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The Allocation of Visual Attention for Aircraft Traffic Monitoring and Avoidance: Baseline Measures and Implications for Freeflight

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ABSTRACT

We describe two experiments in which 17 certified flight instructors flew a series of traffic avoidance maneuvers while their eye movements were recorded. Both experiments were carried out in a high fidelity flight simulator with full visual (outside scene) capabilities, simulating visual meteorological conditions. In a baseline experiment, pilots were instructed by ATC to fly certain lateral and vertical avoidance maneuvers around traffic. In a freeflight experiment, pilots encountered traffic problems with similar geometry and engaged in maneuvers of similar complexity to those in the baseline experiment, but they now self-selected their own avoidance maneuvers by relying upon a cockpit display of traffic information which was mounted within the cockpit. In both experiments the time required for pilots to make visual contact with all traffic was recorded.

In the baseline experiment, pilots spent roughly 60% of the time allocating visual attention (scanning) within the cockpit (on the instrument panel) with dwells that averaged approximately 6 seconds, while scanning outside the cockpit (for traffic) approximately 40% of the time, with dwells of approximately 2.5 seconds. In the freeflight experiment, the allocation of attention within the cockpit increased to approximately 80% given the additional requirement to monitor the CDTI and use it to coordinate avoidance maneuvers. Visual attention was distributed equally between monitoring the CDTI and the outside world for traffic monitoring. The CDTI gained increased attention when pilots used it to plan and execute conflict avoidance maneuvers. In spite of the reduced amount of attention given to the outside world during freeflight, pilots were not less efficient in monitoring the outside world for traffic, nor did they show evidence for any automation-induced attentional tunneling (delay in visually observing an aircraft not depicted on the CDTI), relative to pilots in the baseline condition. The results are described within the framework of a three component model of information sampling, which accommodates components related to the information content (bandwidth and expectancy), the importance of information, and effort required to access each source of information.

INTRODUCTION

Of the many human factors issues raised by the proposed concept of freeflight, one of the most critical for general aviation (GA) pilots is the workload imposed by the responsibilities for self separation. Of course in many respects, visual flight rules already represent a form of freeflight, and these are conditions faced by many GA pilots. Indeed the workload issue of conflict monitoring and conflict avoidance is implicitly addressed by FAA guidance that pilots spend roughly 75% of their time looking outside the aircraft as part of the “see and avoid” responsibilities of VFR (Aeronautical Information Manual, 2000). However different concepts proposed for freeflight may change the nature of these demands considerably. For example freeflight rules would not be restricted to visual meteorological conditions, in the same way that VFR is restricted. Furthermore, in any freeflight scenario, pilots would be equipped with a fairly sophisticated cockpit display of traffic information (CDTI), which they could then employ to monitor for traffic and maintain self separation by choosing appropriate traffic avoidance maneuvers.

The workload imposed upon a pilot by freeflight can be partitioned into at least two components. One component is the **visual** workload of monitoring for traffic, (distributed between the CDTI and the outside world or OW), and of planning conflict avoidance maneuvers (focused most directly on the CDTI). The second component is the **cognitive** workload of planning and executing conflict avoidance maneuvers. These two components of workload will often be correlated, but are not identical. For example it is reasonable to assume that the visual workload of traffic monitoring, a visual spatial task, will not extensively compete with the auditory workload of understanding verbal instructions (e.g., from ATC) because visual monitoring is not a highly demanding cognitive task. However the **cognitive** workload of maneuver planning, involving heavy demands on working memory, may well compete with language understanding. While our previous studies have addressed some aspects of the cognitive workload in maneuver choice in free flight (Helleberg, Wickens, & Xu, 2000; Wickens, Helleberg, & Xu, 2000; Wickens, Gempler, & Morphew, 2000), the current report focuses exclusively on the visual workload component, and in particular, the critical aspect of pilot **head down time** (i.e., time spent not looking at the outside world; Wreggit & Marsh, 1998).

Past Research

There has been a good deal of prior research that is **related** to the question of visual workload in freeflight, but none has directly assessed the visual head down time associated with the tasks of traffic monitoring and self-separation decisions. For example some studies have assessed subjective measures of mental workload associated with self separation (e.g., Kreifeldt, 1980; Williams & Wells, 1986; Wickens, Gempler, & Morphew, 2000), but these did not employ direct measures of visual scanning. Wickens, Gempler, and Morphew did assess an indirect measure of head down time (the delay in response time to reporting head up targets in a simulated “out the window location”), but their simulation was of relatively low fidelity and direct measures of visual scanning were not obtained. Furthermore, they did not include a “no-free flight” baseline condition in their design for comparison. Several studies have examined visual scanning in aviation tasks (e.g., Fitts, Jones, & Milton, 1950; Carbonnell, Ward, & Senders, 1968; Harris & Christhilf, 1980; Bellenkes, Wickens, & Kramer, 1997), but these primarily focused on instrument panel (IP) scanning, and were not designed to examine the **change** in OW scanning behavior brought about by new cockpit responsibilities (e.g., self separation with a CDTI). Correspondingly, several studies have used scanning to infer head down time in **ground vehicle** control (e.g., Wikman, Nieminen, & Summala, 1998; Dingus, Antin, Hulse, & Wierwille, 1988), revealing that some advanced technologies can leave the forward view of the highway (OW) unattended for disturbingly long periods of time. But generalizations from ground vehicle to airplanes must be used with caution, because of substantial differences between both the vehicle environments (roadway vs. air) and their dynamics (Wickens, Gordon, & Liu, 1998).

In one important aviation study closely related to the issue examined here, Wreggit and Marsh (1998) employed visual scanning measures to assess the head down scanning time imposed by the cockpit technology of the GPS receiver. Theirs is quite relevant to the current issue because they employed the same general population (GA pilots) and asked the same sort of research question addressed here: how does the addition of a GPS receiver for navigation alter the nature of cockpit scanning, in a way that might leave the pilot vulnerable to neglect of the traditional sources of flight information. They observed that certain GPS tasks left pilots head down for a mean dwell time of 10 seconds, with some downward excursions lasting as long as 20 seconds. However, their measure of "head down time" included time away from **both** the OW and the IP, and hence could not be inferred to indicate precisely, the amount of time vulnerable to missing traffic in the OW.

The objective of the experiment we report here is to provide explicit data regarding the change in visual scanning strategies of general aviation pilots, imposed by the responsibilities of self separation. In fact, the experiment provides three overlapping sets of results. First, the experiment provides **baseline** data of the scanning strategies of general aviation pilots in the current VMC environment (i.e., no self separation responsibilities, no CDTI). Second, the experiment examines the **changes** in scanning from this baseline, when freeflight responsibilities are imposed. Third, the experiment provides an in-depth characterization of that freeflight scanning, relative to existing models of information access (Moray, 1986; Carbonnell et al., 1968).

Baseline Scanning

As we have noted, the FAA currently recommends that roughly 75% of the pilots' time be spent visually scanning outside the cockpit in VMC. We were unable to locate any data that measured fixations in a visual flight simulation (i.e., with an OW view), to validate the extent to which pilots actually do adhere to such a proportion. Furthermore, strict adherence to a 75% (or any other %) value does not guarantee effective OW monitoring, given that many different styles of scanning may be manifest within a given percentage of time (e.g., 75%). In particular, the 75% (or any other value) could be occupied by a small number of long dwells, or a large number of short dwells, with more frequent saccades, fixations on or **transitions** to the other different areas of interest.

In the following analyses, we define a **dwell** duration to be the duration of time that the eyeball remains within an **area of interest** or AOI, before leaving. A **fixation** defines each event in which the eye enters an AOI, and describes the endpoint of a **transition** from one AOI to another. Thus the percentage dwell time (PDT) on a particular AOI, is simply the product of the mean dwell duration (MDD), and the number of fixations at a given AOI. Prior research has found substantial differences between experts and novices in the percentage dwell time, as well as the mean dwell duration on different flight instruments; suggesting a pattern in which experts make more fixations, for shorter dwells (Bellenkes et al., 1997; Fox, Fadden, Konrad, Marsh, Merwin, Sochacki, Sohn, Tham, Wickens, Lintern, Kramer, & Doane, 1995) but such research has not been carried out in a visual (VMC) flight environment. Thus, in addition to providing baseline data as to the percentage dwell time spent head down (on the instrument panel or IP) vs. head up on the outside world (OW), our study will also characterize in more detail, the qualitative nature of the scanning pattern between the two AOIs.

Free Flight Scanning

The free flight experiment in which these scanning measures were collected has been described previously (Helleberg et al., 2000; Wickens, Helleberg, & Xu, 2000). In addition to describing these measures as a change from baseline scanning (e.g., how much OW scanning is reduced by CDTI scanning requirements), the current report will also describe the qualitative nature of free flight scanning in depth, and will attempt to frame this description within the context of optimal models of scanning and information acquisition (Senders, 1964; Moray, 1986; Wickens, Vincow, Schopper, & Lincoln, 1997), a context we describe in the following section.

A Model of Pilot Information Acquisition

Based upon prior modeling of visual scanning (e.g., Senders, 1964, Moray, 1986, Carbonnell et al., 1968), and of information sampling (Sheridan, 1972), we offer the following description of the three important factors that can be expected to influence where and when a pilot seeks or accesses information. Such access is normally assumed to involve visual scanning, but it may not always do so (if all information sources are in foveal vision), and the scanning may also be coupled with other motor activities, such as head movements, manipulation by the hands of a keyboard or mouse (i.e., to call up a display page), or even physical travel (as when walking to the back of a plane to inspect a suspected faulty control component). An important feature in this model is that different modes of information access may involve different **costs** or amounts of physical effort, costs which will grow larger at greater distances of transition between information sources (Wickens et al., 1997). For example, the costs of eye movements will be less than those of head movements; and the costs of head movement will grow more rapidly with longer distances. We describe as follows the three factors that are anticipated to influence where a pilot looks (to access information) and when: Information, Importance, and Effort.

1. **Information content (expectancies)**. A pilot will look at (or otherwise access) a source that is anticipated to provide information; and will do so to a greater extent as more information is anticipated at that location. Extrapolating from classic information theory (e.g., Hyman, 1953; Moray, 1986), it is possible to identify two subclasses of information drivers: the frequency of information conveying events along a source (higher frequency, more sampling), and the prior context. Senders' (1964) visual scanning data nicely illustrated the near linear relation between event frequency (signal bandwidth) and visual sampling, and this pattern is also consistent with the observation in aviation that the ADI, the most frequently sampled display, is

also the display of the highest bandwidth. While high event rate (information per unit time) thus drives sampling, it is also true that a channel with few events (low bandwidth) may be sampled if the momentary context signals that the channel contains information. Thus the pilot may look very rarely at a data link message display (low bandwidth); but if he receives a "chime" that a message has appeared there (a prior context), a glance will immediately follow. Correspondingly a pilot who is informed by a CDTI that an aircraft is located in a certain part of the sky, may immediately cast a glance to the relevant part of the OW, in order to confirm that aircraft's presence. These are both cases in which momentary context signals the presence of information (an event) at a particular source. It should finally be noted that a given source may be sampled after some duration of time, simply because the pilot has forgotten the state of the source when it was last sampled (Senders, 1964). This phenomenon accounts for the tendency to "oversample" sources of low bandwidth (Senders, 1964; Meyer, Bitan, Shinar, & Zmora, 1999; Wickens & Hollands, 2000).

2. **Importance**. Sources should be sampled more frequently to the extent that the information contained along the source is more important. Importance here can be defined, operationally, in terms of the cost of missing an event that occurs at the source in question. Thus a pilot scanning the OW may look more frequently at the front, and same altitude as ownship, than toward the side, behind or above ownship, for reasons that do not pertain to the relative frequency of seeing traffic in one location or the other (information), but rather because an unseen traffic aircraft in front and at the same altitude, is more likely to create a conflict (and lead to a midair collision – a high cost) than is one located elsewhere. That is, the forward targets are more **important**. It should be noted that combining importance with information content creates an optimum "expected value" model of scanning, used by Carbonnell et al. (1968) and Sheridan (1972) to define "how often a supervisor should sample": the expected cost of not sampling a channel (or source) can be defined as the product of the bandwidth (event rate) of the source and the cost of missing an event at the source.

3. **Information access effort**. As noted above, the cognitive and physical effort of accessing information varies across sources. The greater distance that the eye must move in scanning, the greater the effort that is required (although this effort gradient is not great). Furthermore, analysis suggest that vertical eye movements are more effortful (and literally involve more muscular movement) than lateral movements (Alpern, 1969). When sources are separated by a sufficiently large distance that head movement is required, then effort grows correspondingly (and will do so particularly in a rotating cockpit, where vestibular illusions may operate). Finally, in the aviation environment, one can speak of the "effort" required to reaccommodate the eyes between the optical distance of the instrument panel, and that of the OW. The fact that many aspects of human performance may be described as "effort conserving" (Payne, Bettman, & Johnson, 1993; Shugan, 1980; Wickens & Hollands, 2000; Wickens & Seidler, 1997), and that indeed it may sometime be considered optimal to conserve information access effort in high workload contexts, leads to an expectation that sampling and scanning may be driven by reducing the number of fixations (and transitions), in order to gain longer dwells within in a single AOI. We describe this as an "in the neighborhood" heuristic, by which pilots will visit in turn, a number of sources that are close together. For example they may chose to scan repeatedly across several instruments **within** the IP, before leaving it for a dwell on the OW or CDTI. Furthermore, pilots may avoid vertical transitions (visiting the OW from the CDTI or the IP) relative to lateral travel (between the CDTI and the IP), because the former imposes both

vertical scanning (more cost than lateral) **and** visual reaccommodation. It should be noted here that the expected influence of minimizing transition distance (effort), lies behind optimization models of display or workspace layout (Wickens et al., 1997), in which component pairs with more frequent transitions are positioned closer together.

Predictions. When the above three-component "model" is applied specifically to pilot scanning in a freeflight CDTI scenario, it is difficult if not impossible to dictate one "optimal" strategy of scanning (although it **is** possible to describe a range of non-optimal strategies, such as failing to scan the OW at all, or failing to look at that part of the OW where traffic is likely). It **is** possible however to describe a set of influences, that vary between experimental conditions or phases of flight, that should be expected to drive one of the three factors in certain directions. We describe these as follows.

1. To the extent that **information content**, and more particularly bandwidth or event frequency, has some influence on pilot scanning behavior, then we should expect the following three effects: (1) Across the three areas of interest, the IP has the greatest bandwidth since it contains both the highest bandwidth information (the attitude indicator), and the most additional information sources (the other five instruments). The OW has an intermediate bandwidth since, with the true horizon visible, it mimics the high bandwidth of the attitude indicator. But it does not contain other sources of directly viewable change (e.g., vertical speed; turn coordinator), and the gain with which altitude and airspeed are represented in OW vision, is considerably lower than the gain of changes of those variables when they are depicted on the IP. The CDTI has the lowest bandwidth, as it contains no information regarding attitude. Hence bandwidth influence should predict diminishing fixations (and percent dwell time or PDT) from the IP to the OW to the CDTI. (2) Within the IP, we also anticipate higher bandwidth and hence greater PDT during active maneuvers than during straight and level flight because active maneuvering will cause more rapid changes within the instruments. (3) To the extent that **context** influences information access, as noted above, we can anticipate that pilots will direct their scan toward areas of the OW suggested by the CDTI (prior context) to contain traffic.

2. To the extent that the **importance** component influences scanning we might expect the following two influences: (1) If pilots follow the standard "aviate-navigate-communicate" prioritization scheme thereby rank ordering the importance of these three tasks, we would expect greatest attention to be allocated to the IP, given its essential role in the **aviation** subtask. This should dominate scanning relative to the CDTI or the outside world, given that these two AOI's primarily serve the **navigation** subtask (i.e., in this case, traffic avoidance), since both provide traffic information (albeit in different formats). Of course there are redundant sources of information for both tasks across the three AOIs, which makes precise prediction somewhat difficult. For example the true horizon (OW) provides information for attitude control (and therefore **aviation**) that is redundant with the artificial horizon on the IP. The outside horizon may then be used to help aviating, thereby slightly elevating the importance of the OW for this task. (2) Contrasting a baseline flight scenario with a freeflight scenario, we can assert that the importance of the **navigation** subtask is increased in freeflight, since pilots are now assumed to have full responsibility for self separation. That is, air traffic control is no longer (as) responsible for traffic monitoring. This contrast would increase the importance of both the OW and the CDTI (both traffic information sources), relative to their importance in baseline flight, and therefore increase the importance of both AOIs relative to the IP.

3. Finally, to the extent that the conservation of **information access effort** drives scanning, three influences could be predicted (1) an overall tendency for longer dwells within, and fewer transitions between, the three AOIs (reflecting the "in the neighborhood" heuristic); (2) a tendency to make more lateral transitions between the IP and the CDTI, than vertical transitions between the OW and the other two AOIs (avoiding vertical scans and reaccommodations); (3) because of (2), a tendency to make longer dwells on the OW than on the other two AOIs (i.e., once the eye has accommodated to far viewing on the OW, it should stay there for a while – in the neighborhood – in order to reduce the need for frequent reaccommodations to the closer optical distance of the IP and CDTI).

Experimental Overview

A careful analysis of the predicted influence of these three factors, across AOIs conditions and experiments which is summarized in Table I1, reveals that some of these factors may cancel each other out. Thus for example the greater **importance** of the traffic sources (CDTI and OW) during freeflight, may be counteracted by the greater bandwidth of the IP during freeflight (because of a greater need to maneuver). Nevertheless, the above model of scanning influences can provide a framework within which to describe the influences that are observed in the scanning data we report below. These data are derived from two experiments, conducted in nearly identical circumstances. In both experiments, pilots fly a series of maneuvers, some of which involve changes in altitude, heading or airspeed necessary to avoid traffic (Helleberg et al., 2000). In both experiments, pilots are also responsible for out the window (OW) monitoring, and must call out "traffic in sight" whenever they make visual contact with a traffic aircraft. In both experiments, some of the traffic aircraft presented potential conflicts and entailed strategic avoidance maneuvers, while other traffic was visible, but did not pose a conflict threat.

Table I1. Summary of model predictions.

Source

1. Information
   1. IP > OW > CDTI
   2. IP Conflict > IP Non-Conflict (During Baseline)
   3. OW Increases Following CDTI Context

2. Importance
   1. Task Prioritization (Aviation > Navigate)
      IP > OW ≥ CDTI
   2. OW + CDTI (Free Flight) > OW (Baseline)
      (IP Free Flight < IP Baseline)

3. Information Access Effort
   1. Long Dwells
   2. (IP-CDTI) > (IP-OW) and (CDTI-OW)
   3. OW Dwells > IP + CDTI Dwells

In the baseline experiment, the pilots only fly these maneuvers in response to ATC voice commands and instructions, simulating current IFR/VMC procedures (in a relatively crowded airspace). The only two AOIs for our analysis are the IP and the OW. In the freeflight experiment, pilots have a CDTI and are now responsible for selecting their own maneuvers as they feel appropriate, in order to avoid the loss of separation with the traffic aircraft. The CDTI now becomes a third AOI. In order to assure that the maneuvers that were self selected in the freeflight experiment were roughly equal in complexity and frequency to those instructed in the baseline experiment (and hence that the bandwidth of information on the IP is approximately equivalent between the two experiments), we used a yoking procedure. In implementing this procedure, the freeflight experiment was conducted first, the traffic avoidance maneuvers that pilots self selected (see Helleberg et al., 2000; Wickens, Helleberg, & Xu, 1999) were characterized in terms of a small number of discrete ATC instructions that would reproduce those maneuver profiles, and then these instructions were played back, at the appropriate times during the flight, to pilots in the baseline experiment. Thus each flight profile flown in the free flight experiment was uniquely "yoked" to a corresponding flight in the baseline experiment. Assurance was taken that these baseline instructions would never produce a loss of separation from the traffic aircraft. Care was taken also to insure that all traffic appeared at equivalent times and places in the two experiments, that is, traffic behavior was also "yoked".

A final feature of the freeflight experiment was the presence of occasional "transponder off" aircraft. These were aircraft that were **not** rendered on the CDTI, and would characterize an aircraft that was unknown to the system which generated the traffic information (i.e., as if the pilot of such an aircraft had the transponder turned off, or did not have a transponder). This feature enabled us to look at the potential delays in noting traffic, that might be imposed by a pilot who trusted that all aircraft in the airspace were "known" to the freeflight system. While the concept of "transponder off" aircraft did not apply in the baseline condition (since there is no CDTI), this label is used to characterize the same particular aircraft targets when they appeared in the baseline condition (i.e., same aspect angle, bearing and relative motion), thus allowing us an evaluation of this "trust" effect of automation across experiments, without this being confounded by differences in target visibility or conspicuity.

METHOD

Participants

Seventeen pilots with a mean age of 26 years at the Institute of Aviation, University of Illinois, volunteered to participate, obtained visual scanning data and were paid for their participation (an additional six pilots in the free flight experiment did not have scanning measures taken). All participants were certified flight instructors (CFI). Seven participants were assigned to the free flight condition and the other 10 to the baseline condition (three additional subjects participated in the free flight experiment, but their visual scanning was not measured).

Equipment and Display

Flight simulator. Pilots in both the free flight and the baseline conditions flew a Frasca 142 flight simulator configured as a single engine Beechcraft Sundowner, which included the full set of instruments on the instrument panel. The simulator also had all of the necessary controls (yoke, throttle, and rudder pedals) and very realistic flight dynamics. A Silicon Graphics IRIS workstation with a 20-inch color monitor having a screen resolution of 1280x1024 pixels running at 60 hertz was used to display the CDTI. The monitor was placed as close as possible to the left side of the instrument panel at a height which placed the top of the CDTI display even with the airspeed indicator. The CDTI display subtended approximately 10° horizontal visual angle and approximately 18° of vertical visual angle. An Evans and Sutherland SPX 2400 was used to project a 135° view of the outside visual world. This system was capable of depicting traffic at a range of up to 5 nautical miles away from the participant's aircraft. An 80386 PC was used along with an infinity speaker to play prerecorded simulated Air Traffic Control commands, which instructed the pilots on the appropriate flight parameters (heading, altitude, and airspeed) to use in order to reach the next waypoint.

CDTI. In the free flight condition, pilots interacted with the CDTI, which has the following display features:

1. Ownship – The pilot's aircraft was magenta and began the flight at the initial altitude commanded by ATC. Figure M1 shows the two views of the pilot's ownship. The upper panel shows the view from above the pilot's aircraft and the lower panel shows a profile view from behind the pilot's aircraft.

2. Traffic/Other Aircraft – Other aircraft were depicted as gray under non-conflict conditions. Figure M2 shows the two views of the traffic aircraft, the upper panel shows a view from above and the lower panel shows a view from behind.

3. Predictor Lines – Predictor lines extended from the nose of each aircraft and represented the predicted flight path 45 seconds into the future. Both the pilot's ownship (Figure M1) and the other traffic (Figure M2) had predictor lines. The lines provided both horizontal and vertical flight path information, as well as relative velocity by comparing the length of the lines.

4. Threat Vector – Threat vectors were orange and pointed in the direction at which the pilot would see the other traffic aircraft pass closest to the pilot's ownship (see Figure M2). The end point of the threat vector would move closer to the traffic's predictor line as the pilot's predicted separation decreased. Once there was contact between the threat vector's endpoint and the traffic aircraft's predictor line, as depicted in Figure M3, the pilot was in an undesirable state of predicted conflict, which they were told was to be avoided. The threat vector moved closer to the ownship's nose as time to actual conflict decreased. Once the threat vector touched the traffic aircraft symbol, as in Figure M4, the pilot had entered into a state of actual conflict. While pilots were instructed that a predicted conflict state was to be avoided, they were also told that a state of actual conflict was worse yet, and must not occur.

5. Grid – Dots were separated by one mile. One grid block was five miles by five miles. The grid dots are indicated on Figure M1.

Basic Symbology

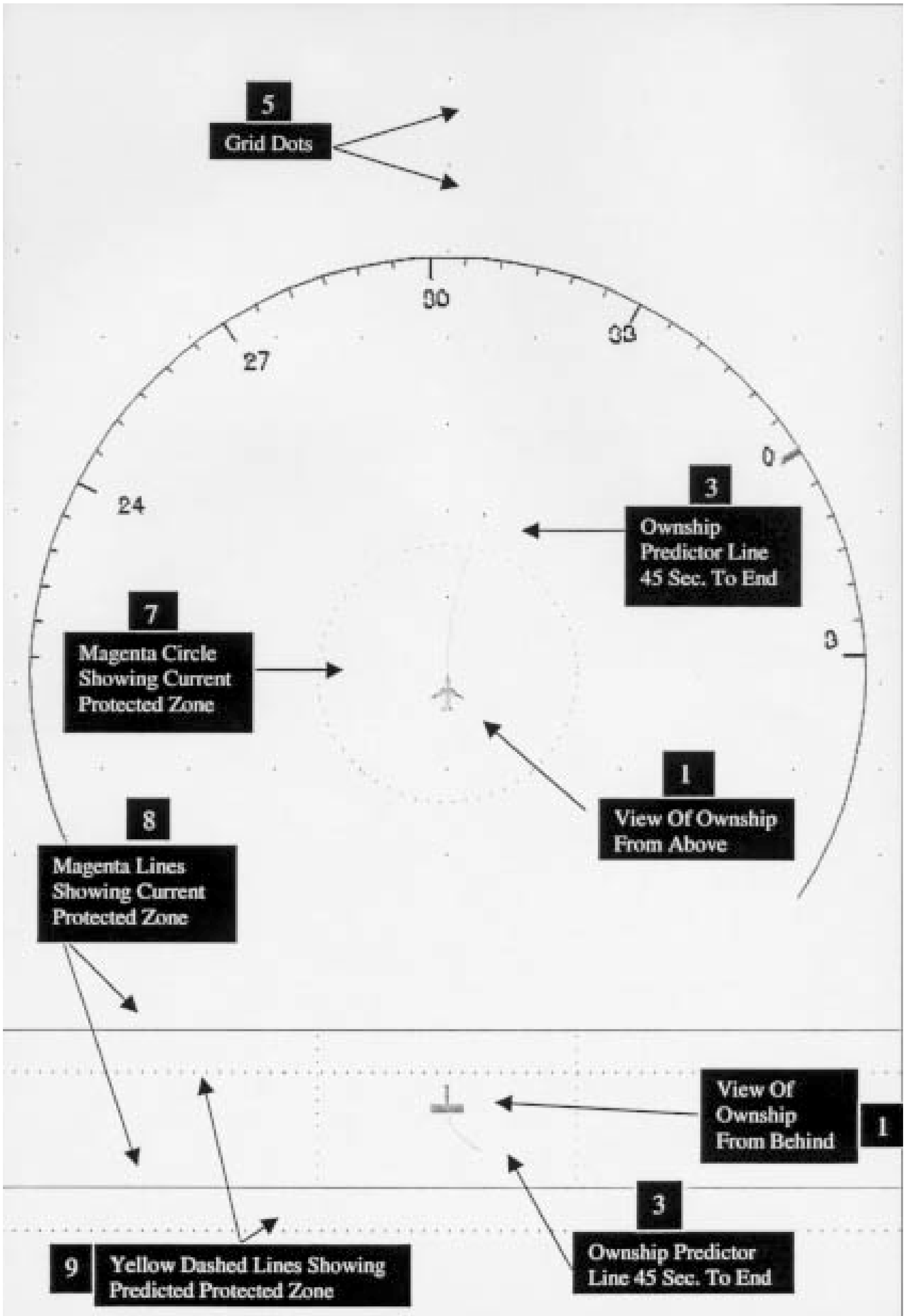

Figure M1.

Traffic Approaches

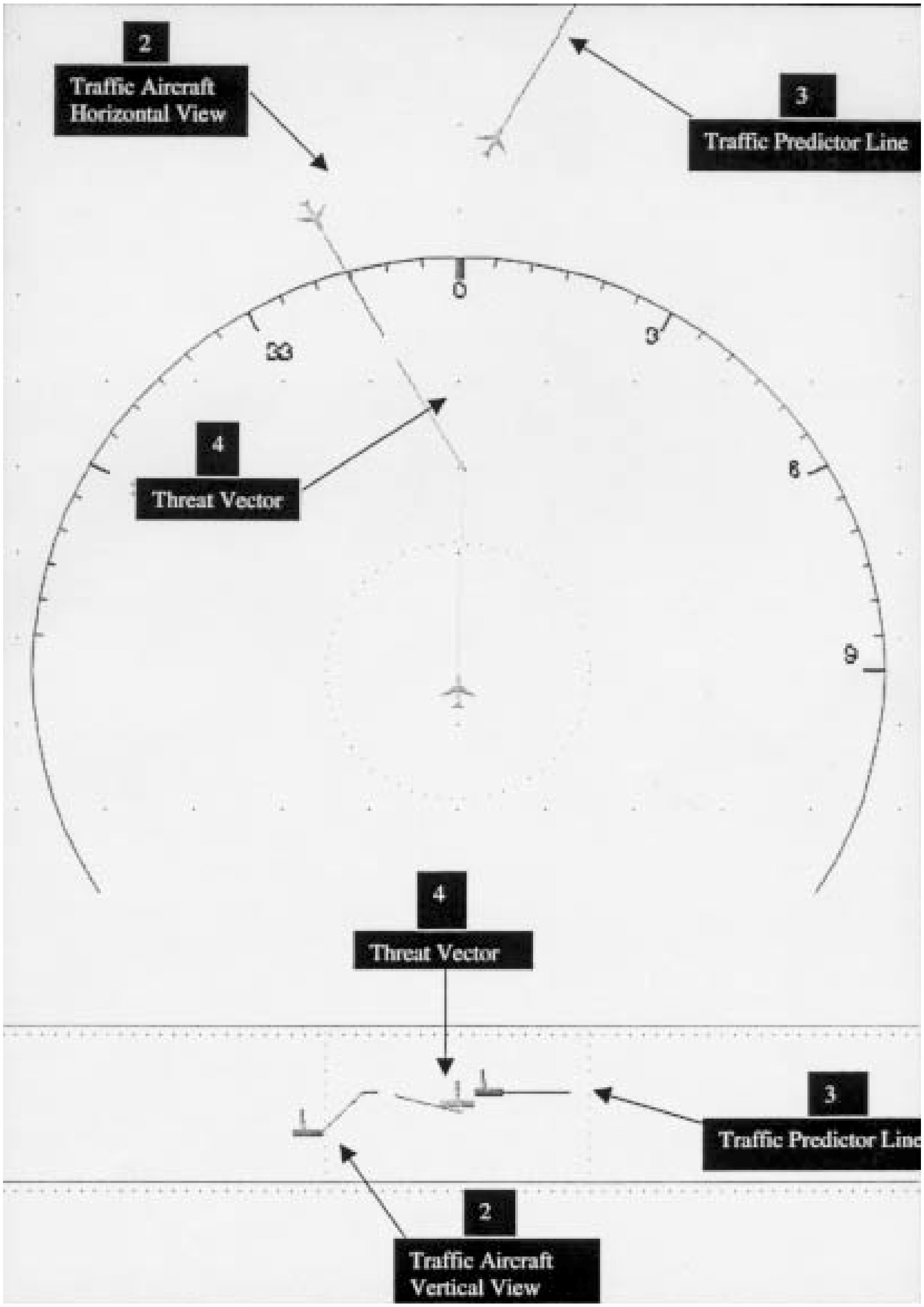

Figure M2.

Predicted Conflict

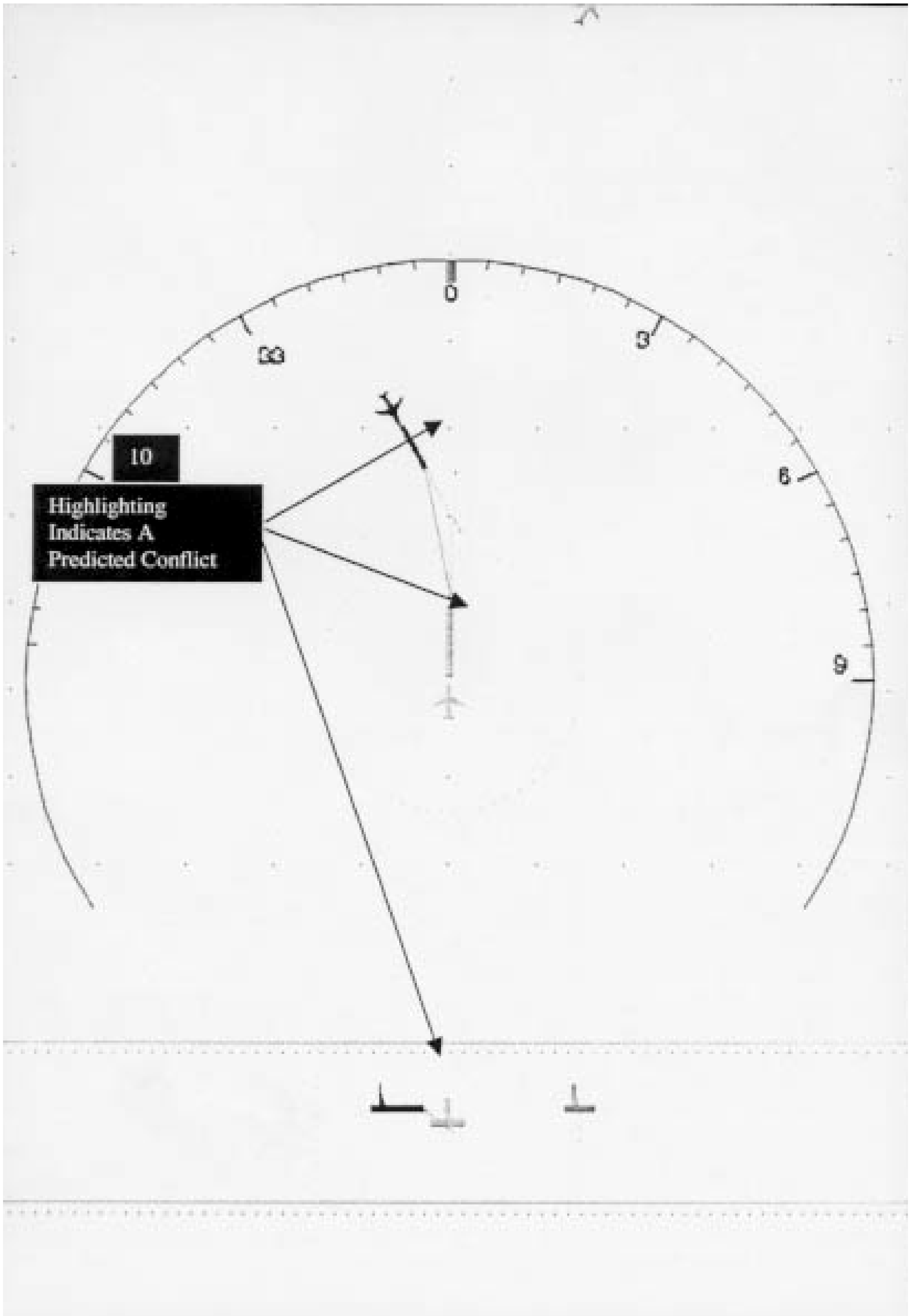

Figure M3.

Actual Conflict

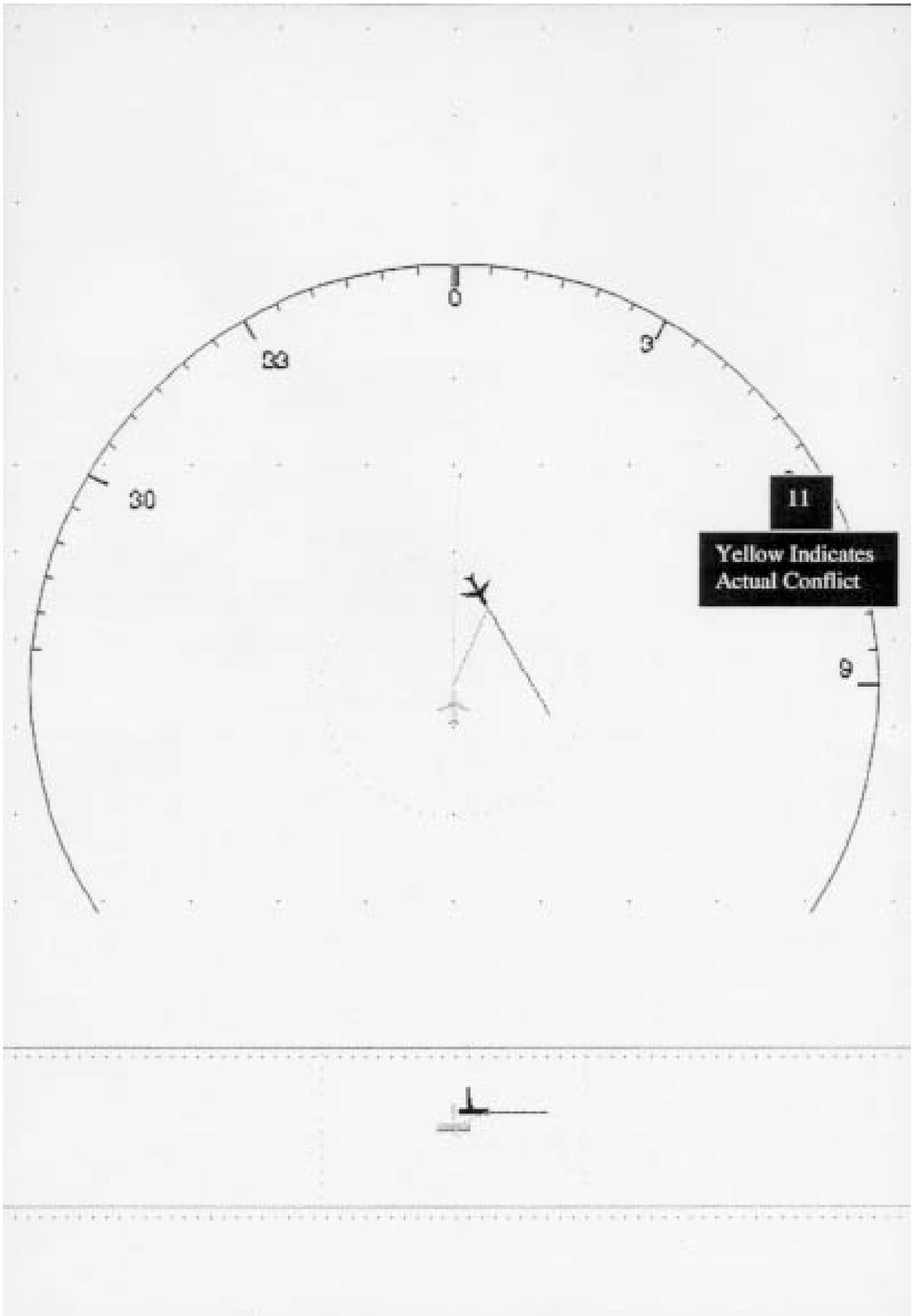

Figure M4.

6. Waypoint (not pictured) – The waypoint was always presented on the ATC commanded course at the altitude specified. Its horizontal position was depicted on the grid once the waypoint was within the range of the CDTI. It was a small yellow triangle, which resembled a VORTAC symbol from a standard sectional navigation chart.

7. Dashed Magenta Circle – The dashed magenta circle around ownship, indicated on Figure M1, depicted the current horizontal protected zone boundary (1.5 mile radius), while the threat vector (described above) depicted the predicted protected zone.

8. Solid Magenta Lines – The solid magenta lines represented the current vertical protected zone boundaries, 1000 feet above and below the pilot's ownship. Figure M4 shows the solid magenta lines.

9. Dashed Yellow Lines – The dashed yellow lines represented predicted protected zone boundaries 45 seconds into the future. These are indicated on Figure M4.

10. Predicted Traffic Conflict – When a traffic conflict was predicted within the following 45 seconds, the threat vector extending from ownship's predictor line touched the predictor line of the other aircraft. When this occurred, as indicated in Figure M3, the other aircraft and its predictor line (from the end of the threat vector to the nose of the aircraft) would then turn white.

11. Current Traffic Conflict – When the threat vector reached the nose of ownship and the traffic aircraft turned yellow, the traffic aircraft was currently within the ownship's protected zone (the dashed magenta circle) and an actual conflict had occurred. Figure M4 shows a state of actual conflict. This was the most serious of conflicts, and pilots were instructed to avoid it.

Head-mounted eye/head tracker. Both the free flight and the baseline pilots wore the eye/head tracker for the last 4 flights. Eye scan measures were made using an Applied Science Laboratories Model 501 head-mounted eye tracking system with integrated magnetic head tracker. The eye tracking system utilizes both pupil and corneal reflection and is sampled at 60 Hz with an accuracy of better than 1 degree of field view. The head tracker tracks head position with six degrees of freedom of movement for the head. When the eye position is combined with head position, a person's line of gaze can be measured with respect to virtually any stationary surface in the environment.

Task

Free flight. The pilot's task was to fly six simulated cross-country flights, which took approximately 70 minutes to complete. Figure M5 shows a graphic depiction of a typical flight used in this experiment. Each flight consisted of 10 waypoint to waypoint legs, with traffic aircraft interspersed between each waypoint. Each flight began with the aircraft at cruising altitude and required the pilot to make an initial maneuver to a new heading in order to begin the experiment. A simulated Air Traffic Controller (ATC) provided vectors (heading, altitude, and airspeed parameters) which directed the pilot to each of the waypoints. These commands were issued at the beginning of the experiment and once the pilot reached each waypoint. The

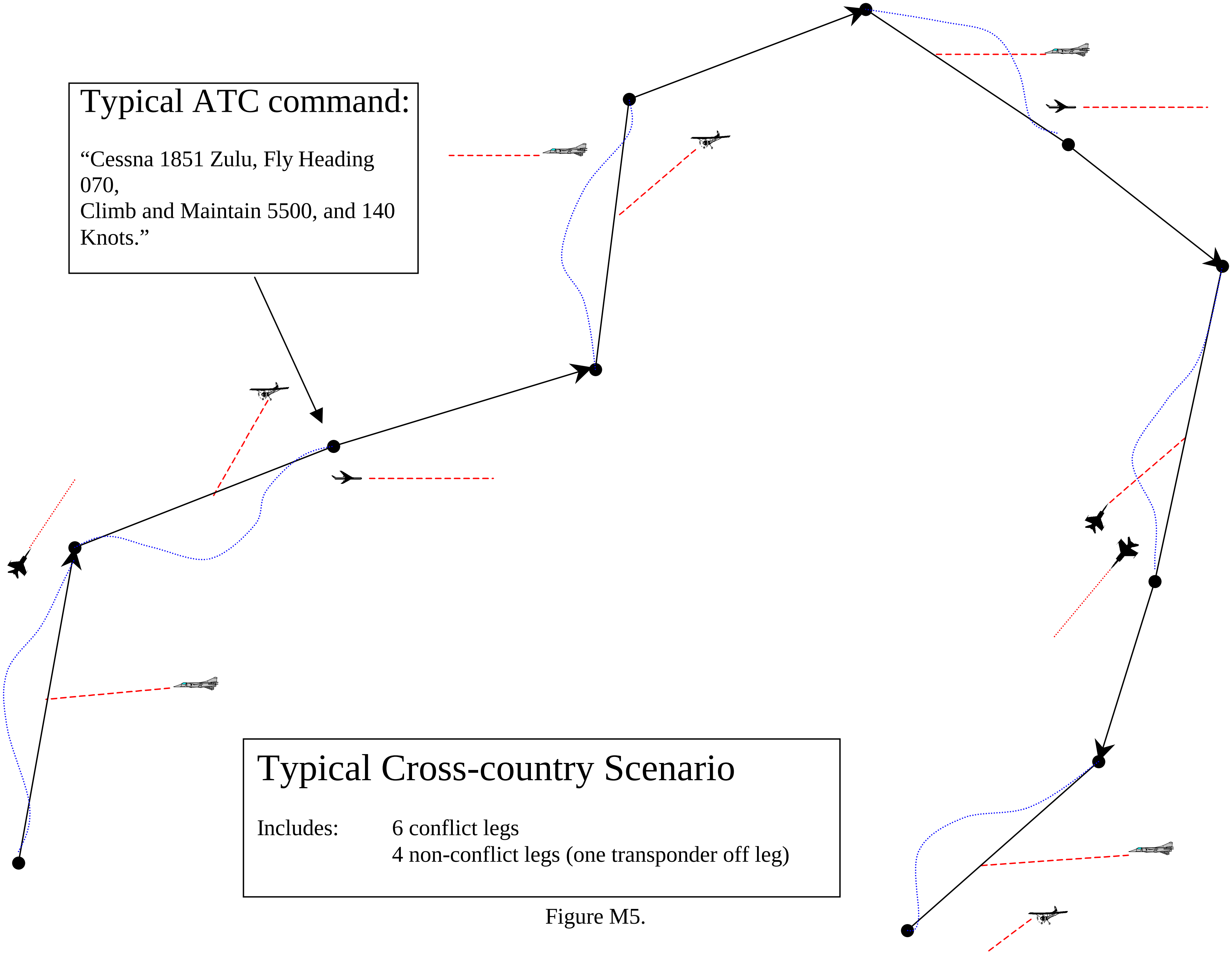
Typical ATC command:
“Cessna 1851 Zulu, Fly Heading 070,
Climb and Maintain 5500, and 140 Knots.”
Typical Cross-country Scenario
Includes: 6 conflict legs
4 non-conflict legs (one transponder off leg)

Figure M5.

prerecorded ATC commands were automatically triggered when the pilot reached each waypoint, and could be repeated upon request of the pilot. Data collection for each leg did not begin until the pilot was within 5° of the new commanded heading. The ATC did not alert the pilots to any of the traffic aircraft. Pilots had the sole responsibility for maintaining separation from other aircraft. An informal pilot study found that a separation minimum of 1.5 nm horizontal and 1000 ft. vertical resulted in roughly equivalent lateral and vertical maneuver times to avoid traffic, and hence this separation minimum was adopted for the experiment.

During each 10 leg simulated cross country flight the pilot was randomly presented with 6 conflict legs where a traffic conflict would occur if the pilot did not execute a traffic avoidance maneuver between the waypoints. The 4 remaining legs contained a single non-conflicting traffic aircraft. Each conflict leg contained 2 traffic aircraft, a conflict aircraft, which would actually collide with the pilot's ownship if no maneuver was initiated, and a non-conflict aircraft, which was placed on a heading and in a location that made it obviously non-threatening to the pilot's ownship. On each leg the ATC command would require the changing of only one flight parameter. At the beginning of a conflict leg, the ATC command always required a heading change, and on non-conflict legs the command was either an airspeed change or an altitude change. Several of the pilots were informally asked if this difference in the ATC commands had alerted them to the nature of the particular leg, none responded that they were aware of this correlation. To ensure that the traffic geometry was the same for all subjects, the traffic was generated, relative to the pilot's current location, after approximately 4 minutes from the time that the pilot achieved the commanded heading.

During the flight pilots were required to scan both visually and through the CDTI for traffic which could pose a threat to their ownship. To ensure that pilots were visually scanning the outside world, they were required to callout "traffic in sight" whenever there was an airplane visible in the projected outside world. On one of the 4 non-conflict legs, pilots were presented with a non-conflict traffic aircraft, which was not depicted on the CDTI. This aircraft was intended to simulate a "transponder off" aircraft or one with malfunctioning CDTI equipment. All traffic was potentially visible in the outside world. However, many simply did not pass in front of the pilot's aircraft within the range (5 nm) and view (135°) provided by the Evans and Sutherland SPX 2400. On non-conflict legs the traffic was visible at a range of 5 nm. However due to limitations of the Evans and Sutherland SPX 2400, on conflict legs only the conflict intruder was visible at the 5.4 nm range, whereas the non-conflict aircraft was visible at a range of 1.8 nm.

Baseline. Pilots in the baseline condition completed the same flight missions as the pilots in the free flight condition, except for the traffic avoidance maneuvers. Instead of asking pilots to determine their avoidance maneuvers based on the CDTI monitoring and visual scanning of the outside world, now ATC issued to the baseline pilots a sequence of avoidance instructions each containing one or at most two flight parameters (i.e., heading, altitude, or airspeed). Each avoidance instruction was an approximate replicate of what another pilot had self-selected in the free flight condition. Traffic avoidance maneuvers efforts were made to take the particular set of maneuvers constructed for a baseline pilot, and yoke then to a pilot of equivalent experience in the free flight condition. The yoking procedures were employed in an effort to assure that any differences in scanning behavior could not be attributed to differences in the type of maneuver profile that were flown.

Experimental Design

Figure M6 shows the conflict geometry used to generate the conflict aircraft. There were three different angles (locations) that the intruder could approach the pilot's ownship from 45°, 90°, or 135°. Also there were three different vertical behaviors that the intruder could engage in climbing, level, or descending. The intruders could also approach from the left or the right side. Another factor that was manipulated was whether the traffic appeared on the CDTI or only in the outside world. Each of these factors was completely balanced across the subjects and randomly presented throughout the six cross-country flights. There was a total of 36 conflict legs and 24 non-conflict legs for each subject. This yielded a total of 720 legs with 432 conflict legs and 288 non-conflict legs. The order of presentation for each unique cross-country flight was counterbalanced using a Latin square. Each cross-country flight began from a different initial heading, altitude, or airspeed, and the direction of heading changes (left or right turns) were balanced for each participant, so that there were an equal number of turns to the right as to the left.

Procedure

Participants in both the free flight and the baseline conditions were asked to make 1 or 2 experimental flights per day. Upon arrival the first day participants first read and signed the informed consent form. They then filled out a short demographic questionnaire which contained the following information: name, age, gender, flight certifications, total flight hours, total instrument hours, and whether they had participated in previous CDTI research. The participants were then given the experimental instructions to read. Once the participants understood the experimental task, they were asked to fly a short 5 leg practice cross-country flight to familiarize them with the experimental procedure, the flight dynamics of the simulator, and the depiction of the traffic on the CDTI (only the participants in the free flight condition interacted with the CDTI) and in the outside world. The participants then proceeded to fly the first and, for some participants, the second experimental flights with a short break between flights. Pilots were asked to return on 2 or more other occasions to complete the remaining experimental flights. After completing the experiment the pilots were debriefed and thanked for their time and cooperation. Participants were asked to wear the eye/head tracker and thus scanning data were collected only during the last 4 experimental flights.

Traffic Geometry

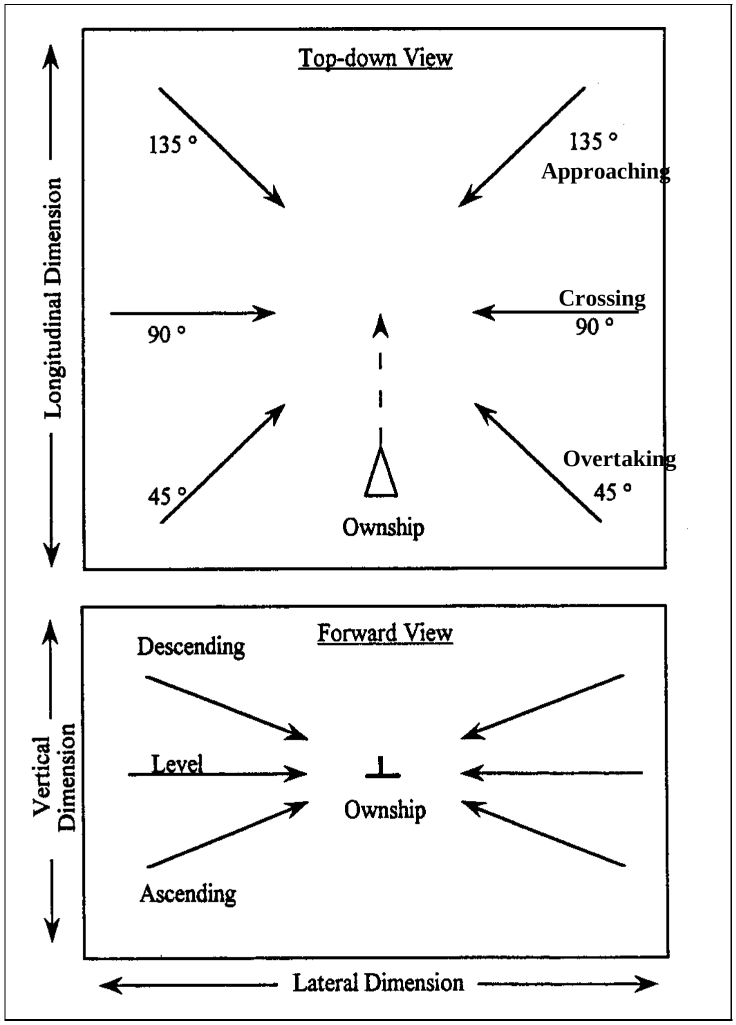

Figure M6.

RESULTS

Baseline Scanning Data

Figure R1a provides an example of the sort of scanning data captured on one leg of a freeflight scenario that were subjected to the analysis to be described below. Each circle represents an individual fixation. Figure R1b shows the cockpit viewing area, to which the scans in Figure R1a may be compared. Thus, Figure R1a portrays scans to the instrument panel AOI on the lower right, within which the upper six cells of the 3x3 matrix correspond to the 6 primary flight instruments. The CDTI occupies the region to the left of the instrument panel, and the OW

Figure R1a.

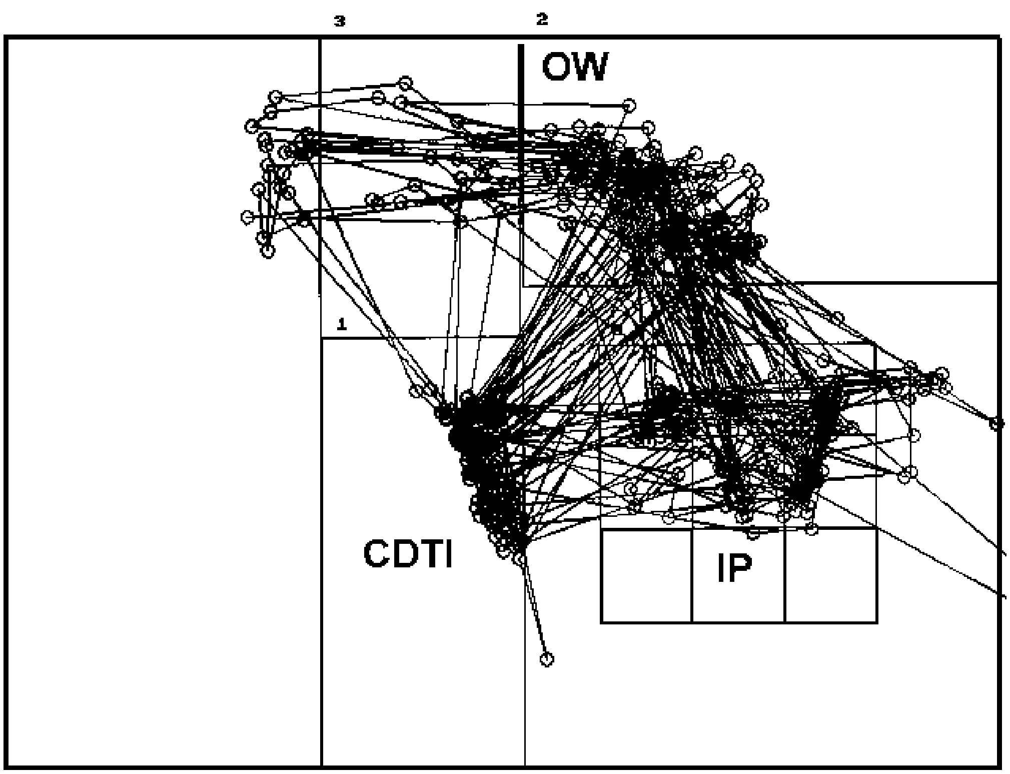

Figure R1b. An example of visual scanning data from one trial in the freeflight condition.

occupies the three panels at the top. Those fixations on the far left of the OW represent fixations on the left screen of the forward view (that is, roughly the 10:00 position).

Figure R2a presents the data for the percentage dwell time (PDT) in the two experiments showing the distribution across the two AOIs (IP and OW) for the baseline experiment (solid bars), and across the three AOIs for the freeflight experiment (open bars). Figure R2b and R2c show identical data, but now broken down into conflict trials and non-conflict trials respectively. The most prominent aspect of these data is the marked asymmetry in baseline scanning (dark bars), favoring the IP (63%) over the OW (37%). On conflict trials, when maneuvering away from straight and level flight is required, this asymmetry increases to 65%-35%, as might be required by the greater need to focus on the instrument panel. But even during straight and level flight (non-conflict), the asymmetry remains at a 60-40 advantage for the IP.

Statistical analyses of these data were carried out in a 2x2 mixed model ANOVA, with experiment as a between-subjects variable, and AOI (IP and OW) as a repeated measures variable. (The CDTI was not considered in this ANOVA.) The ANOVA revealed a highly significant main effect of AOI [$\underline{F}(1,15)=18.55$, $\underline{p}<.01$], replicating the effect described above, favoring the scan to the IP over the OW. A main effect of experiment [$\underline{F}(1,15)=1121$, $\underline{p}<.01$] reflected the diminished scanning of both AOIs, as a function of the added need to look at the CDTI in the free flight experiment. Although subjects did tend to “borrow” more scan time from the OW (15%) than from the IP (5%), the interaction between experiment and AOI was not significant ($p>.10$).

When this analysis of “borrowing” was broken down separately by conflict (Figure R2b) and non-conflict (Figure R2c) trials, a slightly different pattern of results emerged. On conflict trials, there was complete additivity between AOI and experiment, suggesting equal “borrowing” from both the IP and the OW. However on non-conflict trials, pilots **only** borrowed attention from the OW [there was a 15% reduction in OW scanning from the baseline to the freeflight experiment: 40.4%-→ 25.8%; $\underline{t}(254)=6.10$], whereas there was no change whatsoever in the amount of visual attention allocated to the IP between the two experiments (60% vs. 59.5%).

Figure R3 shows the scanning data only for the freeflight experiment, broken down between conflict and non-conflict trials. These data were analyzed in a 2 (trial) x 3 (AOI) repeated measures ANOVA, which revealed a highly significant interaction between the two variables ($F=14.06$). This interaction reveals that, when traffic is present, the CDTI attracts visual attention, increasing its percentage dwell time from 14% to 25%, an increment that is borrowed by diminishing attention to both the IP (by 5%) and the OW (by 6%).

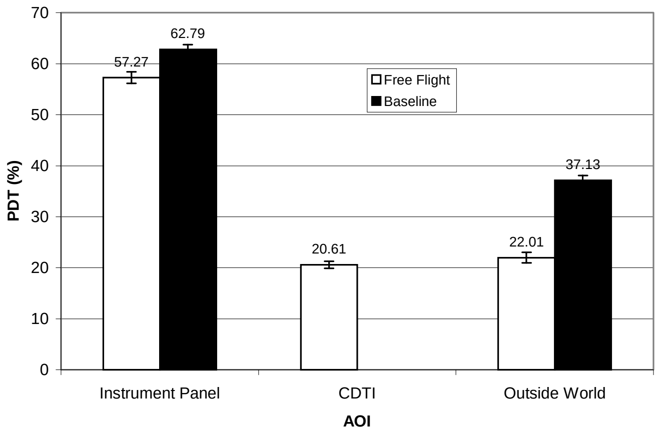

Figure R2a. Overall PDT for free flight and baseline conditions.

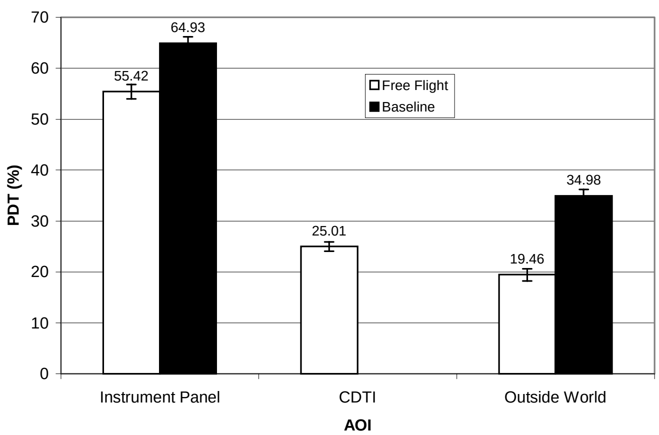

Figure R2b. PDT for free flight and baseline conditions (conflict trials).

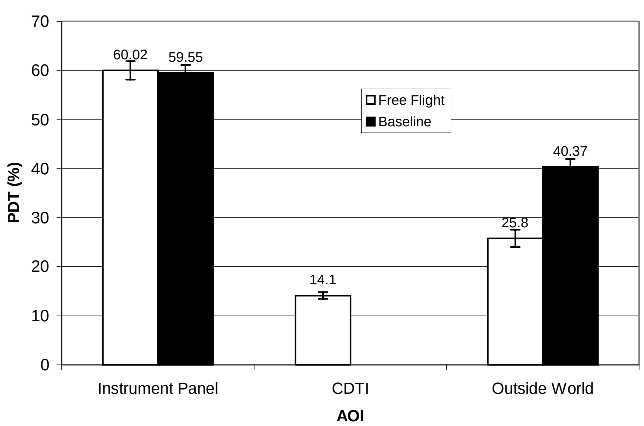

Figure R2c. PDT for free flight and baseline conditions (non-conflict trials).

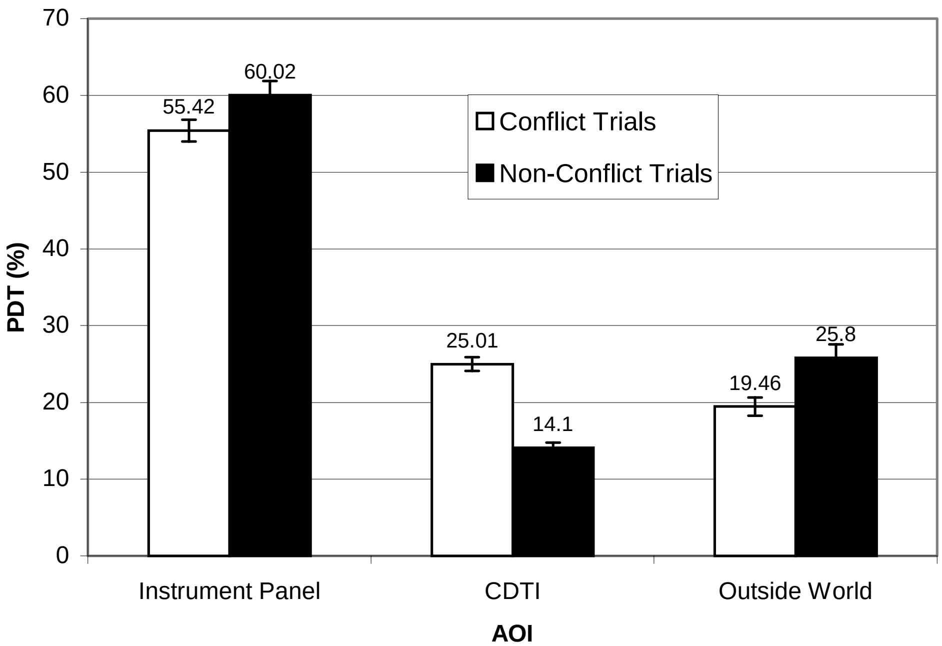

Figure R3. PDT for free flight condition by trial type.

Figure R4a, R4b, and R4c, present the data for the mean dwell duration, in the same format as that presented in Figure R2. Considering only the baseline data (solid bars), it is evident that the dwells are significantly longer on the IP (6.6 seconds), than on the OW (2.9 seconds), a difference that is similar whether there is a conflict (Figure R4b: IP=6.9, OW=2.7) or not (Figure R4c: IP=6.1, OW=3.1). This is an important observation. The value of approximately 6½ seconds represents the baseline time during which visual attention is **not** allocated outside the cockpit. In addition to this mean estimate, the variance around this mean is also important, revealing that approximately 10% of the scans remain head down in excess of 18 seconds.

The manner in which dwell duration was altered by the freeflight responsibility is revealed by comparing the black and white bars in Figure R4, in a 2x2 ANOVA similar to that conducted in the context of the PDT. The most salient effect here is that the responsibility for freeflight shortened the dwells substantially on both the OW and IP [Experiment effect: $\underline{F}(1,15)=78$, $\underline{p}<.01$], although the longer dwells on the IP still remained in freeflight, as they had been in the baseline (AOI effect; $\underline{F}=10.8$, $\underline{p}<.01$). In freeflight, the dwells on the OW were considerably shorter (1.85 seconds) than on the IP (4.3 seconds), and were of approximately the same length as the mean dwells on the CDTI (1.80 seconds).

Figure R5 shows the dwell duration data only for the freeflight experiment, in the same format as Figure R3. The highly significant interaction in these data between trial type and AOI [$\underline{F}(2,12)=15.97$, $\underline{p}<.01$], is primarily attributable to the fact that, on conflict trials, dwells on the

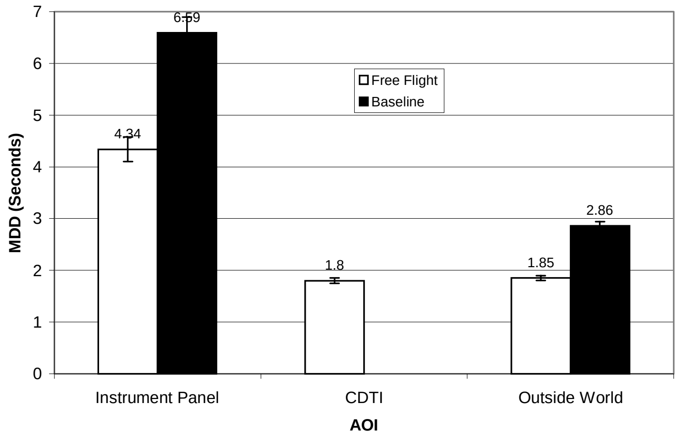

Figure R4a. Overall MDD for free flight and baseline conditions.

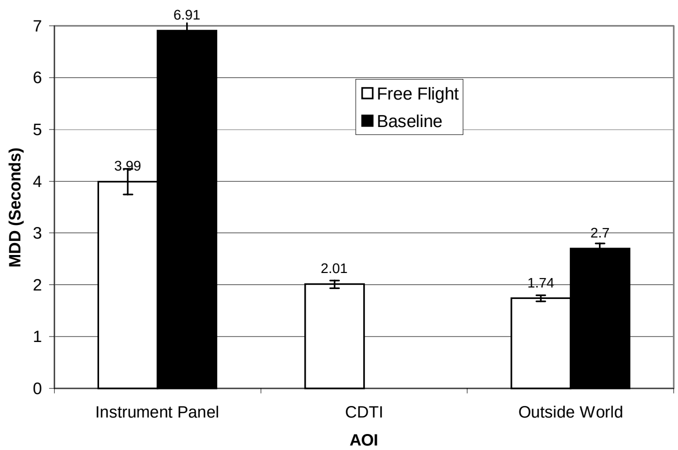

Figure R4b. MDD for free flight and baseline conditions (conflict trials).

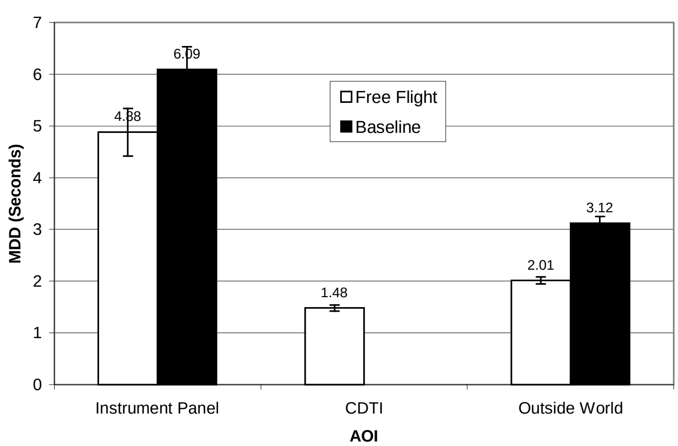

Figure R4c. MDD for free flight and baseline conditions (non-conflict trials).

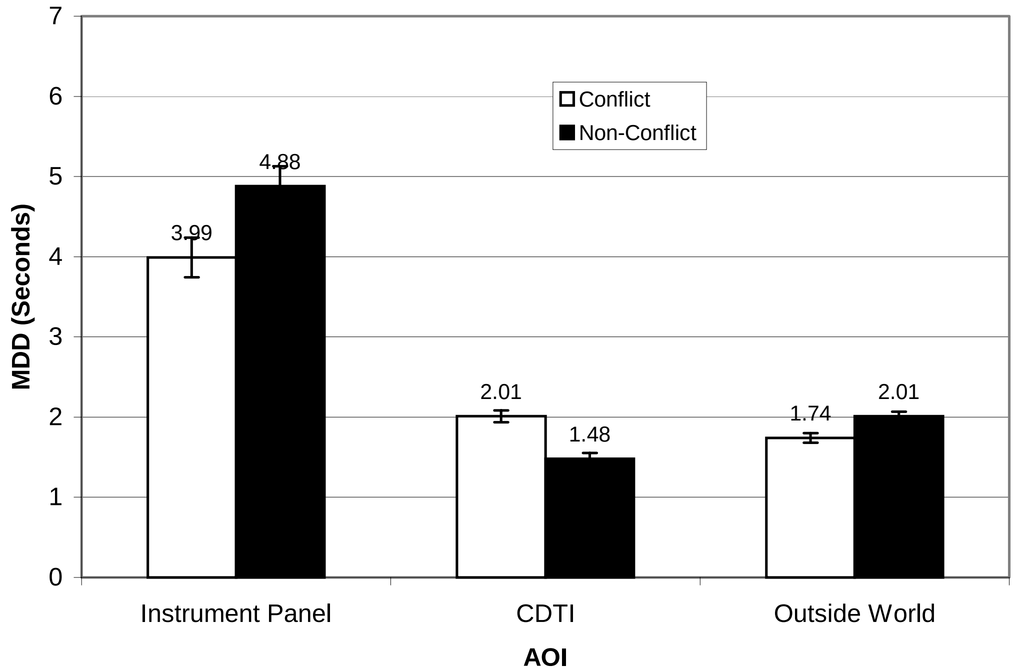

Figure R5. MDD for free flight condition by trial type.

IP grow shorter (despite the fact that these trials require more maneuvering), whereas those on the CDTI grow longer. This latter increase presumably reflects the role of the CDTI as a visual problem solving tool during conflict, for which relatively long dwells are needed to calculate the impact of traffic avoidance maneuvers.

In addition to the analyses reported above, both PDT and MDD were analyzed as a function of both the conflict geometry (level, ascending or descending), and the maneuver type selected (lateral, vertical, airspeed, combined). Interestingly neither of these variables, whose effects on maneuver choice are described in Helleberg et al. (2000; Wickens et al., 1999) had large or interpretable effects on scanning parameters, a dissociation between scanning and performance that suggests that maneuver choices are relatively independent from visual information sampling parameters. [Further data analysis of the specific instruments sampled **within** the IP AOI would probably reveal important differences due to geometry and maneuver type, similar to those found by Bellenkes et al. (1997); for example we would anticipate greater PDT on the altimeter and airspeed instruments during vertical, than during lateral maneuvers. These analyses have not yet been undertaken.]

Free Flight Strategy Analysis

In the context of Figures R3 and R5, we provided some detailed analysis of the scanning strategies specifically undertaken in the freeflight experiment. In the current section, we explore these strategies in more detail in two directions. First, we consider the pattern of first order **transitions** between the three AOIs: From these data, coupled with the mean dwell duration on each AOI, we are able to estimate what is called the **mean first passage time** (Moray, 1986) for the OW; which provides an estimate of the consecutive time during which the OW is left "unattended". This value is analogous to the mean dwell duration on the IP for the baseline experiment. Second, we examine the specific scan patterns across the three AOIs in terms of four different phases within the conflict trials, in a manner that reveals the dynamics of scan strategy as a conflict emerges.

Fixation transitions. Table R1 is a contingency table showing the first order transition matrix for the overall data in the free flight condition with three AOIs. The AOIs in the top row represent those from which the eyes were coming on Fixation N, and the AOIs in the far-left column represent those into which the eyes were going on Fixation N+1. The numbers in each cell are the probabilities expressed in percentage that the eye transited from the AOI on fixation N to the AOI on fixation (N+1). So for example, as shown in Table R1, when the fixation left the IP, it transited to the CDTI 52.56% of the time, and to the OW 47.44% of the time.

Table R1. First order transition matrix for overall data.

		AOI on Fixation N		
		IP	CDTI	OW
AOI on Fixation (N+1)	IP		68.83	71.22
	CDTI	52.56		28.27
	OW	47.44	30.05	

Comparison 1 (52.56 vs. 47.44) Comparison 2 (68.83 vs. 30.05) Comparison 3 (71.22 vs. 28.27)

Three t-tests for Comparison 1, 2, and 3, were conducted as labeled in Table R1. Comparison 1 asks, "when the fixation leaves the IP, does it more likely travel to the CDTI or to the OW?" Comparison 2 asks, "when the fixation left the CDTI, did it more likely travel to the IP or to the OW?" In a similar way, Comparison 3 asks, "when the fixation left the OW, did it more likely travel to the IP or to the CDTI?" The results of Comparison 1 show that, after the fixation left the IP, it was slightly more likely to move to the CDTI (52.5%) than to the OW (47.4%), $t(788)=3.74$, $p=.01$. Comparison 2 reveals that after the fixation left the CDTI, it traveled much more often to the IP (68.8%) than to the OW (30.0%), $t(788)=21.7$, $p<.01$. The results of Comparison 3 indicate that when the fixation left the OW, it was also more likely to go to the IP (71.2%) than the CDTI (28.3%), $t(778)=31.39$, $p<.01$. These results thus suggest that the IP is the "home base" to which the scan usually returned from either of the other destinations.

Tables R2a and R2b present the transition probabilities separately for the non-conflict and the conflict trials, and for each table, we conducted three t-tests similar to Comparison 1, 2,

Table R2a. First order transition matrix for non-conflict trials.

AOI on Fixation N

AOI on Fixation (N+1)		IP	CDTI	OW
	IP		65.00	77.06
	CDTI	43.93		22.77
	OW	56.07	33.42	

Comparison 1 Comparison 2 Comparison 3

Table R2b. First order transition matrix for conflict trials.

AOI on Fixation N

AOI on Fixation (N+1)		IP	CDTI	OW
	IP		71.41	67.28
	CDTI	58.39		31.98
	OW	41.41	27.77	

Comparison 1 Comparison 2 Comparison 3

and 3 in Table R1. Whereas transition pattern from the CDTI (Comparison 2) and the OW (Comparison 3) remained the same for both trial types, those transitions from the IP (Comparison 1) were quite the opposite on conflict and non-conflict trials. Specifically, we found that in the non-conflict trials, the eye went from the IP to the OW 56% of the time, whereas it went to the CDTI only 43% of the time, $t(317)=4.69$, $p<.01$. For the conflict trials, however, the eye went from the IP more frequently to the CDTI (58%) than to the OW (41%), $t(470)=9.27$, $p<.01$, presumably because when the pilot realized that there would be conflict, he/she would need to consult the CDTI more frequently for avoiding the traffic.

Mean first passage time (MFPT) from OW. In the baseline condition there are but two areas of interest, so the mean head down time can be estimated reasonably closely from the mean dwell time on the instrument panel, shown in Figure R4 to be about 6.5 seconds. In contrast, in the free flight experiment this consecutive time away from the OW – vulnerable to the appearance of an intruder aircraft not within the CDTI database -- is known as the **mean first passage time** (MFPT) and was analyzed on the basis of the second and higher order transition matrices, coupled with the dwell time at the two head down AOIs. This would include for example instances in which the eye leaves the OW, visits the IP or CDTI and then returns directly, as well as those in which the eye leaves the OW and repeatedly transition **between** the IP and CDTI before returning to the OW.

These data are shown in Table R3, as broken down by conflict and nonconflict legs. The table also shows the probability that the scan makes a **direct return** to the OW after only one visit head down, the MFPT for those direct returns and the MFPT for the (less frequent) indirect returns in which one or more scans are made **between** head down instruments before returning upward. Finally, for comparison purposes, we present the MFPT (= mean dwell duration on the IP) for the baseline conditions, the same data presented in Figure R4.

Table R3. Mean first passage time away from outside world.

	MFPT (sec)	Probability of Direct Return	MFPT Direct Return	MFPT Indirect Return	Baseline MFPT
Conflict	5.22	0.58	2.19	9.00	6.91
Nonconflict	4.41	0.65	2.38	7.93	6.09

The MFPT data reveal that, despite the fact that there are two head down AOI's in the free flight condition, pilots spend less consecutive time away from the OW than in the baseline condition. They are more likely to make a direct return to the OW than to "stay head down" for repeated transitions between the IP and the CDTI. Such direct returns enable them to leave the OW unattended for only a brief duration of a little over 2 seconds, probably short enough so that their comprehensive OW scan pattern is little disrupted.

Phase analysis. During each conflict trial, it was possible to identify four discrete phases separated by three distinct events labeled a, b, and c below: (1) An initial period of time during which no conflict was evident (a period that, from the pilot's point of view, is equivalent to the non-conflict trial); (2) a period following the initial appearance of a conflict on the CDTI (event a), during which time the pilot presumably is trying to decide if a maneuver is necessary, and if so, what it should be; (3) a period after which the conflict, previously seen on the CDTI, becomes visible in the outside world (event b); (4) the period following the pilot's reporting of "traffic in sight" (event c) (i.e., after visual contact has been made). The event b (the appearance of the plane in the OW), marking the transition from Phase 2 to Phase 3 may not necessarily be evident to the pilot. However this event is important for two reasons. First, we use it to start our "clock" for timing the pilots' RT to call out "traffic in sight" a measure that will be described below. Second, it serves as a somewhat arbitrary boundary between the period of time when the pilot should be focusing on the CDTI, to understand the traffic pattern (Phase 2), and when the pilot should be using the CDTI context to start actively searching outside, to confirm the visual existence and location of the CDTI (automation) rendered traffic (Phase 3). It should also be noted that active maneuvering to avoid the traffic maneuvering to avoid the traffic typically begins sometime during phase 2.

Table R4 depicts the percentage dwell time across the three AOIs, as a function of the four phases of the conflict trials. Note first that Phase 1 shows essentially equivalent scanning behavior to that seen during non-conflict trials (Figure R2c), an equivalence that is to be expected. When the traffic appears upon the CDTI (Phase 2) scanning changes in a pronounced fashion: OW scanning drops from 24.8% to 15.5%, IP scanning drops even further from 65% to 49% and CDTI scanning rises from 10% to 35%. Toward the end of this period (Phase 3) we see the scanning on the OW rise again (to 20%) presumably as the pilot is searching the OW to visually confirm the traffic. Then, once the traffic is sighted, attention shifts somewhat back to the IP, whose PDT increases from 47% (Phase 3) to 53% (Phase 4).

Table R4. Percent dwell time by phase (standard error in parenthesis).

	OW	CDTI	IP
Phase 1	24.8 (1.55)	10.3 (0.75)	64.8 (1.80)
Phase 2	15.5 (1.22)	35.1 (1.37)	49.4 (1.68)
Phase 3	19.9 (1.70)	33.2 (1.85)	46.9 (2.34)
Phase 4	17.4 (17.4)	29.5 (1.49)	53.0 (1.80)

The current data do not precisely delineate the time at which the actual avoidance maneuver started, although presumably this event, which defines a period of greater importance for the IP and CDTI, occurs sometime toward the end of Phase 2.

Table R5 provides data on mean dwell duration, in equivalent form to those in Table R4. Following the same logic described above, it is not surprising that the MDD for Phase 1 shows a trend across AOI that is roughly equivalent to that shown in the non-conflict trials (Figure R4c). Once traffic appears on the CDTI (Phase 2), the most noteworthy change is the substantial shortening of the dwells on the IP, from 6.2 seconds (Phase 1), to 3.6 seconds, and the corresponding doubling in dwell duration on the CDTI from 1.27 seconds to 2.5 seconds, an increase associated presumably with the problem solving support of the CDTI. As this mid period progresses from Phase 2 to Phase 3, dwells shorten on the CDTI, and lengthen on both the OW and the IP, the longer OW dwells again illustrating the more systematic context-driven search of the OW to visually confirm the traffic, and the longer IP dwells presumably reflecting the added demands of traffic maneuvering. Finally, once the traffic is sighted (Phase 4) dwells on all areas are short.

Table R5. Mean dwell duration (seconds) by phase (standard error in parenthesis).

	OW	CDTI	IP
Phase 1	1.75 (.07)	1.27 (.06)	6.21 (.55)
Phase 2	1.44 (.07)	2.50 (.11)	3.60 (.32)
Phase 3	1.76 (.14)	2.20 (.13)	4.10 (.56)
Phase 4	1.54 (.08)	2.22 (.18)	3.22 (.17)

Table R6 presents the MFPT data according to the four phases in the same format as Table R3. Most evident is the fact that the MFPT value abruptly jumps by about 2 seconds as the plane becomes visible on the CDTI, in part because direct returns become less probable (but still occurring over 50% of the time). To compensate, however, the head down times for those direct returns (3^{rd} column) are shortened, from 2.5 seconds to under 2 seconds once the plane has become visible in the OW. In contrast the **indirect** returns are now characterized by fairly long head down time, averaging around 10 seconds during segments 2 and 3 in which active maneuvering is taking place.

Table R6. Mean first passage time away from outside world.

	MFPT (sec)	Probability of Direct Return	MFPT Direct Return	MFPT Indirect Return
Phase 1	3.96	0.704	2.56	7.28
Phase 2	6.00	0.534	2.10	9.85
Phase 3	5.67	0.619	1.82	10.61
Phase 4	5.48	0.488	1.99	8.52

First order transition data were computed, as in Table R1, for each of the four phases separately. These data are shown in Table R7. We have also re-presented these data in a different format in Table R8, using the following logic: (1) each cell in the transition Table R7 represents a uni-directional transition between two instruments. In Table R8 we have averaged the data across both directions, to estimate the frequency of transitions **between** a pair of instruments, independently of which way the transition went. These values are represented at the top line of each cell in Table R8. They are associated with each of the four phases and with each of the three instrument pairs (across the three columns). We have labeled these three pairs as "**standard scan**" (OW and IP) to define the relevant scan in the baseline experiment, "**head down**" (CDTI

Table R7a. First order transition matrix for conflict trials for Segment 1.

		AOI on Fixation N		
		IP	CDTI	OW
AOI on Fixation (N+1)	IP		68.25	73.47
	CDTI	36.27		18.58
	OW	63.73	29.11	

Comparison 1 Comparison 2 Comparison 3

Comparison 1: $\underline{t}(452)=-10,89$, $\underline{p}<.0005$;

Comparison 2: $\underline{t}(452)=14.55$, $\underline{p}<.0005$;

Comparison 3: $\underline{t}(452)=23.81$, $\underline{p}<.0005$.

Table R7b. First order transition matrix for conflict trials for Segment 2.

		AOI on Fixation N		
		IP	CDTI	OW
AOI on Fixation (N+1)	IP		73.63	57.88
	CDTI	64.52		34.78
	OW	32.83	24.68	

Comparison 1 Comparison 2 Comparison 3

Comparison 1: $\underline{t}(452)=15.06$, $\underline{p}<.0005$;

Comparison 2: $\underline{t}(452)=18.23$, $\underline{p}<.0005$;

Comparison 3: $\underline{t}(452)=8.52$, $\underline{p}<.0005$.

Table R7c. First order transition matrix for conflict trials for Segment 3.

AOI on Fixation N (columns); AOI on Fixation (N+1) (rows)

	IP	CDTI	OW
IP		66.01	45.39
CDTI	64.27		41.28
OW	30.73	29.55	

Comparison 1   Comparison 2   Comparison 3

Comparison 1: $t(359)=11.55$, $p<.0005$;

Comparison 2: $t(359)=10.77$, $p<.0005$;

Comparison 3: $t(359)=1.10$, $p<.274$.

Table R7d. First order transition matrix for conflict trials for Segment 4.

AOI on Fixation N (columns); AOI on Fixation (N+1) (rows)

	IP	CDTI	OW
IP		69.58	58.91
CDTI	64.45		40.81
OW	34.40	29.20	

Comparison 1   Comparison 2   Comparison 3

Comparison 1: $t(260)=12.74$, $p<.0005$;

Comparison 2: $t(260)=13.47$, $p<.0005$;

Comparison 3: $t(260)=5.47$, $p<.0005$.

Table R8.

	Standard Scan OW→IP	Head Down CD→IP	Traffic Concerns OW→CD
Phase 1			
Frequency	68	54	24
Asymmetry	← **10%**	→ 32%	→ 11%
Actual Trans %	47% ↑	36%	16% ↓
Predicted Trans %	40.5%	34%	25.5%
Phase 2			
Frequency	45	68	30
Asymmetry	→ 25%	—	→ 10%
Actual Trans %	31%	48% ↑	20% ↓
Predicted Trans %	32%	40%	27%
Phase 3			
Frequency	38	65	36
Asymmetry	→ 15%	—	→ 11%
Actual Trans %	27%	47% ↑	26% ↓
Predicted Trans %	30%	40%	30%
Phase 4			
Frequency	46	65	35
Asymmetry	→ 24%	—	→ 11%
Actual Trans %	31%	45% ↑	24% ↓
Predicted Trans %	32.4%	39%	28%

and IP) to define the two AOIs at a head down (and near accommodation) location, and "**traffic concerns**" (OW and CDTI) to define the two AOIs that represent traffic information. (2) On the second line within each cell is shown either an arrow facing left or right, or a non-directional line. The arrow represents the direction of asymmetry between the two members of the pair. An arrow facing right indicates a dominant scan corresponding to the order of the two AOIs at the top of the column (i.e., OW→IP, CDTI→IP, OW→CDTI). An arrow pointing left reverses this trend, and the non-directional line indicates relative symmetry. The percentage next to the arrow reflects that magnitude of the directional asymmetry (i.e., the difference between transitions one way and transitions the other way).

(3) We have normalized the transition values (shown in the top line) across rows, to show in the third line the relative frequency of transitions between each of the three pairs (by dividing each by the sum of the three). Thus for example in Phase 1, 47% of all scans were between the outside world and the instrument panel. (4) Under each of these values in line 4, we have provided a **predicted-percentage** value, which is the frequency of transitions that would be predicted, if each transition from A to either B or C, was dictated ONLY by the overall relative frequency of visits to A or B and was not driven by any sequential constraints (Ellis & Stark, 1986). In determining this predicted value, we computed the mean number of visits to each AOI, in order to compute an "attractiveness value" of the AOI. We then assumed that the choice to visit one of two AOI's on fixation N+1 (given the scan's residence of the third on fixation N) would be dictated **only** by the relative attractiveness of the two alternatives. Thus for example if the IP were visited twice as frequently overall, as the OW, we would assume, given independence, that travels from the CDTI to the IP would be twice as likely as from the CDTI to the OW. The comparison between the independence assumption values (line 4), and the actual values (line 3) then provides a specific quantification of the "in the neighborhood" heuristic. For example, if the eye, once looking down (at the IP or CDTI) would tend to stay there (to avoid re-accommodation), then the actual % transitions between CDTI and IP (head down, column 2) would tend to be greater than the value predicted on the basis of independent scanning.

Focusing first on the numbers in the top line of each cell, it is evident that the dominant transitions evolve in a predictable fashion, across phases of flight. For example the **standard scan** pair dominates Phase 1 when there is no traffic, and reduces in frequency as traffic becomes more of a concern (in Phases 2-4), just as the **head down scan** transitions increase in frequency across this period. The **traffic concern scan** transitions also increase, and do so abruptly from Phase 2 to Phase 3, in a manner unlike the head down scans (which slightly decrease between these two phases). As noted above, these raw data do not themselves indicate an increased "coupling" between an AOI pair, because an increase could be expected to result simply from an increase in the PDT for the two members of a given pair. This independence predicted value is shown in line 4, and can be compared with the actual transition value.

We have highlighted what we believe to be substantial (>4%) deviation of predicted from actual transitions by the arrows that appear in line 3. An up-arrow indicates **more** scanning between the pair than predicted; a down-arrow indicates **less** scanning than predicted. Thus, the data reveal in Phase 1, a strong tendency to preserve the "standard scan" pattern, linking the OW to the IP (as would be true entirely in baseline scanning). This pattern is broken when traffic appears (Phase 2) and is replaced instead by a tendency to stay "head-down" (i.e., transition more frequently between the two head down AOI's than would be predicted on the basis of independence). Interestingly, across all phases there is a tendency to **avoid** direct transition between the OW and CDTI (avoid staying with traffic concerns, column 3), as if this pattern of seeking (partially) redundant information from the two sources of traffic information, is intentionally disrupted by the need to check the instruments. However, it is also of note that this "traffic concern avoidance tendency" is itself reduced to 4% (but not eliminated) as Phase 3 is entered, at which time the pilots are presumably engaged in visually confirming traffic (OW) represented on the CDTI.

The final feature of note is revealed by the asymmetry analysis in line 2. For Phase 1, the scan pattern assumes a generally "counter clockwise" formation, going from CDTI → IP → OW → CDTI etc. Once traffic is identified a marked reversal occurs in scanning between the instrument panel and the OW. Now transitions become substantially more frequent in the opposite direction, tending to go from the OW in the IP, rather than the reverse.

<u>Traffic Detection Times</u>

In all conditions, and in both experiments, pilots were instructed to call out "traffic in sight" any time an aircraft became visible in the outside world. These times were recorded, and subtracted from our best estimate of the time at which the traffic airplane became visible in the outside world, to estimate a callout RT. There was of course variability in both of these numbers. Actual callout time was influenced by traffic conspicuity (e.g., head on versus profile aspect, relative motion), as well as by the pilot's momentary scan (i.e., the pilot who is fixated on the forward view or the IP will detect a traffic on the left screen more slowly than one who is doing a systematic OW scan across both screens). The estimate of initial visibility time was also variable because it was estimated on the basis of a standard flight path orientation, and not calculated individually for each pilot. Thus for example a momentary large shift in heading for one pilot, could have made a plane invisible (off the screen) while that heading was in effect, even as it might have been on screen for pilots who maintained the standard heading.

Despite this variability in estimates, the relatively large number of aircraft used in the experiment allowed us to collect some relatively stable data, shown in Table R9, which presents traffic callout time (and accuracy) for the freeflight experiment (top row) and the baseline (bottom row), on conflict (left side) and non-conflict (right side) trials. Considering first the detection performance on the conflict trials, we note that the only aircraft to be called out were those aircraft that represented a conflict traffic (i.e., one for which a maneuver was required). There were no non-conflict aircraft on such trials. The data on the left side of the table suggest a significant 4 second cost to detection (visual confirmation) time in the freeflight condition, relative to the baseline condition. There is also a slight cost in the accuracy of visually detecting these aircraft in freeflight. It should be borne in mind however that pilots did have good knowledge of the position of these aircraft from their CDTI.

The right side of Table R9 presents data for the non-conflict trials, in which two kinds of aircraft were presented, those with the transponder on (painted on the CDTI) and those with the transponder off, with the former occurring roughly four times more frequently.

Table R9. Time to call out “traffic in sight” [standard error, accuracy]

	Conflict Trials	Nonconflict Trials	
Free Flight (N=13)	26 sec (1.01, 74%)	Transponder On (CDTI) 19 sec (2.13, 58%)	Transponder Off (OW only) 36 sec (4.20, 69%)
Baseline (N=10)	22 sec (1.03, 77%)	“Transponder On” 24 sec (2.82, 63%)	“Transponder Off” 46 sec (8.97, 67%)

In the freeflight experiment, portrayed at the top, although there is a 17 second RT cost to detecting the transponder-off aircraft, relative to the aircraft portrayed on the CDTI (36-19 sec), this cost is (a) offset by an 11% GAIN in accuracy for those transponder-off aircraft and (b) appears to be attributable to the particular low visibility or conspicuity characteristics of those aircraft in the scenario that had their transponder off, rather than to the fact that they were not shown on the CDTI. This second conclusion is supported by the baseline data, shown at the bottom, in which RT and accuracy of those exact same aircraft (i.e., appearance with the same geometry and aspect angle on the same, yoked, maneuver trials) were recorded. We refer to these as “transponder off” aircraft, to indicate their equivalence in conspicuity with that class in the freeflight trials, even though the label “transponder off” did not have any direct meaning in the baseline experiment (i.e., NO aircraft had transponders, since there was no CDTI).

In examining the second row of table R9, we see that the RT cost to these “transponder off” aircraft was actually greater (46-24=22 seconds) in the baseline experiment, than it was in freeflight (17 seconds in the top row), and furthermore what had been an 11% benefit in the accuracy of detecting those “transponder off” aircraft in freeflight (top row) is here diminished to only 4%. Thus, if anything, these aircraft are actually harder to detect in the baseline condition, relative to their status in the freeflight condition in which a CDTI was present, but did not paint them. Hence the current data allow us to reject a hypothesis that suggests that a CDTI might cause pilots to tunnel in and notice only those aircraft painted on the CDTI.

Finally, in comparing the bottom and top row, we find significantly faster detection of conflict aircraft in the baseline experiment than in freeflight, but significantly faster detection of non-conflict aircraft in freeflight than in the baseline.

It should be noted that the data in Table R9 contain observations from **all** 13 pilots in the free flight experiment, and not just those seven for whom scanning was measured. For the latter subset, we observed an equivalent pattern of RT data to that shown in Table R9; and we infer also that the scan data from the seven measured pilots is representative of that of the larger set of 13.

DISCUSSION

Our discussion of the results is presented at three levels. We present first the conclusions that we draw from baseline scanning. Then we describe how these scanning patterns are altered by self separation responsibility, and finally we try to put the observed changes and differences within the framework of the three component model of scanning.

Baseline Scanning

The most prominent feature in the data presented in Figure R2, is that the pilots in our experiment spent approximately 37% of their time attending to the out the window view, a value that contrasts sharply with the FAA recommended figure of approximately 75% (Aeronautical Information Manual, 2000). This value is only slightly modulated by the maneuvers involved in traffic separation. OW scanning decreases from 40% to 35% as traffic maneuvers are initiated, a decrease that presumably reflects the increased bandwidth of the instrument panel during the departure from straight and level flight (conflict trials). This shift in attention from the OW to the IP may also reflect the added importance of IP scanning, given that the aircraft's departure from straight and level flying can render stall considerations more important (e.g., particularly if climbs are instructed by ATC at lower airspeeds).

Baseline scanning was also accomplished with reasonably long dwells on the instrument panel, averaging approximately 6.5 seconds. Given that dwells on individual instruments within the IP tend to be equal or less than a second (Bellenkes et al., 1997; Harris & Christhilf, 1980), the 6.5 second figure suggests that pilots are engaged in perhaps five to six separate transitions between instruments **within** the IP, before moving upward to the OW, thereby demonstrating a good bit of "in the neighborhood" behavior. As the pilots engage in the conflict avoidance maneuvers instructed by ATC, the IP dwells lengthen by about one second (Figures R4b and R4c), and the OW dwells shorten (by about ½ second), a change also reflecting both the greater bandwidth and greater importance of the IP upon departure from straight and level flight.

These scanning strategies appeared to leave pilots relatively vulnerable to detecting traffic in the forward view, with RT's averaging 35 seconds for the report of traffic in sight. While this value may appear to be particularly long, it should be noted that traffic was **not** particularly salient at the moment that our RT "clock" started. As in real world scanning, pilots had a wide field of view to cover; and our display system, mimicking real world viewing, rendered sufficient haze, and a small enough visual angle at the initial visibility distance (particularly with a 0 degrees or 180 degrees aspect angle), that the initial visibility of the targets was quite low, even for the experimenters, who knew where and when it would appear.

Two factors should be considered in interpreting the above results. First, the majority of maneuvers were vertical changes (since these had been "yoked" to the self selected maneuvers of the freeflight pilots, who spontaneously preferred vertical maneuvering; Helleberg et al., 2000). However we did not find that the nature of maneuver choice exerted much influence on either the percentage or dwell time of head down views. Second, it was very apparent to the pilots in our experiment that they were flying IFR (but in VMC), given the consistent sequence of instructions provided by ATC. At some point it would be of importance to measure this scanning behavior under true VFR conditions, to determine if the heightened traffic monitoring responsibilities in this "see and avoid" environment would substantially alter the scan pattern.

Scanning Changes With Freeflight

In contrast with the baseline data reported above, we observed several prominent changes when the responsibility for self separation was imposed, using a CDTI. Fortunately, most of these changes appear to be relatively adaptive ones. Not surprisingly the CDTI was frequently attended, particularly when it was used to plan a conflict avoidance maneuver. When compared with the percentage dwell times from the baseline experiment, it appeared that pilots “borrowed” more of their visual attention from the OW monitoring, than from the instrument panel, in order to attend to the CDTI. This asymmetry was particularly pronounced during conflict avoidance trials. When averaged across all phases of these trials, it appears that pilots consistently chose to “conserve” 60% of their visual attention for IP monitoring, while allocating and distributing the remaining 40% between the two sources of traffic information (the OW and the CDTI), attending a little more (25%) to the OW when no conflict was present, and a little less (15%) to the OW on the conflict legs. However a more detailed analysis of the change in scanning, as a conflict leg evolved, revealed that instrument panel scanning **did** drop to slightly under 50% as conflict avoidance planning was undertaken with the CDTI (Table R4, Phases 2 and 3), while CDTI scanning increased to 35%. OW scanning remained low during these phases, occupying well under 20% of the pilots’ attention.

In spite of the decrease in OW monitoring from the baseline (40%) to free flight (25% and as low as 15% in phase 2 of conflict trials), pilots were still able to preserve, if not improve their performance in monitoring for OW traffic. Most critically, the detection time for the particular “transponder off” aircraft shortened from its value of 46 seconds (baseline; in which the phrase “transponder off’ had no operational meaning) to 36 seconds. This shortening clearly reflects a heightened vigilance for traffic, demonstrated by the freeflight pilots, a consequence of the increase in **importance** of the navigation (traffic detection and avoidance) subtask, that was manifest with the assigned responsibility for freeflight. A different view of this benefit to traffic detection, is that it reflects the removal of “boredom” which affected the baseline pilots, a boredom that is not unknown in real flying, but might have been enhanced here within the flight simulator. On non-conflict trials (Table R9) when traffic did appear on the CDTI in freeflight, it was also detected more rapidly than its counterpart in the baseline experiment, whether it presented a conflict or not, a phenomena that was unsurprising, given that the CDTI directed pilots to the point on the OW where such traffic might be seen. On conflict trials, detection was slower in free flight then in baseline, a difference that can be related to the heavy engagement of visual attention in the CDTI, for maneuver planning.

It is apparent that pilots in the freeflight experiment, while reducing the overall percentage of time on the outside world relative to those in the baseline, qualitatively altered their scanning strategies in ways that presumably mitigated some of the unfortunate effects of having less visual attention available. In particular, pilots shortened their dwells on all AOIs (a general characteristic of better pilots; Bellenkes et al, 1997), and did so particularly on the instrument panel. Here dwells were shortened by about 3 seconds (from 7 to 4 seconds), and were shortened most of all on the final phase of the conflict legs, down to 3.2 seconds. As a consequence of such shortening of IP dwells, which was of greater magnitude than the mean dwell time on the CDTI, pilots left the OW **unattended** for a shorter period of time than had been true in the baseline condition (4.8 seconds vs. 6.6 seconds in Table R3). Furthermore, a majority of the downward glances involved a “direct return” to the OW within about 2 seconds, a value of sufficiently short magnitude that one would expect little decay of the remembered scan sequence upon return to the OW. We also note that the shorter dwells on the instrument panel reveal a substantial reduction of "in the neighborhood" scanning at that location. Presumably our pilots chose (wisely) to expend more information access effort (frequent transitions) to compensate for the loss of ATC as redundant a traffic monitoring agent.

The traffic call out data shown in Table R9 may be interpreted in the context of the effects of imperfect automation-driven attentional cueing (Yeh, Wickens, & Seagull, 1999; Yeh & Wickens, 2000; Parasuraman, Sheridan, & Wickens, 2000; Ockerman & Pritchett, 1998; Mosier, Skitka, Heers, & Burdick, 1998; Skitka, Mosier, & Burdick, 1999; Hooey, Foyle, & Andre, 2000). Here investigators have noticed the advantages of automation in directing visual attention to targets when that direction is correct, but the costs (relative to unaided performance) on those cases when automation fails, a characteristic sometimes labeled "complacency" (Parasuraman & Riley, 1997). The benefits of automation were in evidence in the current study, a faster call out for non-conflict traffic when an aircraft was on the CDTI, than where equivalent traffic was not portrayed in the baseline study. Somewhat surprisingly, however, there appeared to be no cost to the detection of unannounced traffic (transponder off), which can be considered to be a failure of automation (the CDTI database is unaware of the existence of traffic). This absence of cost was revealed in the comparison with the baseline data. A number of reasons may be offered to explain why such a cost was not observed.

First, as we have noted, pilots in the free flight condition were probably in a heightened state of vigilance in monitoring for outside traffic, given the absence of ATC. Second, we have noted elsewhere that users in general (Merlo et al., 2000), and pilots in particular (Wickens, Gempler, & Morphew, 2000) are relatively proficient at calibrating their monitoring and attention allocation strategies between automation attention guidance (here the CDTI) and "raw data" (here the visual aircraft in the OW), when the former is known to be fallible, as was the case here (pilots were very much aware of the possible existence of the transponder-off aircraft).

Third, it is also the case that conditions in which imperfect automation overtrust and complacency effects would be most likely to occur, were not explicitly examined here. These would be circumstances in which (a) such failures were **very** infrequent and (b) pilots were concurrently engaged in an avoidance maneuver at the time that the transponder-off aircraft appeared. Under such circumstances the vulnerability of human performance to imperfect automation might be revealed.

In any case, the current data speak optimistically to the pilots' ability to adapt to an imperfect free flight system without compromising vigilant out-of-cockpit scanning behavior.

Finally, with regard to the implications of these results for freeflight, these data can be looked at from two perspectives. On the one hand, the 5 second periods of the unattended outside world (which may increase to as long as 16 seconds for some percentage of the pilots given the variance), coupled with the mere 15-25% allocation of visual attention to the outside, has disturbing implications for the visibility of outside traffic, particularly that traffic which may be unknown to the data base generating the CDTI. But on the other hand, these data can be contrasted more favorably with the baseline scanning data, and in this case the loss of OW scanning in free flight is seen to be compensated for by more effective scanning **strategies** (i.e., shorter dwells, changes in transitions, reduced mean first passage time) that are more effective in identifying traffic.

Implications for a Model of Information Access

In the Introduction we presented a three component model of the factors that would be expected to influence visual sampling, as these might vary between experiments (baseline vs. freeflight) and between AOIs and phases of flight. In Table I1 we presented some basic predictions of how these components might be reflected in the data, to the extent that they do influence scanning and sampling (as they are suggested to have done by prior research; Senders, 1964; Carbonell et al, 1968; Sheridan, 1972). We revisit the entries in Table I1 here to examine if these influences were in fact reflected in the data.

With regard to **information bandwidth** (frequency), it is apparent that the predictions were generally upheld. Certainly the instrument panel, the highest bandwidth source, dominated the OW and the CDTI; and on non-conflict legs, the OW dominated the CDTI. Furthermore, as predicted by the second line of the table, the IP demanded more visual attention during conflict avoidance maneuvers because of its higher bandwidth than during straight and level flight, even during the baseline experiment (when the added traffic information of the CDTI was not part of the pilot's responsibility).

Finally, we note that the contextual influence of the CDTI (row 3 of Table I1) was **indirectly** signaled in the data on non-conflict trials by the shortened RT when traffic was announced on the CDTI (Table R9). Interestingly however one might have expected this contextual influence to cause scanning patterns to go directly **from** the CDTI **to** the OW, once the former depicted a traffic aircraft. Examination of the asymmetry data from the second line of Table R8 does not indicate this to be the case. The scan is just as likely to go from the CDTI to the IP as it is to the OW.

With regard to the influence of information **importance**, evidence is again provided. As we have noted before, the overall dominance of the IP over the OW and the CDTI, observed in our data, is consistent with the prioritization of "aviate—navigate—communicate". The weak dominance of the OW over the CDTI on non-conflict trials (and also on conflict trials during phase 1) is also reflective of this prioritization, since the OW is a source of attitude information (important to aviate) while the CDTI is not. The second predicted influence of the importance component is one suggesting that the sources of traffic information (OW in baseline, and OW+CDTI in freeflight) would increase in dominance from the baseline to the freeflight experiment, as the "traffic monitoring and avoidance" component of the navigation subtask gets shifted from ATC to the pilot. This influence was only partially confirmed. Across all trials, the percentage of fixation time allocated to traffic sources (the OW and, in freeflight, the CDTI) did not increase above 40% when freeflight responsibility was imposed. However a somewhat muted version of this effect **was** evident when the data were broken down by phase within the conflict avoidance legs of freeflight; here attention allocated to the two sources of traffic information increased to above 50% (and the IP decreased below 50%), as a traffic conflict became imminent in Phases 2 and 3.

Finally, with regard to **information access effort**, which we define operationally here by the fixation transitions, and, to some extent by the reaccommodation between near and far sources, some evidence of influence was also provided. When not burdened by the sole-responsibilities of traffic monitoring (i.e., in the baseline), dwells were fairly long on the instrument panel, revealing a good deal of "in the neighborhood" scanning, before attention was re-allocated outside. It should be noted here, that when responsibilities for freeflight were imposed, the IP dwells shortened considerably, indicating that the combined influences of importance and information bandwidth clearly dominate that of reducing information access effort. However, it should also be noted that on slightly less than half the trials, pilots stayed head down for at least two fixations (Table R6), and these were associated with very long durations, with the mean first passage time averaging around 10 seconds.

The second prediction of an effort based effect is that the eye would tend to remain "head down" longer than predicted by an independence model, in order to increase the amount of (easier) lateral scanning, and to reduce the amount of re-accommodation. The data from Table R8 indicate that this is indeed the case, particularly as the pilot starts to deal with traffic problems (during the latter three phases of the conflict legs). An implication of this finding, worth examination, would be whether this head down tendency would be alleviated by presenting traffic information at a greater optical distance, through collimation.

The third effort-based prediction that we made was that dwells out the window would be longer than those inside; in other words, once visual attention had gone outside, it would stay there for a while, taking advantage of the accommodation to the distant screen. This prediction was not really confirmed by the data.

Conclusion

In conclusion, the current results provide insight into how pilots allocate their visual attention, to cope both with the demands of routine flight and of the self separation responsibilities imposed by freeflight. These results indicate that a majority of time is spent fixating in the cockpit, and that with freeflight, this time would be increased still further, but not at the overall expense of traffic monitoring and detection. This research will need to be followed by further explorations of the implications for teaching scan strategies, and for reliance upon automation based traffic alerting and planning devices (such as the CDTI), for detection of traffic that is both "known" and "unknown" to the system.

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