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THE EFFECT OF PILOT VISUAL SCANNING STRATEGIES ON TRAFFIC DETECTION ACCURACY AND AIRCRAFT CONTROL

Donald A. Talleur and Christopher D. Wickens
University of Illinois at Urbana-Champaign
Institute of Aviation

Twelve pilots flew a high fidelity visual simulation, guided by either a Cockpit Display of Traffic Information (CDTI) or Air Traffic Control (ATC) communications to call out "traffic in sight" on a 135 º forward view. Visual scanning was measured and strategies were classified into sweep, sector, central, random or follow-target scan patterns. Results revealed that: 1) Sector scan strategy was associated with more outside viewing (which had been previously correlated with faster and more accurate detection), and also allowed best flight path tracking. 2) The sweep scan strategy was little better in these respects than central or random strategy scanning. 3) All scanning strategies appeared to be disrupted by ATC callouts or CDTI traffic appearance leading to a focus of vision on the area suggested by the auditory or visual traffic cue. 4) The outside/inside scanning ratio is far less than the recommended 2:1 value, but we believe that this lower ratio can be considered optimal because of the premium that it places on accurate attitude sampling and flight path control.

Introduction

Pilots in visual flight conditions must "see and avoid" traffic. Failure to do so can lead to disastrous mid-air collisions (Wiener, 1980). In order to assist in this process, organizations (e.g., Federal Aviation Administration, International Civil Aviation Organization), have recommended strategies for outside scanning; for example, the Aircraft Owners and Pilots Association (AOPA) recommends either a "sector scan" or a "sweep scan", with a ratio of approximately 2:1 for outside to inside viewing (See figure 1 and 2). In spite of the plausibility of such recommendations, there is little data available on whether some strategies are better than others, and whether the 2:1 ratio really is "optimal", given a pilot's critical need for in-cockpit instrument panel monitoring. Few studies have examined traffic detection performance in real world settings (Harris, 1979, Marshall and Fisher, 1969, Prinzo, 2001), and in high fidelity simulations (Wickens, Helleberg, & Xu, 2002), though all of these show far less than perfect traffic detection performance (60-70%). Furthermore, none of these have compared the efficiency of different strategies. Wickens et al (2002), measured the ratio of outside/inside scan, and found this to be nearly reversed from the recommended optimal, although they found that pilots who looked outside more frequently did show faster detections.

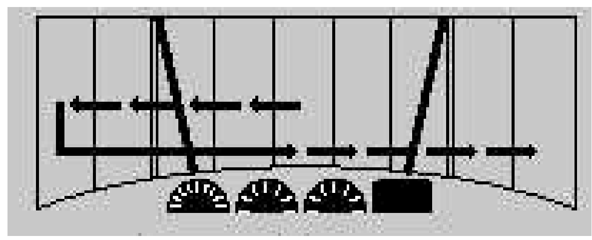

Figure1. Sweep Scanning: scanning is continuous from one side to the opposite side but without pauses in each sector.

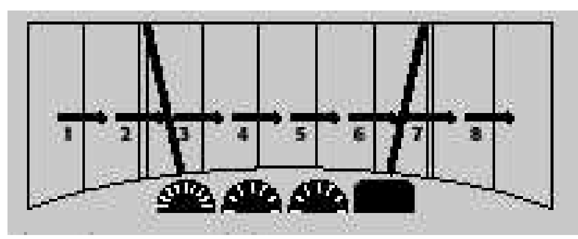

Figure2. Sector Scanning: scanning starts on one side and continues to the opposite side with approximate pauses in each 10-15º sector; pauses shown by numbered arrows.

While the available literature for piloting aircraft clearly endorse specific scanning procedures and ratios of outside to inside visual scanning (U.S. Department of Transportation, 2000, AOPA Air Safety Foundation, 1993), it remains unclear if theses procedures are optimum for all phases of flight. It is expected that pilots will optimize time spent scanning for traffic when considering the likelihood of a traffic conflict, availability of ATC traffic cueing, and cockpit cueing of traffic (e.g., TCAS, CDTI). Also, a pilot's experience may drive scanning behavior. In particular, a pilot's lack of exposure to traffic conflicts in the context of relatively dense traffic areas may lead to belief in the "big sky" theory (Jeppesen Sanderson, 1992) and subsequently, the pilot may use a less than optimum scanning strategy. Likewise, a pilot who has experienced one or more near misses with traffic is more likely to adopt a scanning strategy that amplifies outside viewing. The purpose of the current study was to determine the influence of different visual scanning strategies on traffic detection accuracy and aircraft control. Also, this study provided an opportunity to determine if recommended traffic scanning procedures are used by experienced pilots.

Method

Subjects

The participants for the work described in this paper were originally recruited for a NASA funded project looking at modality differences in advanced cockpit displays (Wickens, Goh, Helleberg & Talleur 2002). Thirteen certified flight instructor pilots, eleven males and two females, participated. One pilots' data was not included in the analysis due to corrupt data. The pilots' age ranged from 21 to 60 years, with a mean of 42 years. Flight experience ranged from 200 to 3700 hours, with a mean of 1184 hours. Pilots were paid $10.00 per hour with a bonus for completing all experimental sessions. All pilots completed the sessions, allowing for a full within-subjects analysis.

Equipment

Pilots flew a Frasca 142 flight simulator configured as a Beechcraft Sundowner. The simulator had a standard arrangement of six primary flight instruments, navigation radios, and standard flight control (yoke, throttle and rudder). An Evans and Sutherland SPX 2400 visual system was used to project a 135º outside view on two 10x17 foot projection screens (See figure 3). One screen was centered directly in front of the simulator while the other was just to the left of the forward screen. This system is capable of presenting simulated traffic at ranges up to 5 nautical miles from the pilot's aircraft. A standard PC was used to simulate ATC instructions (e.g., "traffic to your upper left") in the auditory and redundant conditions.

A Silicon Graphics IRIS workstation with a 20-inch color monitor, placed just to the left of the instrument panel, was used to display both data-link messages and a cockpit display of traffic information (CDTI). The data link message display window subtended approximately 12 º and 8º of horizontal and vertical visual angle respectively. The CDTI display subtended approximately 10º and 18 º of horizontal and vertical visual angle respectively. Both displays were visible for visual and redundant conditions. For a more complete description of the appearance of the CDTI and datalink information, see Wickens, Goh, Helleberg, & Talleur (2002).

Participants were fitted with an Applied Science Laboratories Model 501 head-mounted eye tracking system with integrated magnetic head tracker. This system measures both pupil and cornea reflection at a rate of 60 Hz with an accuracy of better than one degree field of view. The head tracker measures head movements with six degrees of freedom. The two measurements used together allow for a line of gaze measurement relative to any stationary surface in the environment.

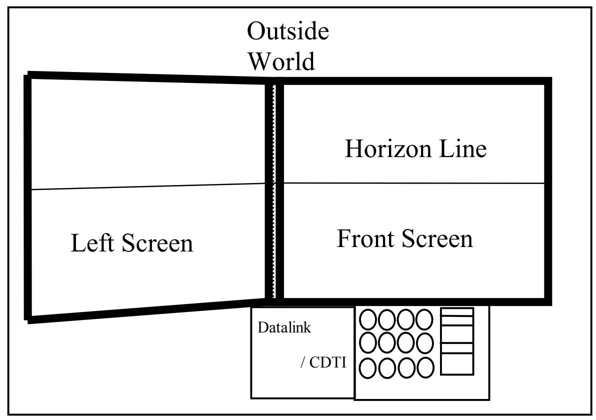

Figure 3. Cockpit, CDTI/Datalink and Screens.

Experimental Design

Traffic could be depicted in six possible projection screen locations (See Wickens, Goh, Helleberg, & Talleur, 2002, for a more detailed description of traffic positioning). Six flight scenarios, each with five legs where traffic would appear, were designed to include legs of either high (4 aircraft) or low (1 aircraft) traffic loads.

The pilot was cued to look for traffic on the basis of cueing presented in one of three modalities, depending on the flight scenario. An **auditory** condition employed a synthesized voice; a **visual** condition employed a cockpit display of traffic information (CDTI) and datalink display configured to the left of the instrument panel; and a **redundant** condition presented the same information using both formats simultaneously. Pilots were notified of an incoming ATC instruction by a PC speaker beep, and the ATC instruction was presented immediately following the alerting tone. The pilot was required to read back the entire ATC instruction including directions (left, climb, etc.) and the numeric parameters (180°, 4800ft, etc.), and then execute the maneuver.

The ATC traffic call-outs, during the auditory and redundant conditions, were presented relative to the time when the traffic aircraft became visible in the outside world such that equal numbers of callouts occurred ~10 seconds before the traffic was visible, simultaneously with the traffic appearance, and ~15 seconds after the traffic became visible. This variability was provided to better mimic actual flight conditions.

Procedure

After reading and signing an informed consent form, the pilots then filled out a short demographic questionnaire. The pilots were then given the experimental instructions to read. Once the pilots understood the experimental task, they were asked to fly two short (two-leg) practice flights to familiarize them with the experimental procedure, the flight dynamics of the simulator, and the two display formats for the ATC instructions and traffic information. The practice flights also contained an example of the traffic that would be depicted in the outside world. Prior to the experiment the eye-tracking apparatus was fitted on the pilot and used to collect the eye scanning data. The pilot then proceeded to fly the six flight scenarios. After completing the experiment the pilots completed a short questionnaire, were debriefed, and paid for their time.

Results

In order to categorize the specific scanning strategies employed by different pilots, each single traffic trial was reviewed using visualization software that depicted eye fixation points within the three areas of interest (AOI); specifically, Outside World (OW), Instrument Panel (IP), and Cockpit Display of Traffic Information, (CDTI). Four-traffic trials were not employed in this analysis, since we found that heavy traffic density tended to obliterate the more natural scan patterns that pilots might use. Each trial could be replayed in real-time (or faster) such that the pilot's fixation points could be viewed in the order in which they occurred. Using this visualization tool, the scanning strategy used by each pilot was easily observable, and five distinct scanning strategies were identified. If more than one strategy was employed during the trial, the predominant strategy used during the time period between traffic cueing and traffic identification was considered to be the overall strategy for that trial.

Five distinct scanning strategies were labeled as sweep, sector, central, random, and follow-target. Two of the strategies observed (sweep and sector) are recognized as acceptable scanning strategies by the both the FAA (2000) and AOPA (1993). The other three strategies (central, random, follow-target) were observed frequently enough to warrant analysis but are not specifically endorsed by the FAA as suggested strategies. Participants' trials were divided into "correct" and "missed" traffic detection. The 10% of single-traffic trials in which subjects failed to correctly locate the traffic were distributed equally across all scan strategy types, and so strategy did not appear to influence the probability of detection. In the remaining 154 trials, the pilot correctly identified the cued traffic and it is on these trials that the following analysis is based.

Scanning Strategies

Two of the five strategies observed in the current study are formally defined in the literature as "sweep" and "sector" strategies (AOPA, 1992, Wynbrandt, 2001). The sweep strategy involves large horizontal changes in fixation within the OW AOI with individual fixations of relatively short duration and few, if any, fixations in between the two end extremes of a single sweep. In contrast, a "sector" strategy (Figure 4) was also observed and involves making several "stops" while scanning from one side of the OW to the other (usually in 10-15 degree segments) with a fixation dwell of nearly 1-2 seconds during each stop (Wynbrandt, 2001). Three other strategies were observed and are defined as follows: A trial was identified as reflecting a "central" scanning strategy (Figure 5) if the fixations to the OW were predominantly directly ahead of the pilot's own aircraft. Central scanners appeared to scan the OW as frequently as the other types of scanners, however, the horizontal extent of their scan while looking outside was limited and did not extend to the left side. The "random" strategy showed fixations that failed to exhibit any recognizable pattern of scanning whether or not the pilot was searching for cued traffic. The final strategy was observed only when little or no scanning for traffic took place prior to cueing. In these cases, once traffic was cued by ATC or appeared on the CDTI, the pilot's eyes went directly to that location on the OW, the pilot identified the traffic and continued to follow it until it left the OW field of view. This method of scanning was labeled as "follow-target".

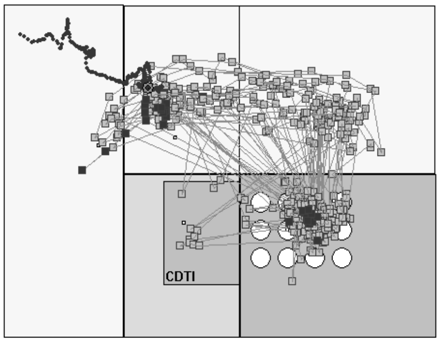

Figure 4. Prototypical example of Sector Scanning Strategy: squares indicate eye fixation dwells within the three AOIs.

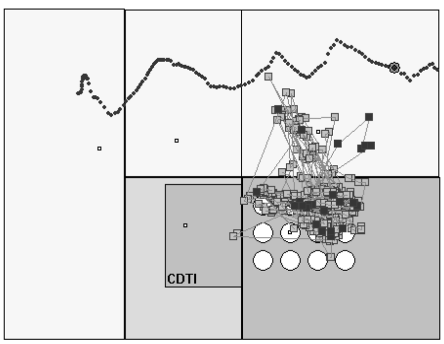

Figure 5. Prototypical example of Central Scanning Strategy**:** squares indicate eye fixation dwells within the three AOIs.

One clear observation we made of the traffic scanning strategies is that many pilots, upon traffic cueing, altered their scanning strategy. While the strategy used after cueing, during the visual search, is of most interest here, it is also interesting to note that several pilots exhibited no particular scanning strategy until cueing occurred. In addition, many pilots, after identifying their traffic, modified their initial scanning strategy to a "follow-target" strategy, suggesting the possibility of an attentional tunneling effect (Yeh, Wickens, & Seagull, 1999; Harris, 1979).

Our goal in analyzing the traffic detection trials was to determine if one or more scan strategies would yield a significantly faster response time to identify the traffic following the cueing. A Multivariate between-subjects analysis of scan strategies was performed in which each individual trial was treated as an independent observation. The five strategies did not differ in their effect on callout response times, $F(4,151) = .681$, $p = .61$. In addition, the percent of a pilot's time spent looking in the OW during the interval between traffic cueing and traffic detection did not vary with different scanning strategies. However, scanning behavior reflecting the allocation of attention, both prior to traffic cueing and after detection of that traffic, did differ across scanning strategies (see Table 1). Specifically, those pilots who employed sector scanning prior to traffic cueing were found to have spent a significantly higher percentage of their time attending to the OW (39%) than pilots who were classified primarily as central (26%) or random (15%) strategy scanners. On average, sector scanners spent 25% more time OW than random scanners and 14% more time OW than central scanners. Post-hoc Tukey HSD tests indicated these differences to be significant, ($p \leq .001$ in both cases). Sector scanners also showed a nonsignificant trend for more time spent OW than sweep scanners (30%), ($p = .13$). Sweep scanners spent 15% more time OW than random scanners. Tukey HSD tests indicated this latter difference to be significant, ($p = .003$).

Table 1. Percent Time Spent OW prior and after traffic cueing .

%Time OW Scanning

Strategy	Sector	Sweep	Central	Random
Before Cueing	39.4	29.6	25.5	14.5
After Detection	38.6	33.0	24.2	17.9

OW scanning behavior after traffic detection also differed between groups (see Table 1), and therefore differed from that observed during visual acquisition of the traffic (during which there were no group differences). Specifically, those pilots who used the sector scanning strategy on a given trial spent significantly more time in the OW (39%) than either central (26%) or random (18%) strategy scanners. Tukey HSD tests indicated these differences to be significant, ($p \leq .001$ for both). Sweep scanners spent significantly more time in OW (33%) than random scanners, ($p = .001$) and showed a trend for spending more time in OW than central scanners, ($p = .16$).

One clear result of our analysis of scanning behavior was that pilots do not always use the same scanning strategy from trial to trial (see Table 2). Although some pilots (e.g. pilot #2) clearly prefer a particular scanning strategy, other pilots (e.g. pilot #4) appear to change their strategy, possibly adapting to unique circumstances of a particular traffic scenario. Also, no particular pattern of scanning strategies employed by a pilot appeared to affect average time from cueing to spotting and calling out traffic in sight.

Table 2. Scan strategy frequency by pilot: Number of trials in which scan strategy was identified as primary from cueing to correct traffic callout.

Pilot	Sweep	Sector	Central	Random
1	3	2	7	1
2	0	0	6	3
3	11	0	3	0
4	3	6	3	1
5	7	2	3	3
6	2	3	5	1
7	1	2	4	4
8	2	0	3	8
9	0	7	0	1
10	0	3	4	4
11	0	13	1	1
12	1	1	2	10

A multivariate analysis of the relation between scan strategy and the flight performance variables (heading, and altitude error) was performed. Four scanning strategies were included in the analysis (sector, sweep, central, and random). The follow-target strategy was not analyzed for performance differences since this strategy was observed for only 4 trials out of 147 available for this analysis. A significant between-subjects effect was found for scan strategy when considering altitude RMS error from the commanded altitude values, $F(3,147) = 2.83$, $p = .041$. Post-hoc Tukey tests show that the pilots who used the sector strategy had 110 feet less altitude error than random scanners ($p = .020$). No other scanning strategies yielded a significant difference nor a trend for a difference between other strategies when considering the altitude control variable. Sweep scanners showed a trend for better heading control (by 2 degrees) than random scanners ($p = .163$), but this was the only trend for a difference between scanning strategies that was observed and no overall effect of scan strategy was found for the heading control variable.

Finally, our analysis focused on the extent to which the different display modalities tended to induce certain strategies. There was some evidence that this was the case. In particular, the redundant condition induced a central scanning strategy (21 out of the 40 manifestations of central scan were with the redundant display: $Chi^2(2) = 6.48$, $p < .05$) and the auditory condition induced a sector scan (22 of 38 sectors scans were with the auditory display: $Chi^2(2) = 10.47$, $p < .05$). Given the association of the sector scan with generally "better" performance (reduced altitude error, more OW scanning), this suggests that the presence of the CDTI may disrupt the tendency to engage in the more beneficial broad-coverage sector scan.

Discussion

With regard to the major issue addressed in this study, scanning strategies, the current data appears to be the first to document the effectiveness of certain scanning strategies, as measured through eye-movements, and their effectiveness measured through traffic detection performance. In this regard, it is important to note that the FAA-recommended "sector scan" comes up as a clear "winner" over all others, including slightly better performance than the recommended "sweep" strategy, availing increased OW scanning, and less disruption with flight control. The sector scan also appeared to be encouraged by the auditory condition and this auditory condition was itself associated with somewhat better traffic detection. Furthermore, this strategy is coupled with more total OW scan time (although this proportion still did not approach the FAA-recommended values).

It appears that whatever strategy is generally adopted, the appearance of a cue, whether visual (CDTI) or auditory, often served to preempt that strategy, to bring scanning into the region where the traffic is expected to be seen. This qualitatively different "find cued traffic" scan pattern seems to be fairly uniform across all pilots, but may leave them vulnerable for detecting a second, unexpected traffic aircraft that might appear after the cue is presented, an observation described by Harris (1979) in traffic detection, and observed as a statistically robust consequence of cueing in both free-flight scanning (Wickens, Helleberg, & Xu, 2002), and in other target detection domains (Yeh, Wickens, & Seagull, 1999; Yeh & Wickens, 2001).

The results have also shown that cueing or attention guidance, provided in either modality, appears to maintain detection performance at a level of around 90%, clearly better than the un-cued rate of around 60% revealed in other studies, as previously mentioned, in both simulated (Wickens, Helleberg, & Xu, 2002) and real flight (Marshall & Fisher, 1959) environments. Nevertheless, it is important to note that this detection level still remains far from perfect, and appears to bring with it a cost of some attentional tunneling. Finally, we note that the overall ratio of OW to inside scanning (slightly less than 1:2), as observed in prior research (Harris, 1979; Wickens et al., 2002), is one that departs from FAA guidelines to favor the OW. Even though all three modality conditions in this study had other sources of traffic cueing information (ATC, CDTI, or both), parallel studies where these resources were not available (Wickens, Helleberg & Xu, 2002), have shown that the optimal ratio was still not found.

Acknowledgements

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