon the expected human behavior as demanded by the experiment tasks to elicit the best results.

For the NextSafe-2 experiment, specified flight segments during the low visibility instrument approach and landing operations were defined, shown in Figure 2, and associated analyses were conducted based on assumptions of pilot visual behavior within these segments. Eye tracking data were used to support or refute the use of SVS to improve the safety and performance of instrument approach to landings.

Within the "instrument segment," the use of SVS was assumed to not significantly change the pilot's visual behavior from that of conducting the instrument approach using the "blue-over-brown" baseline display condition. The only difference in the displays concepts was the presence of terrain and landing runway information on the PFD for the SVS concept.

Around the 150 ft Height above threshold (HATh) point – the Decision Height (DH) for the instrument approach - the instrument-to-visual transition flight segment eye tracking data was analyzed to identify if SVS improved the pilot's ability to visually transition from instrument to visual conditions. The contention was that SVS, because of its intuitive depiction of the runway, would induce a more efficient visual scan outside the airplane to find the runway and align the aircraft for landing.

Within the Visual Segment, it was assumed that SVS would not affect visual behavior or attention. The pilot's visual attention was assumed to be ~100% directed out-the-window, attending to the pre-flare (line-up laterally and vertically) and preparing for the visual landing, including 'clearing the runway' or visually searching for the presence of other aircraft, vehicles, objects, or animals on the runway.

Similarly, within the Flare Segment (flare to touchdown), it was assumed that SVS would not affect visual behavior or attention. The pilot's visual attention was assumed to be 100% OTW, attending to the visual landing.

Lastly, within the Landing Segment (touchdown to a safe taxi speed), it was assumed that SVS would not affect visual behavior or attention. The pilot's visual attention was assumed to be 100% out-the-window, attending to the roll-out, tracking the runway centerline, and decelerating to a safe taxi speed.

Based on these assumptions, percent of eye gaze (i.e., attention) OTW and number of transitions between OTW and head down was calculated for each analysis segment as a comparator across display conditions.

Another inquiry to pilot behavior was the determination when pilots transitioned from instrument-flight to OTW (i.e., visual-flight) to complete the approach to land task. Determining the specific altitude, distance from threshold, and direction of the glance required new methods to analyze the data structured upon eye movement science.

In development of the transition of attention algorithm, the AOI for which the lookpoint resided simplified the analysis. Time spent in an AOI by the lookpoint denoted attention, either head-up OTW or head-down on the instrument panel.

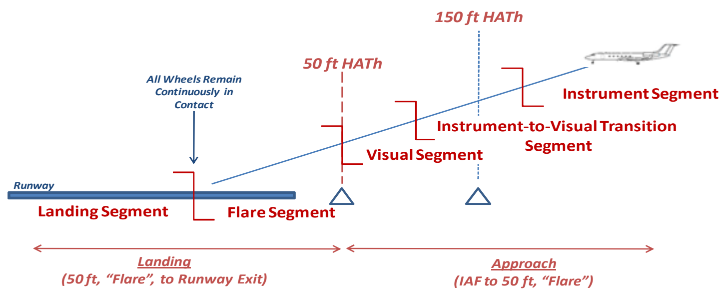

Figure 2. Eye Tracking Analysis Segments

Eye tracking data was analyzed by creating a binary value to specify if the pilot attention was OTW or not. If the lookpoint was tagged in the OTW AOI, a value of 1 was assigned for that data point, if not, a zero was designated. If there was no calculated lookpoint due to loss of eye tracking, head tracking was utilized by referencing a running average of head tracking pitch. If the head pitch was greater than the head-up reference pitch, that data point was tagged as OTW, and a value of 1 was assigned.

A moving time window of two (2) seconds, calculating an average of the past 2 seconds of the binary OTW value, was used to determine when the first occurrence of both a glance and a full transition OTW occurred. This 'gated average' value was then compared to a set-point threshold of 10% (200ms) to signify the occurrence of the "initial glance", and 100% identifying a full transition to OTW, shown in Figure 3. The algorithm reports the reference times when the transition set points of 10% and 100% are reached, and simulator and eye tracking data such as altitude above field-level (AFL), distance from threshold, or gaze direction at that instant in time are recorded. The 200ms time duration was chosen as the initial glance threshold based upon 200 ms being the experimental definition of a single fixation.

The 2-second time window was chosen due to the eye movement behavior of the pilots. Several size windows of time were reviewed to process the eye movement signal, including 10s, 8s, 6s, 4s, 2s, and 1s, and evaluated over each pilot's visual behavior to estimate when the defined transitions occurred. The time window size specifically impacts the full transition metric. An exceedingly large window neither quickly nor accurately captures a full transition point. In a approach and landing environment, small differences in time, (as small as 1 second of elapsed time) can result in large lateral and vertical distances. A window that is too small may result in an inaccurate depiction of a full transition, in which pilot attention is falsely classified as fully transitioned OTW when it may only be an extended glance between transitions.

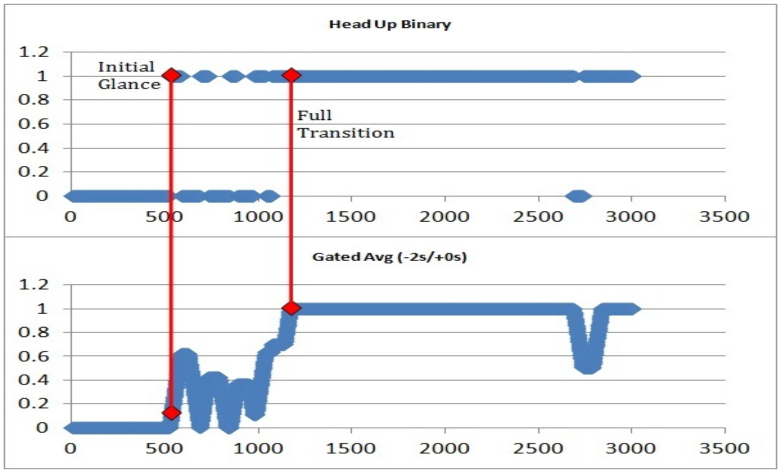

Figure 3. Binary Attention and Signal Analysis

2.5 Data Analysis

The data were analyzed across the pilot subjects to determine if statistical significance existed in three operational comparisons; SVS display location (HUD vs. HDD), SVS HDD Equipage (SVS vs No SVS), and effects of single versus crewed pilot operations. The results presented herein specifically focus on eye tracking and its analysis. The operational results from the NextSafe-2 experiment are discussed elsewhere (Kramer, et al., 2011).

3 RESULTS

The NextSafe-2 experiment observed a data collection rate of 87% across all experiment scenarios. Eye tracking was robust across all segments of the approach, with consistent and operationally rational results, providing strong operationally comparable human performance metrics. Spatial accuracy was observed in calibration of the eye tracking system for each subject to the order of approximately 2 to 3 degrees. The spatial accuracy proved sufficient due to the decisive pilot eye behavior in transitioning across gross AOIs on the HDDs and OTW. The spatial accuracy could have been improved but was not necessary to meet the research objectives.

3.2 Flight Simulation Study Results

The analysis of the eye tracking data was grouped into SVS operational comparisons, yielding several significant findings in SVS location and crewed versus single pilot operations.

In Figure 4, differences in head-up percentage across eye tracking segments revealed that pilots retain a significant level of attention head down, even in "head-up" flight segments (i.e., ~30% during the visual segment of flight, and as much as 10% in the flare segment). This information reveals that pilots allocate a significant attention to guidance and instrumentation during these "visual" segments, suggesting this information is still utilized until the beginning of the flare. The HUD, with or without SVS, allows for this information to be observed while maintaining an OTW view, an impossible behavior to achieve with only HDD presentation of guidance and instrumentation. Transition count data between HDD and OTW, shown in Figure 4, provides insight into how pilots without a HUD transition their attention during the visual segment, indicating, on average, that two transitions occur (OTW to HDD, HDD to OTW). However, combining information from both transition count and head up percentage, the transition to head down accounts for 30% of the head down time, suggesting pilots are still flying guidance in the visual segment and not merely referencing it.

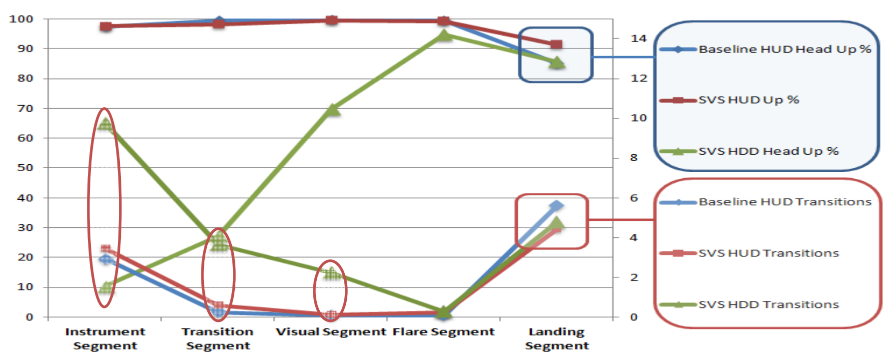

Figure 4. SVS Operational Comparison SVS HUD vs. SVS HDD

The specific altitude at which visual transition occurred was examined. The data showed that pilots using a HDD with SVS maintained their visual attention on the HDD until closer to the DH than without SVS. The data also showed that the time between a pilot's initial and full transition to OTW. Table 2 shows the operational comparisons between baseline HDD and SVS HDD indicate the initial glance and full transition of attention, as defined previously. Transition of attention data also shows the difference in altitude for SVS operations are less than that without SVS. This finding, coupled with the findings of initial glance being closer to DH with SVS, suggest pilots operating with SVS are making a more decisive transition from HDD to OTW, thereby suggesting greater confidence in their trajectory and position and a more efficient visual behavior.

Table 2. SVS Operational Comparison Visual Transition Altitude

		Baseline HDD	*SVS HDD*
Initial Glance AGL (ft)	Mean	367	276
Full Transition AGL (ft)	Mean	197	178

A comparison of utilization of SVS with crewed vs. single pilot operations was also conducted. This analysis was made to evaluate the influence of crew assistance on visual behavior and attention. Surprisingly, no significant differences in visual attention were found during the approach and flare segments. Significant findings were, however, observed during the landing/roll-out segment, shown in Figure 5, indicating single pilots made several more transitions between the HDD and OTW. This is explained by the difference in task loading between the two comparisons. Crewed operations allow for the pilot flying to maintain attention OTW with the other crew member providing speed, runway remaining, and turn-off information callouts especially using the NextSafe-2 advanced airport moving map display. These tasks are critical in the rollout phase, made particularly more difficult in low visibility operations, and are all tasked to the individual pilot in single crew operations. This information is only available head-down, requiring the single pilot to transition with increased frequency to retain critical attention OTW while at the same time collecting the necessary information from the HDDs.

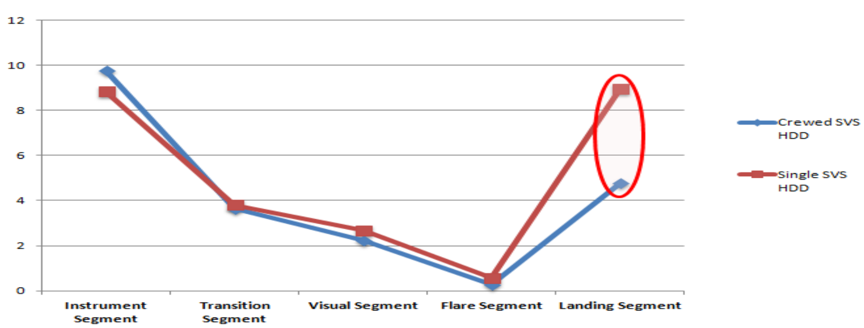

Figure 5. Crew of 2 vs. Single Pilot SVS Operational Comparison OTW/HDD Transition Count

4 CONCLUDING REMARKS

The eye tracking capabilities integrated into the flight simulators at NASA Langley provide a critical capability to HITL research. The measures of attention and transition of attention algorithm used in the NextSafe-2 experiment demonstrate the significance and efficacy of characterizing pilot visual behavior. The data provide strong support to the efficacy of both HUD and SVS operations to improve the efficiency of pilot visual behavior and furthermore, provide a rationale to describe variability observed in flight technical performance. Without eye tracking these results would not have been discovered, and flight technical performance would be the sole comparator to define the operational advantages or disadvantages to SVS and are not typically significant. The methodologies produce quantifiable results across operational comparisons revealing visual behavior data affording researchers improved understanding of pilot performance.

ACKNOWLEDGMENTS

This work was jointly sponsored by the NASA Aviation Safety Program, Vehicle Systems Safety Technologies project, led by Dr. Steve Young (Project Scientist), Mr. Randy Bailey (Team Lead), and the FAA Human Factors R&D Project for NextGen, led by Dr. Tom McCloy, Mr. Dan Herschler, and Mr. Stephan Plishka. Mrs. Terry (Stubblefield) King of the FAA Flight Standards was instrumental in the motivation, planning, and conduct of this work.

REFERENCES

Comstock, J. R., Coates, G. D., & Kirby, R. H. (1985). Eye-Scan Behavior in a Flight Simulation Task as a Function of Level of Training. *Human Factors Society, 29th* (p. 5). Baltimore, MD: Human Factors Society.

Ellis, K. K., & Schnell, T. (2009). *Eye Tracking Metrics for Workload Estimation in Flight Deck Operations.* Iowa City: University of Iowa.

Ellis, K. K., Kramer, L. J., Shelton, K. J., Arthur III, J. (., & Prinzel, L. J. (2011). Transition of Attention in Terminal Area NextGen Operations Using Synthetic Vision Systems. *Human Factors and Ergonomics Society 55th Annual Meeting.* Las Vegas, NV: Human Factors and Ergonomics Society.

Jacob, R. J., & Karn, K. S. (2003). Eye tracking in human-computer interaction and usability research: Ready to deliver the promises. *The Mind's eye: Cognitive The Mind's Eye: Cognitive and Applied Aspects of Eye Movement Research*, 573 - 603.

Kramer, L. J., Bailey, R. E., Ellis, K. K., Norman, R. M., Williams, S. P., Arthur III, J. J., . . . Prinzel III, L. J. (2011). Enhanced and Synthetic Vision for Terminal Manuevrering Area NextGen Operations. *SPIE Defense, Security, and Sensing.* Orlando, FL: SPIE.

Latorella, K., Ellis, K. K., Lynn, W., Frasca, D., Burdette, D., Feigh, C. T., & Douglas, A. (2010). *Dual Oculometer System for Aviation Crew Assessment.* San Francisco: Human Factors and Ergonomics Society Annual Meeting.

Norman, R. M., Baxley, B. T., Ellis, K. K., Adams, C. A., Latorella, K. A., & Comstock, J. R. (2010). *NASA/FAA Data Comm Airside Human-In-The-Loop Simulation.* Washington DC: Federal Aviation Administration.

Spady, A. A., & Waller, M. C. (1973). The oculometer - A new approach to flight management research. *AIAA Visual and Motion Simulation Conference.* Palo Alto, CA: AIAA.