IS PILOTS' VISUAL SCANNING ADEQUATE TO AVOID MID-AIR COLLISIONS?

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The "See and Avoid" concept is crucial to visual meteorological condition (VMC) operations. The FAA and other organizations prescribe a specific systematic out the window (OTW) visual scanning pattern to avoid traffic conflicts, however little research has been published on what scanning patterns pilots actually use and how effective their scanning is. In our study, commercial pilots flew VFR scenarios in a general aviation flight training device (GAFTD) equipped with head and eye tracking equipment. We developed new algorithms to analyze the effectiveness and patterns of visual scanning. The scanning patterns used by the participant pilots did not resemble the prescribed patterns.

Introduction

The "see and avoid" concept remains the primary defense against mid-air collisions in VMC. Although airliners and many corporate aircraft are now equipped with Traffic Collision Avoidance Systems (TCAS) that alert crews to the presence of conflicts with aircraft with an operating transponder, these systems are intended to supplement rather than replace "see and avoid". Further, most light aircraft are not equipped with TCAS because of the expense.

The FAA and other organizations recommend a systematic visual search scan for traffic in which the pilot fixates at a location for at least one second, then shifts gaze no more than 10 degrees in order to sequentially scan the entire the visual field outside the window. Pilots are advised to look inside the cockpit no more than 4-5 seconds for every 16 seconds spent scanning the outside world (FAA, 1998a; AOPA, 2001). Although all pilots are exposed to this concept, they do not receive systematic or extensive training in how to execute and maintain it over long periods in coordination with other cockpit tasks. Humans are notoriously poor at maintaining vigilance in searching for targets or monitoring for events that rarely occur (Baker, 1960; Smith, 1969). Further, the type of scan traditionally recommended requires considerable cognitive effort, competing with other cockpit task demands, It is not known to what extent, if any, pilots may be able to learn to scan automatically, which would reduce cognitive effort. Thus it would be highly desirable to learn what scanning patterns pilots actually use and how effective those patterns are. To date little research has been reported to this end.

Previous studies that have used eye tracking have focused primarily on monitoring of cockpit systems and displays; however, some of these studies included measures of percentage of time spent looking outside the cockpit and found that this percentage is substantially less than the FAA's recommendation (e.g., Wickens, et. al, 2000; Mumaw, Sarter & Wickens, 2001; Anders, 2001). Howell (1957) conducted an actual flight study in which pilots encountered conflicts arranged by the experimenter with other aircraft. Of the 128 conflict trials, nine (7%) ended without the participant pilot detecting the conflict (the experimenter arranged for the conflict to terminate before safety was compromised). On successful trials the average detection distance varied from 3.4 to 5.4 miles, and performance was not affected by whether the pilots were informed that they would encounter traffic.

Sophisticated navigation equipment and "glass cockpit" displays are rapidly coming into use in light general aviation aircraft. This equipment is generally more complicated than traditional systems, and pilots are vulnerable to becoming preoccupied with using this equipment and remain head-down for prolonged periods. This development may require greater emphasis in training on maintaining effective visual scanning, however development of better training requires better understanding of how scanning is accomplished and of the nature of vulnerability to lapses in scanning.

This paper provides an update on our continuing project to investigate pilots' visual scanning behaviors, using eye tracking as pilots fly in a GAFTD (Colvin et al., 2003). Our goal is to determine what patterns pilots use, differences among pilots, the effects of various conditions on scanning, and the adequacy of scanning to avoid conflicts with other aircraft. This paper focuses on the adequacy of scanning, reports considerable differences among pilots, and provides preliminary data on patterns of scanning. We are developing new ways to measure and evaluate these functions, and report here a measure of the fraction of time the outside world was adequately searched. Determining scanning patterns turns out to be difficult because these patterns vary enormously moment to moment. We found large differences among pilots in adequacy of scanning, with most pilots failing much of the time to scan

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frequently enough in the lateral dimension to detect conflicting aircraft.

Methods

Participants

Twelve pilots were recruited and paid to participate in the experiment. All possessed at least a current FAA instrument rating with appropriate airplane ratings and had 20/20 visual acuity or were corrected to that value. The median of their total flight hours was 1400, and the median number of years flying was 15.

Apparatus

Eye tracking data were collected using the ISCAN, Inc. Line Of Sight (LOS) system. This equipment consists of a headband fitted with a camera to determine the eye position, a magnetic sensor to determine head orientation and a computer that performs the computations necessary to determine where the pilot is looking in the cockpit. To facilitate analysis, the cockpit was divided into six two-dimensional planes, referred to as the areas of interest (AOIs). Four of these AOIs were the GAFTD's windscreens displaying the "outside" visual world, and the other two AOIs were the instrument and engine indicator panels. The LOS system calculates the plane to which gaze is directed, the location of gaze within the plane (X and Y coordinates), and pupil diameter of the eye. These parameters are sampled at a rate of 60 Hz.

An AST Hawk 201 FAA-approved flight-training device was used to simulate a high performance, complex single-engine piston aircraft. The four cockpit windows have 17" CRTs that depict the scene outside the window, including terrain, sky, and traffic, as programmed.

Procedure

Participants were given written instructions that emphasized that they were to perform all tasks, including scanning for traffic, just as they would in actual flight. They then flew a scripted 45-minute training session to familiarize them with the GAFTD, after which they were calibrated on the eye-tracking apparatus.

Participants then flew the experimental scenario, a 45-minute VFR cross-country flight in which they navigated by reference to VORs on a flight plan without interacting with ATC. After reaching cruise altitude, participants encountered in sequence a low workload period (LWL1 – 3 minutes), a high workload period created by moderate turbulence in the vicinity of high terrain (TURB – 3 minutes), a second low workload period (LWL2 – 3 minutes), a traffic period (TRAFFIC – 14 minutes), and a final low workload period (LWL3 – 3 minutes). During the traffic sequence, aircraft appeared for periods ranging from 43 to 75 seconds at various crossing angles. Nine aircraft appeared, one at a time, with 30 seconds between aircraft. These aircraft were traveling level at either 500 feet or 1000 feet above or below the participants' aircraft, however it was not initially obvious that the aircraft were not on a collision course.

Results

Eye fixations were extracted and saccades were eliminated from the raw data by the absolute deviation method (Salvucci & Goldberg, 2000). A clustered sequence of data points is counted as a fixation if the absolute deviation of the cluster is less than one degree of visual angle and the duration of the sequence is greater than 100msec. This analysis results in four parameters for each fixation—area of interest (plane), mean horizontal and vertical location within the plane and fixation duration—that are used by our algorithms for calculating spatial and temporal patterns of eye movements.

We report here four measures of visual scanning:

1) Percent time that fixations are directed toward the cockpit windscreens (denoted as percent time OTW.

2) Distribution of fixations over AOIs.

3) Fraction of time each part of the outside world is searched safely. This is calculated by first determining a "grace period": the time from the first moment that a pilot would be likely to detect an aircraft if fixating gaze at or near the aircraft's position to the time of collision, minus the time required to execute an evasive maneuver. If, after having fixated a point outside the windscreen, the pilot returns gaze to that point (within 2.5 degrees) before the grace period is over, that area of space has been searched frequently enough to avoid collision. If gaze does not return before the end of the grace period, that area of space is considered unsafe until re-fixated. The fraction of time each area of space is searched safely is calculated, using specific assumptions about parameters. We selected six miles as the average distance at which pilots could reliably detect another aircraft in most daytime meteorological conditions, and used a combined

closure rate of 385 knots, representing a conflict that might occur between light aircraft and transport aircraft below 10,000 feet. (The closure rate only varies by a factor of 15% for collision angles between zero (head-on) and 40 degrees.) Little published data is available on the range at which pilots can detect aircraft. Harris' data (1973) suggest that pilots would have about an 86% chance of detecting a DC-3 if fixating the target at six miles, and Andrews (1977) data also suggest that six miles is a reasonable approximation. We allowed 15 seconds as the average time a pilot would require to recognize an aircraft, determine that if it is on a collision course, and complete an avoidance maneuver (FAA 1998a). Other assumptions about detection range, rate of closure, and response time can easily be substituted in our algorithm.

4) A transition matrix depicting the relative proportion of transitions from one AOI to each of the other AOIs.

Results

Figure 1 shows that on average participants spent just under one third of their time looking outside the cockpit, except during the traffic period, in which looking outside increased to 51%. When participants detected traffic they monitored the path of the observed aircraft, increasing the total percentage of time looking outside. However when traffic ceased, the percentage of time looking outside again dropped. During the time not spent looking outside, fixations were predominantly directed to the instrument panel (data not shown). The standard deviation bars on the figure reveal large variation among the 12 participants.

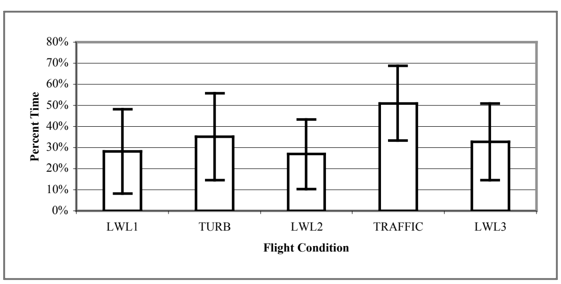
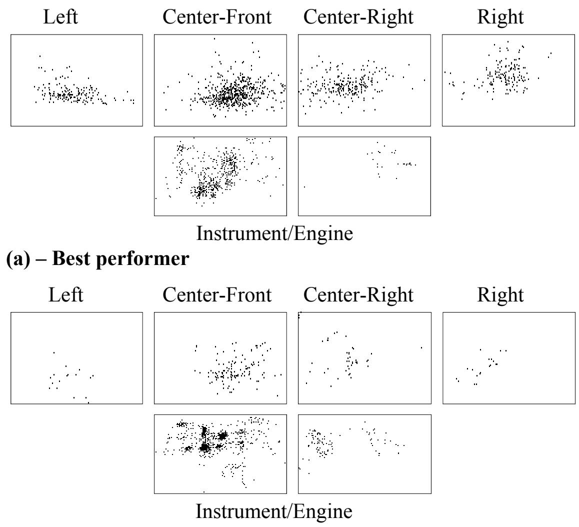


Figure 1. Percent time gaze directed out the windscreen

Figure 2 is a scatter plot of fixations over the six AOIs during low workload periods for two participants, one that spent the great majority of his time gazing at the instrument panel, and another that distributed his gaze primarily outside. Both pilots directed gaze more often to the center-front windscreen AOI than to the other three windscreens combined. Outside fixations tended to line up with the horizon, with relatively few fixations being directed to either the top or the bottom of the windscreen. Also, fixations tended to cluster more toward the center of the windscreen than to either side.



(b) – Worst Performer

Figure 2. Total fixations of two participants during combined low workload periods (IP: instrument panel; EP: engine indicator panel).

Figure 3 depicts the average rate of fixation on the six AOIs during low workload periods. The standard deviation bars reveal large variation among participants, however this variation is driven more by the relative distribution of gaze between the instrument panel and outside the windscreen than by variation in distribution of gaze across the windscreens (data not shown). On average participants fixed the instrument panel far more frequently than the windscreens, and they fixated the center-front windscreen far more frequently than the other three windscreens.

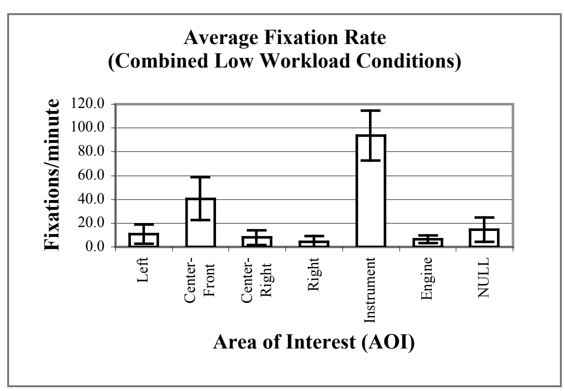


Figure 3. Average Fixation Rate

Our metric of the fraction of time the outside world was safely searched reveals substantial differences in scanning of the four windscreens and in scanning within each of the windscreens (Figure 4). On average, pilots' scanning of the center-front windscreen was adequate most, though not all, of the time, and scanning of the left and right sides of this windscreen was adequate less than 50% of the time. Scanning of each of the windscreens tended to favor the center of the display over the edges. The asymmetry is largest vertically, however, analysis of collision geometries for rates of climb and descent typical of civil aircraft reveals that pilots need search only about three degrees above and below the horizon to avoid collisions (Fries, 2004).

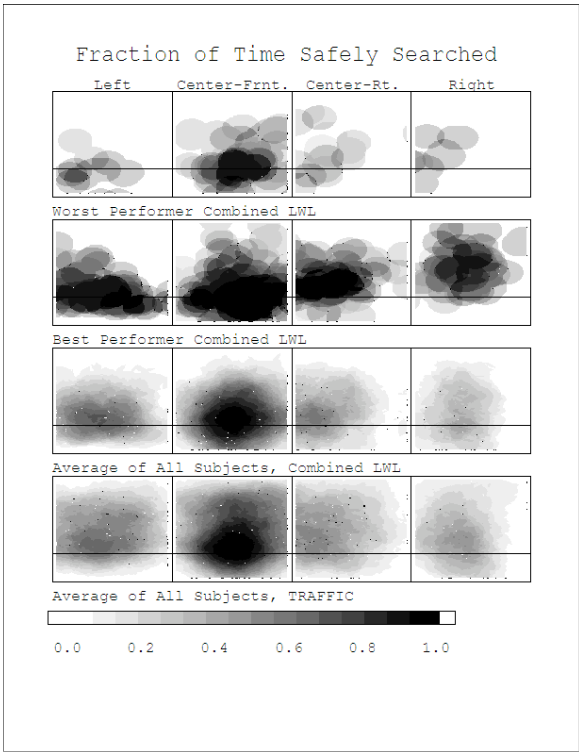


Figure 4. Fraction of time safely searched.

Scanning the off-center windscreens was much less adequate: Fraction of time adequately scanned ranged from around 0.5 for the left windscreen, to around 0.4 for the center-right, to around 0.3 for the right (values at the center of each windscreen). Scanning was even less adequate near the left and right edges of each windscreen. However, participants varied greatly in adequacy of scanning. The best performer scanned all four windscreens adequately the great majority of the time, though he also scanned the left and right sides of the windscreens less often than the centers. The worst performer would have had little chance of detecting a traffic conflict except for a head-on collision course.

The transition matrix shows a strong tendency for gaze to return to the center windscreen from whatever other AOI was previously fixated (Figure 5). When gaze exited the center windscreen it predominantly went to the instrument panel and vice versa. (The instrument panel and engine indicator panel were combined for this analysis. Gaze was directed to the engine indicator panel far less than to the instrument panel). One-step transitions (moving from one windscreen to another immediately adjacent) predominated over two-step and three-step transitions (jumping over adjacent windscreens), and this weighting remained even after correction for the fewer number of two-step and three-step transitions possible (correction data not shown).

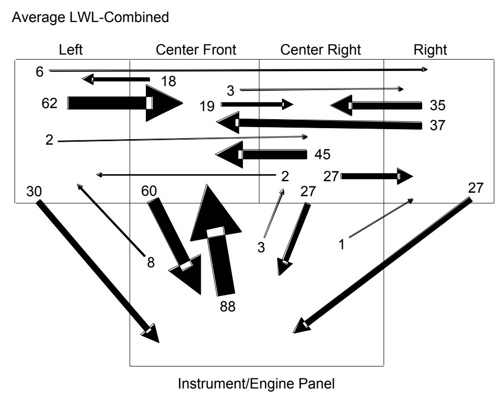


Figure 5. Transition matrix for all participants, combined low workload periods

Discussion

Although not one of the largest causes of accidents, mid-air collisions persist in general aviation, around 15 per year (FAA, 1998b), and are usually fatal. Increasing traffic density, as may occur now that the FAA has published the light sport aircraft rule, will increase this threat. The "see and avoid" concept is the primary defense against mid-air collision for aircraft operating under VFR. Does the relatively low (though still unacceptable) number of mid-air collisions indicate that the see and avoid concept generally works well, or merely that mid-air collisions are fairly unlikely because of the "big sky" in uncongested areas? To what extent do pilots use the visual scanning technique recommended by the FAA and other organizations, and to what extent is it even practical to use this technique, especially in coordination with other cockpit tasks? If pilots use other scanning patterns, how effective are these?

Few research data exist to answer these questions, however previous eye-tracking studies in flight simulators/training devices suggest that pilots look outside less often than recommended (Wickens, et. al, 2000; Mumaw, Sarter & Wickens, 2001; Anders, 2001). Furthermore, Howell's (1957) empirical study of actual airborne conflicts found that pilots did not always detect conflicting traffic.

Our data, consistent with previous studies, reveal that pilots participating in this study, spent more time looking inside the cockpit than outside. This behavior was probably influenced to some degree by the requirement that they follow a VFR flight plan, navigating by VORs. It is also conceivable that pilots did not use the scanning patterns they normally employ in actual flight, perhaps not thinking traffic detection to be important in a simulation. However two facts argue against this possibility: (1) we emphasized in our instructions that participants were to perform all normal flight duties, including watching for traffic, and (2) when participants observed traffic they monitored the course of that traffic.

Our several measures provide converging evidence on the visual scanning performance of the participants. Large differences occurred among the participants: Scanning by the best performer was largely though not completely adequate; scanning by the worst performer was abysmal, and the average participants' performance left them vulnerable to not detecting conflicting aircraft quickly enough to avoid a collision much of the time.

Scanning the outside world strongly favored looking straight ahead, with many fixations directed only a few degrees to either side. We suspect that many of these fixations represent not searching for traffic but rather the default position for gaze, centered along the central axis of the pilot, the aircraft, and the direction of travel. Gazing mainly straight ahead, coupled with peripheral vision, allows pilots to maintain control of the aircraft.

All participants did scan all windscreens to some degree; averaged data show the distribution of these fixations to be centered just above the horizon and to relatively neglect the edges of the windscreen. The neglect of the upper part of the windscreens is not problematic: typical rates of descent for civil aircraft would not allow collision for vertical angles much more than about three degrees above the horizon (Fries, 2004). However, neglect of the left and right sides of the windscreen is more problematic. We suspect it occurs because the windscreen provides a frame that guides gaze toward its center. This left and right neglect, coupled with other data from this study, suggests that participants did not systematically scan small segments of the outside world sequentially.

We are still working to analyze the patterns of visual scanning. The transition matrix shows that participants were not consistently following a systematic left-to-right or right-to-left scan, however the matrix does not eliminate other types of systematic scanning, such as a pattern in which the participant would look from the center to another windscreen, back to the center, then on to the next windscreen, back to the center, and then on the last windscreen. However, even if participants followed this pattern some of the time, they clearly were not following it most of the time, because of the relative neglect of the outer windscreens.

Conceivably the transitions among AOIs are random, driven only by the relative probabilities of each type of transition. However, we have conducted a preliminary Markhov analysis that indicates that the probability of transition from one AOI to another is partially influenced by which AOI was previously fixated. This suggests some sort of patterns longer than single transitions do occur. We are currently analyzing the sequences of transitions among AOIs, and so far have found that many different patterns of different chain lengths occur. The data are very noisy, indicating that participants are not following a single or even a few scan patterns.

We do not find it surprising that participants did not use the FAA recommended scan pattern. The recommended scan pattern requires considerable cognitive effort. In the absence of frequent traffic, whose detection would provide a positive feedback loop, scanning becomes a vigilance task, and humans are well known to be poor at maintaining vigilance beyond short periods. Further, effortful visual scanning must compete with other cockpit tasks for limited cognitive resources.

Some caution is required in interpreting our results. Conceivably our sample of 12 pilots does not well represent general aviation pilots, although their flight experience probably exceeds the average. Also it is conceivable that our participants did not scan as well in the GAFTD or in this scenario as they normally do in actual flight. However, if these participants' performance is indeed representative, our data suggest that the relatively low (though unacceptable) rate of mid-air collisions in general aviation aircraft not equipped with TCAS is as much a function of the "big sky" as it is of effective visual scanning.
Lest this analysis sound too pessimistic, we raise the

possibility that pilots may, through practice, develop scanning techniques that can be executed largely automatically, reducing the demand for limited cognitive resources and perhaps making it possible to maintain the scan with little overt attention. Conceivably the more effective scanners in our study had developed such techniques on their own—we are currently investigating that possibility.

Acknowledgments

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