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Predictive Features of a Cockpit Traffic Display: A Workload Assessment

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Abstract

Eighteen pilots flew a series of traffic avoidance maneuvers in an experiment designed to assess the support offered and workload imposed by different levels of traffic display information in a free flight simulation. Three display prototypes were compared which differed in traffic information provided. A BASELINE (BL) display provided current and (2^{nd} order) predicted information regarding ownship and current information of an intruder aircraft, represented on lateral and vertical displays in a coplanar suite. An INTRUDER PREDICTOR (IP) display, augmented the baseline display by providing lateral and vertical prediction of the intruder aircraft. A THREAT VECTOR (TV) display added to the IP display a vector that indicates the direction from ownship to the intruder at the predicted point of closest contact (POCC). The length of the vector corresponds to the radius of the protected zone, and the distance of the intersection of the vector with ownship predictor, corresponds to the time available till POCC or loss of separation. Pilots time shared the traffic avoidance task with a secondary task requiring them to monitor the top of the display for faint targets. This task simulated the visual demands of out-of-cockpit scanning, and hence was used to estimate the head-down time required by the different display formats.

The results revealed that both display augmentations improved performance (safety) as assessed by predicted and actual loss of separation (i.e., penetration of the protected zone). Both enhancements also reduced workload, as assessed by the NASA TLX scale. The intruder predictor display produced these benefits with no substantial impact on the qualitative nature of the avoidance maneuvers that were selected. The threat vector produced the safety benefits by inducing a greater degree of (effective) lateral maneuvering, thus partially offsetting the benefits of reduced workload. The three displays did not differ in terms of their effect on performance of the monitoring task, used to infer head-down time, nor in the extent of vertical or airspeed maneuvering. The results are discussed in terms of their implications for cognitive engineering design features.

Introduction

In two previous studies on this contract, we have examined three issues with regard to cockpit displays of traffic information, using a general paradigm in which pilots flew a low fidelity simulator in a series of conflict problems with one or two intruders. (Merwin and Wickens, 1996; Merwin, O'Brien, and Wickens, 1997; O'Brien and Wickens, 1997).

(1) In both studies, we comparatively evaluated 2D (coplanar: plan view and profile) with a 3D (perspective) displays. The latter option had been considered promising, on the basis of the earlier findings of Ellis, McGreevy, and Hitchcock (1987), and on the basis of the fact that tactical maneuvering for free flight might often require integrated maneuvering in both the lateral and vertical dimension; an integration which we hypothesized might be facilitated by the integrated perspective display. In fact however, both studies yielded a consistent pattern of results indicating an advantage for the coplanar display, particularly in depicting traffic conflicts in which the intruder showed vertical behavior. We attributed the differences between these findings, and those of Ellis et al., who had found a cost for the 2D display, to the fact that their study, in contrast to ours, did not incorporate a separate analog profile display, to accompany the plan view display in the 2D condition.

(2) In O'Brien and Wickens (1997), we considered the joint representation of weather and traffic, concluding that these two important hazard data bases would be best represented if they were integrated on a single display panel (whether 2D or 3D), rather than separated. Consistent with the Proximity Compatibility Principle (Wickens and Carswell, 1995), this integration was observed to be most beneficial on traffic problems in which the solution required joint consideration of traffic AND weather.

(3) Both studies examined the preferred maneuver stereotypes, and both revealed pilot preference to maneuver in the vertical, rather than in the lateral dimension, although this overall preference was sometimes modulated by the particular conflict geometry, and by the display type.

In spite of the three fairly robust conclusions drawn above, the two studies left a number of important issues unresolved, issues which will be addressed by the third experiment in our project, reported here.

The first issue concerns the particular aspects of the symbology that we employed. Following a cognitive task analysis of the pilot's information needs during conflict avoidance planning, we developed what appeared to be a reasonable symbology set. By applying principles of ecological interface design (Vicente and Rasmussen, 1992), we developed two features that would represent perceptually, information necessary for decisions that pilots would otherwise have to derive cognitively. One set of features were predictive indicators for the intruder traffic. The second feature was a threat vector, that indicated the direction and bearing to the point of closest passage. Its length was proportional to the size of ownship's protected zone, and the position at which it intersected ownship's predictor line, indicated the time remaining till the point of closest passage (or loss of separation) was reached. Characteristics of both of these features will be more fully described in the Methods section.

Although pilots in the first two studies appeared to find these tools useful, there was no firm validation that they WERE in fact useful, since we did not manipulate their presence. Indeed two possible arguments could be raised as to why these tools might **not** be desirable. On the one hand, they both add some "clutter" to the display, possibly hindering pilot's ability to search for other information. On the other hand, while both might offer additional useful information for conflict negotiation, pilots may process this added information by investing additional cognitive resources, and hence increase workload. Indeed Yeh and Wickens (1988) have reported that the added information provided by predictive displays, while improving tracking performance, can also increase workload (Herron, 1980). In the multitask environment of the cockpit, any added workload associated with a traffic display would be likely to impose a clear cost on the performance of other tasks.

The possible workload effects associated with the traffic display leads to the second issue addressed in the current study: examining the traffic displays in the multitask context. In order to establish whether the added features of the traffic displays actually did impose added workload, we chose two approaches to workload measurement. First, subjective workload measures of the 3 different display options, varying in the presence of predictors and threat vector, were compared using the NASA TLX measure (Hart & Staveland, 1988). Second, the possible resource costs associated with the different displays were evaluated by imposing a secondary task, simulating the visual demands of out-of-cockpit monitoring. Other investigators have evaluated the workload (and resulting head-down time) associated with cockpit traffic displays (Battiste and Bortulussi, 1988; Hart and Wempe, 1979; Abbott et al., 1980). All revealed that there is, naturally, some resource cost to these displays, although none have quantified the costs in terms of head-down time. Sirevaag et al. (1993), have specifically examined head-down costs associated with cockpit technology, but they compared digital and auditory display of navigational information, rather than graphical portrayal of traffic information. Finally, Kreifeldt (1980) did examine the workload costs associated with traffic predictor information; but used a workload measure of communications frequency, rather than one that could be directly translated into a measure of spare time or effort. Using his measure, Kreifeldt reported no differences between conditions with and without traffic prediction.

While our study falls far short of real cockpit realism, the current effort does go beyond the single task evaluations of CDTI symbology carried out in the previous two studies of this contract (Merwin, O'Brien, and Wickens, 1997), to consider the use of the display in the context of two important flight tasks; aircraft control, and out-of-cockpit scanning.

The third issue we address concerns pilot preference for different maneuver types. As noted above, the two previous studies found a preference for vertical conflict avoidance; but both studies constrained pilots to fly at a fixed airspeed. In actual flight of course, three degrees of freedom are available; lateral, vertical, and longitudinal (airspeed) control. Indeed it is easily possible to envision circumstances in which a momentary slowing or speeding, rather than a climb, descent, or a turn, can prevent a possible penetration of a protected zone. However, the overall economic costs and feasibility of the three different classes of maneuvers is not equivalent (Krozel and Peters, 1997), nor is the time window within which each form of maneuver is a viable option. For example, vertical control is the most feasible to be implemented at the last minute. To address this issue more fully, in the experiment we report here we provided pilots with throttle control, which they could use in addition to (or instead of) lateral and vertical control to avoid conflicts.

Thus in the present study, our pilots flew a series of conflict traffic encounters with a single intruder, whose geometry (approaching, crossing, overtaking, ascending, level, descending) was varied unpredictably. Pilots were to judge if the intruder was likely to penetrate the protected zone (most intruders were), and if so, to maneuver the aircraft in such a way as to avoid penetration, and also minimize deviation from the overall initial flight parameters of the trial. While pilots flew, a series of very faint targets appeared in random positions across the top margin of the display, targets that required foveal vision for detection. Because of their unpredictable nature and the fact that they could not be detected with peripheral (upper field) vision, these target probes imposed the same demands as out of cockpit scanning. Delays in their detection could be directly attributable to visual workload associated with processing the display.

Experimental Method

Participants

All participants were licensed flight instructors from the University of Illinois Institute of Aviation and received $5 per hour for their participation. Fifteen male pilots participated in the study. The mean number of flight hours for all participants was 341 hours. All pilots were instrument rated, and had a mean number of 80.3 instrument flight hours.

Simulation Flight Dynamics and Apparatus

The simulation was run on a Silicon Graphics 4D/30 Super Turbo workstation and viewed on a Silicon Graphics 20-inch color display. The display screen resolution was 1280 x 1024 pixels and was run at a frequency of 60 hertz. The simulation allowed subjects to control ownship's airspeed, altitude, and heading. These variables were controlled through a flight stick located on the right-hand side of the Silicon Graphics workstation. The flight stick allowed maximum pitch and bank angles of +/-5 degrees and +/-30 degrees respectively, in order to preclude any extreme maneuvers aimed towards evading impending traffic conflicts. Speed control was maintained through the flight stick as well, with increased speed (at a constant rate) resulting from pushing the button on top of the flight stick and decreased flight speed corresponding with pressing the trigger. The maximum speed change capability was +/-150 knots, which translated into a maximum flight speed of 475 knots and a minimum of 175. Although pilots were provided with the capability of using speed control as a means of managing traffic conflicts, they were instructed to deviate from the prescribed speed of 325 knots as little as possible. The same was instructed for ownship's prescribed altitude (10,000 feet) and heading values (towards the waypoint). Light turbulence was programmed into the simulation, causing ownship to at times drift slowly from the prescribed heading and pitch angles should active control not be maintained. A linear crosscoupling function was also included in the flight simulation dynamics, causing cross-coupled responses to input to the flight controls (e.g. pitching up resulted in a decrease in the aircraft's speed, and banking resulted in a pitching down of the aircraft nose) as is found in real flight.

Task and Simulation

Pilots flew a series of six "missions" throughout two separate experimental sessions (3 missions per session). Each mission was comprised of ten consecutive (1-2 minute) flight scenarios. In each scenario, pilots were required to fly to a designated navigational waypoint (a VOR located directly ahead of ownship) without coming into conflict with the "intruder" aircraft located in their airspace, while maintaining the prescribed flight parameters to the greatest extent possible (heading, speed and altitude). In all scenarios, airspace traffic was comprised of one additional aircraft (referred to as the "intruder") within ownship's airspace. In every mission, nine of the ten flight scenarios were designed as "conflict" scenarios requiring the pilot to execute avoidance maneuvers in order to resolve an impending conflict. The task required pilots to determine if the intruder's flightpath would penetrate the protected zone around ownship, and if so, use any means of maneuvering (including speed, heading, or altitude control) in order to avoid coming into conflict with the intruder. Pilots were instructed to do this in a way so as to minimize deviations in speed, heading, and altitude from their prescribed values. Ownship's designated conflict zone was +/-1,500 feet vertically and 3 miles horizontally, meaning that if the intruder aircraft came within these minimum separation boundaries, both aircraft would engage in a conflict. Pilots were instructed to avoid such engagements.

Displays

A schematic of the general display format used by all participants is presented in Figure 1 . The display format chosen for the experiment was a 2-D coplanar display, with a top-down and corresponding forward-looking view of the airspace surrounding ownship. The display included an ADI (attitude directional indicator) located in the top center region of the screen which was used by subjects to maintain aircraft attitude (pitch and bank levels). The vertical strips located on adjacent sides of the horizontal situation indicator (HSI) represent the altimeter (right) and airspeed indicator (left) respectively. Visual Scanning demands of the FFOV (forward field of view) or "out-the-cockpit view" were represented abstractly by ellipses that appeared at random locations and times throughout each trial within the horizontal bar extending across the top of the screen.

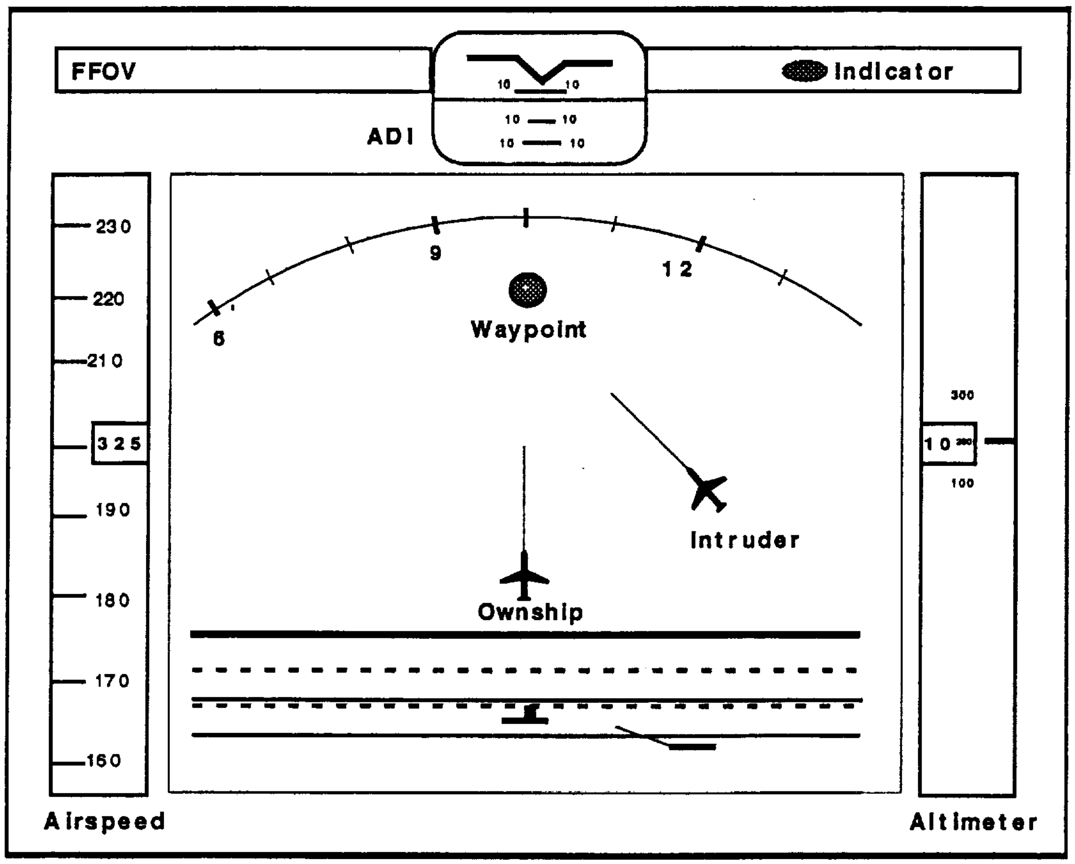
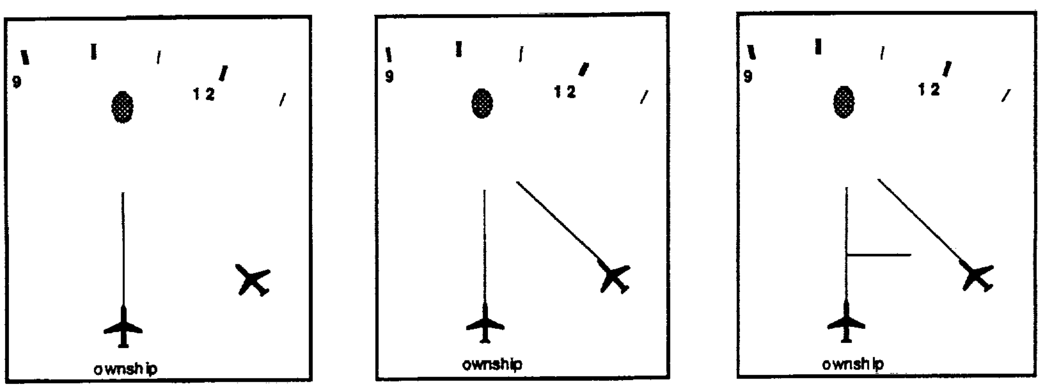


Figure 1.
The Present Experiment's Airborne *Free Flight* Display
Values in the boxes on the airspeed and altitude scales represent command values.

The horizontal situation indicator (HSI), used to represent traffic, portrayed a top-down (x-z axes) and forward-looking (x-y axes) view of the pilot's surrounding airspace. The traffic symbology was overlaid on a grid of equi-spaced lines representing 5 nautical mile increments.

The lines were comprised of dots positioned at intervals of 1 nautical mile. The grid rotates with ownship to provide consistent spacing information of traffic symbology. The top-down view of the traffic display contained air traffic symbology consisting of ownship and intruder's aircraft icons, a hexagonal VOR (navigational waypoint) symbol representing the location of the subject's destination and dependent upon the display condition the subject was viewing, predictor lines on both aircraft, and a threat vector stemming from ownship's predictor line. The three display conditions are illustrated in figure 2.



Baseline (BL) Condition
(othership w/no predictor or threat vector)

Predictor (IP) Condition
(othership with predictor)

Threat Vector (TV) Condition 3
(othership w/ predictor & threat vector)

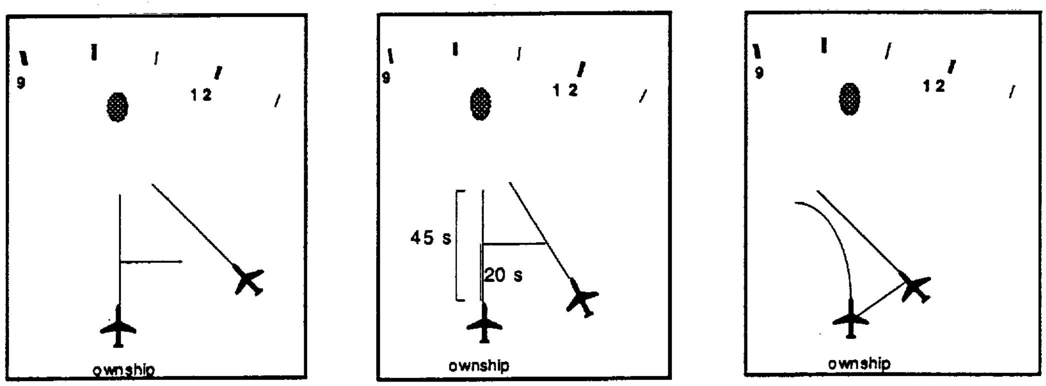
Figure 2
The Three display Conditions

All display conditions presented ownship with a *predictor line*— a vector projected from the nose of the aircraft extending 45 seconds into the future which provided pilots with a graphical depiction of their aircraft's future position based on currently maintained parameters (heading and airspeed). In the baseline (BL) display condition, only ownship had a predictor line, and no threat vector was displayed. The second condition (IP= intruder predictor) included predictor lines on both ownship and the intruder aircraft. The third condition (TV=threat vector) included predictor lines on both aircraft, in addition to a threat vector emanating from somewhere along ownship's predictor line. The threat vector indicated the point of closest possible conflict with the intruder's aircraft.

As illustrated by Merwin & Wickens (1996), the threat vector extends from somewhere along ownship's predictor line and points in the direction at which the intruder would pass closest to ownship if both aircraft maintained their current heading and vertical velocity. The endpoint of the threat vector moved closer to the intruder's predictor line as the predicted minimum separation decreases. Additionally, the threat vector moves closer to ownship's aircraft symbol as the time to actual conflict decreases. Pilots were instructed to avoid contact between the threat vector's endpoint and the other aircraft's predictor line or aircraft symbol at all times, for such contact would signal a *predicted* or *actual* loss of separation (conflict). The threat vector allowed pilots to directly perceive, rather than having to estimate, the proximity of the intruder to ownship's protected zone. As the time to conflict between ownship and intruder decreased, the threat vector moved along the predictor line toward ownship's aircraft symbol, explicitly representing the time to actual conflict. In the current simulation, the dimensions of the protected zone were +/-1,500 feet vertically and 3 miles horizontally. In the display condition which included the threat vector (TV), if the threat vector touched the intruder's predictor line, a *predicted* conflict occurred and both aircraft would highlight indicating to the pilot that he was engaged in a predicted conflict.

The distinction between the display symbology for a *predicted* conflict and for an *actual* conflict is depicted in figure 3. As demonstrated in Figure 3a, when ownship's threat vector is not touching the intruder's predictor line or aircraft symbol, no conflict is predicted. As illustrated in Figure 3b, a conflict is predicted when ownship's threat vector is touching the intruder's predictor or aircraft symbol. In this case, ownship is in a *predicted* conflict with the intruder, and as indicated by the position of the threat vector along ownship's line, an *actual* conflict will occur in

20 seconds if no evasive action is taken by ownship. Figure 3 c depicts ownship in an *actual* conflict.



(a) No predicted or actual Conflict (b) Predicted conflict (c) actual conflict

Figure 3
Predicted and Actual Conflict Illustrations

The forward-looking view of the coplanar display contained a set of parallel yellow horizontal lines representing ownship's *current* vertical protected zone boundaries (1,500 feet above and below ownship). The dashed yellow horizontal lines represented the *predicted* vertical protected zone boundaries 45 seconds into the future.

Color-coding was implemented for the symbology in the traffic display as a means of facilitating pilot perception of aircraft status states. The pilot's aircraft symbol and predictor line were colored magenta while the intruder and its predictor line were colored gray. The threat vector was always orange in color. When ownship was in *predicted* conflict with the intruder, the two aircraft and associated predictor lines would highlight.

The traffic display incorporated a "FFOV indicator symbol" superimposed on the horizontal strip extending across the top of the screen, which simulated the visual scanning demands of the forward field of view (FFOV) or "out-the-window" view. The indicators appeared in randomly designated locations across the horizontal bar, at randomly generated times throughout each trial. Each indicator remained visible for a 15s period, or until noticed and acknowledged by the subject by pressing the space bar on the flight simulator keyboard. Three or four FFOV indicator symbols were presented in each approximately 1.5 minute trial. The pilot's task was to maintain his flight duties (heading, airspeed, and altitude) while detecting and avoiding traffic conflicts, and maintaining attention in the FFOV region in the display. The appearances of the FFOV indicators were configured so as to not be detectable through the pilot's peripheral vision, but rather had to be directly observed in order to be detected. In addition to the collection of response time (RT) measures (time to notice and respond to the occurrence of the FFOV indicator by pressing the space bar), accuracy was calculated as a proportion of hits (times when the change is responded to) to the total number of FFOV indicators that occured).

Experimental Design

A 3 x 3 x 3 factorial, *within-subjects* design was used. The factors of interest included *display type* (BL, IP, or TV), *vertical traffic geometry* (ascending, level, descending) and *longitudinal geometry* (45, 90, and 135 degrees). The three *display types* sought to evaluate the effectiveness of flightpath predictor and threat vector display aids on pilot performance. The three display types included: (BL) ownship had a predictor line while intruder did not, (IP) both ownship and intruder had predictor lines, and (TV) both ownship and the intruder had a predictor line, and additionally, a threat vector was present. The order in which subjects saw the three display types was randomized and counterbalanced across sessions 1 and 2. Pictorial examples of each display type are illustrated in figure 2.

The intruder approach geometries with respect to ownship were varied in order to ensure exposure to a variety of traffic patterns, including three vertical geometries (ascending, level, and descending), and three longitudinal geometries (45, 90 and 135 degrees) and approached from either the left or right side of ownship. The intruder approach geometries were randomized over both sessions 1 and 2 so that each subject saw every possible combination of intruder vertical and lateral geometry (including left and right approaches). While an approximately equal number of intruder approaches were from the left and right, this was not classified as an independent variable.

Together, these geometries combined to produce eighteen ways in which ownship was approached by the intruder aircraft, as can be seen in the illustration below in Figure 4.

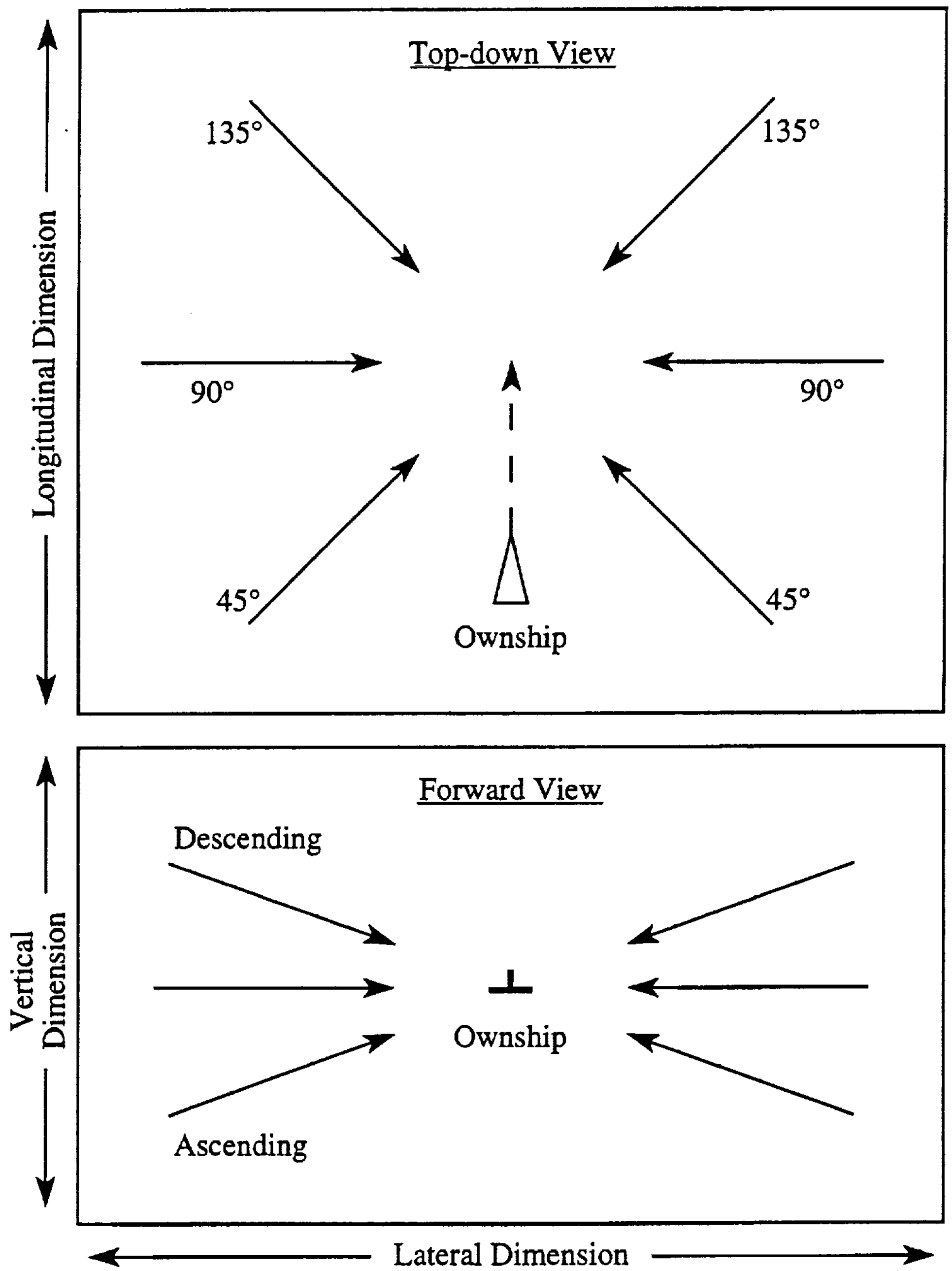


Figure 4
Diagram of Intruder Approach Geometries.

Procedure

Subjects were asked to participate in two sessions on two separate days, each lasting approximately 1.5 hours. In the first session, participants were read instructions and shown illustrations relating to the task and display symbologies used in the experiment in order to familiarize them with the simulation. Upon completion of the instructions, the experimenter clarified any aspects of the task that remained unclear to the subject. Subjects then flew twelve practice scenarios in which they familiarized themselves with the displays (including the three display conditions), the display symbology, and the flight task. Upon successful completion of these practice trials, subjects began session 1 and completed the first three missions.

In the second session, subjects flew an additional set of six practice trials and then completed the last three missions. Upon completion of each mission in this final session, participants were administered the NASA TLX subjective workload scale for each display type (BL, IP, TV). They then completed a post-experiment questionnaire which queried pilots as to their preferred traffic avoidance maneuvers and strategies, as well as their preference in display type. Finally, participants were asked for any other additional comments and thanked for their participation. The full instructions for the participants are presented in the Appendix.

Results

Primary Task: Traffic Avoidance

Figure 5 presents the effects of display on the mean number of conflicts with the protected zone of the traffic. A repeated measures ANOVA revealed that this critical parameter of safety yielded a marginally significant effect of display type ($F_{2,28}=3.01$; $p=.09$), revealing a monotonic improvement in safety as more display information was provided (i.e., from baseline to intruder predictor to threat vector). Figure 6 portrays a stronger effect of display type on the number of **predicted conflicts** (see Figure 3b; $F_{2,28}=19.28$; $p<.01$). These are less serious conditions, but ones that, if they occur, would probably alert ATC in a free flight scenario. In this case, each added display feature produced a reliable reduction in the number of predicted conflicts. There were no interactions between display type and the conflict geometry for either of the two safety parameters.

The actual flight trajectories were analyzed by assessing the RMS deviations of the maneuver away from the commanded trajectories (i.e., initial target parameters) on each of the three controlled axes. Analysis of these data revealed a marginally significant effect of display type on lateral deviations ($F_{2,28}=3.10$; $p=.10$), with a pattern suggesting that the TV display induced more lateral maneuvering than did either the BL or IP displays. This pattern was reinforced by the finding that the TV display also yielded longer trajectories than the other displays (and significantly longer ones than the IP display; $F_{1,14}=4.46$; $p=.05$), and induced a greater amount of lateral control displacement than the IP display ($F_{1,14}=3.20$; $p=.10$). There was no evidence from the flight path deviation measures that the display type altered the amount of vertical maneuvers selected, although the TV display did induce a marginally greater amount of vertical control (i.e., elevator) activity when compared with the IP display ($F_{1,14}=3.98$; $p<.07$). We attribute this to the greater amount of altitude compensation, to result from the greater amount of lateral maneuvering, given the tendency of the simulated aircraft to pitch down in a turn. The data suggested that display type did not influence the amount of airspeed maneuvering.

Primary Task: Workload Analysis

Analysis of the overall TLX workload score (average across the 6 subscales) as a function of display type, revealed a pattern very similar to that shown by the safety measures ($F_{2,28}=3.08$; $p=.08$). That is, a monotonic and marginally significant trend toward lower workload was found, as progressively more display information is provided.

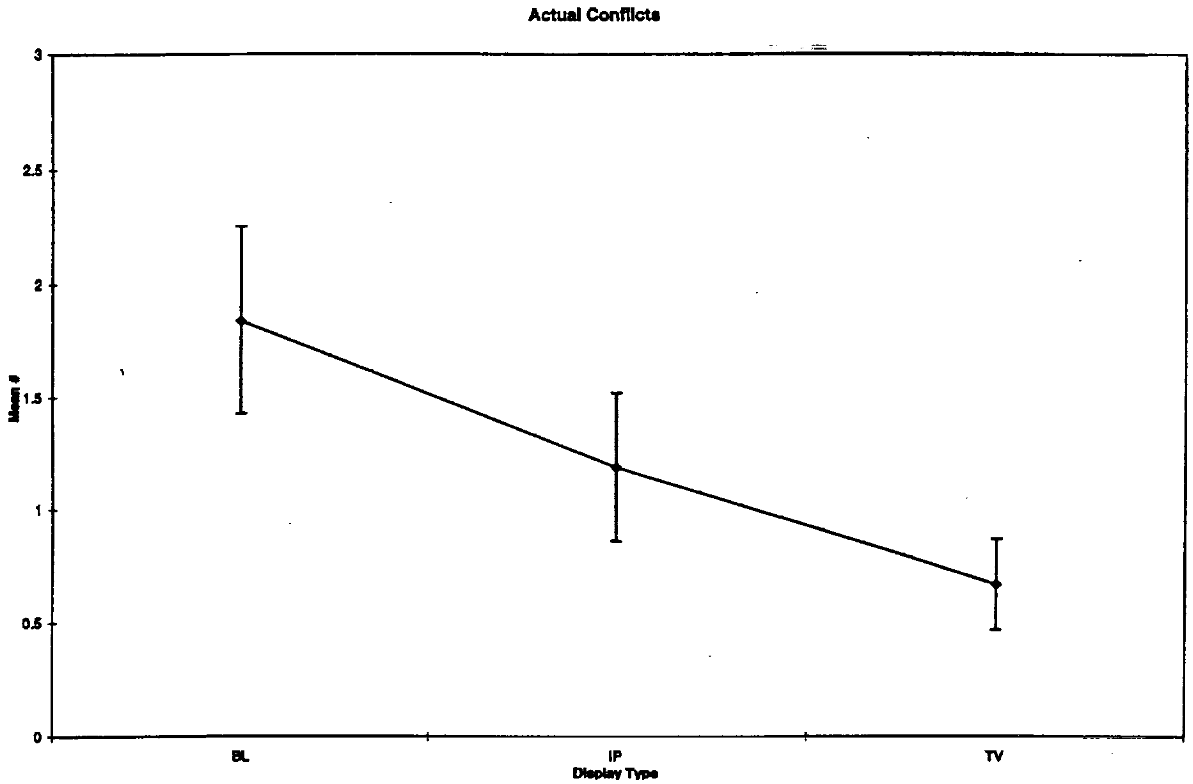


Figure 5

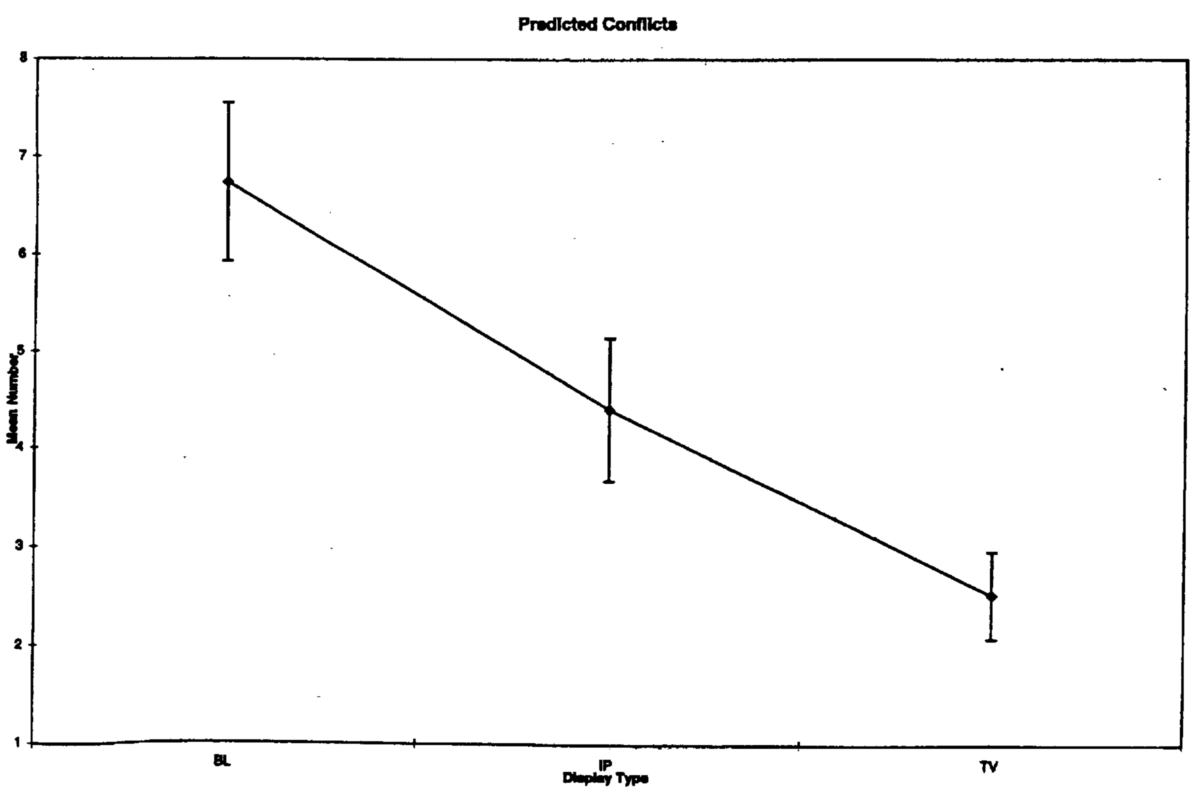
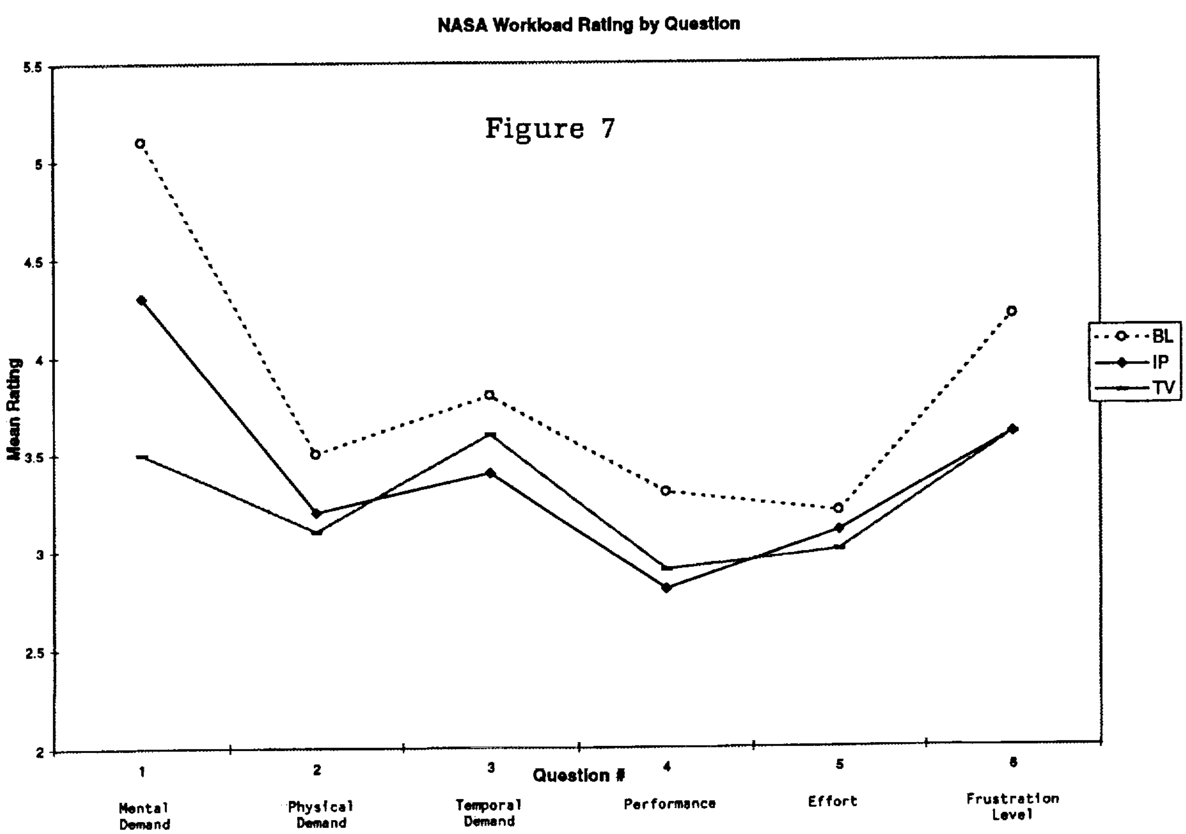


Figure 6

Figure 7 breaks the workload effects down into the separate subscales, and reveals two interesting characteristics. First, the major reduction in workload across all scales is evident between the baseline (BL) and intruder predictor (IP) displays, with few differences observed between the IP and TV displays. Second, the exception to the first characteristic is in the mental demand scale (#1), which separates the three conditions by approximately equal amounts. Indeed a separate ANOVA conducted only on this subscale revealed a highly significant main effect of display ($F_{2,28}=9.39$; p,.01). It is noteworthy that in the mental demand scale, the larger differences (greater variance accounted for) was observed between the BL and IP display ($F_{1,14} = 7.0$), than between the IP and the TV display ($F_{1,14}=3.6$). This difference will have some importance in interpreting the results that were obtained.

Secondary Task: Event Detection

Mean response time for the monitoring event detection task was approximately 4.1 seconds, indicating that pilots spent a good deal of their time head down, and hence produced a substantial lag in detecting the events. This time did not differ between the three display conditions. Mean accuracy was also equivalent between conditions, with an average hit rate of about 0.70. Finally, while false alarm rate showed a monotonic trend to increase with more display information (i.e., from BL to IP to TV), this effect did not approach statistical reliability ($P>0.10$).



Conflict Geometry Effects

There were two relatively weak effects of conflict geometry on safety measures. Descending traffic produced fewer predicted conflicts than either level or ascending traffic ($F_{2,891} = 2.76$; $p < .06$), and overtaking (45°) conflicts produces fewer actual conflicts than orthogonal or converging conflicts ($F_{8,891} = 2.38$; $p = .10$).

Discussion

The primary objective of the present study was to examine the workload implications of different levels of information for traffic depiction. The results reveal that the original design intentions used by Merwin and Wickens (1996) to create the display symbology according to cognitive engineering principles was successful. Such principles are based upon providing information in a format that directly serves the cognitive characteristics of the pilots' task, and does so in a way that replaces cognitive operations with perceptual ones (Vicente and Rasmussen, 1992). In this context, the impact of two display components can be examined, the addition of intruder predictor information, and the addition of the threat vector.

Table 1 summarizes the primary results of the study, in terms of the implications of adding each "layer" of information.

Condition	BL	IP	TV
Manipulation	→ Adding Intruder Predictor		→ Adding Threat Vector
Safety	Improves		Improves
Control Activity	Unchanged		More Lateral
Subjective Workload	Decreased in All Respects		Decreased Mental Demands Unchanged Effort, Physical Demands
Task Interference (head-down time)	Unchanged		Unchanged

Table 1

As Table 1 reveals, both of these additions supported safer performance, marginally so, in the case of actual conflicts, and strongly in the case of predicted conflicts. Further analysis however revealed that the nature of the support provided by each element was slightly different. Providing the threat vector allowed, or encouraged pilots to fly slightly different maneuvers, using a greater amount of lateral deviations and lateral control. In contrast, providing the intruder predictor information had no influence on control or maneuver strategy behavior, but, presumably allowed pilots to do the same job better than in the baseline condition. This difference in the effects of the two display augmentations was reflected in differences in assessed workload. Figure 7 reveals the pronounced drop in all workload aspects created by providing the intruder predictor. However, the figure also reveals that, except for the mental demand scale, any further workload reduction that might have been provided by the threat vector, was offset by either the added control activity that was induced, or by the added cognitive effort required to process the (very useful) information offered by the threat vector.

However, summarizing the overall workload results, and focusing particularly on the mental demand scale, it is apparent that our efforts to make perceptually visible, quantities that would otherwise need to be cognitively derived, reduced the workload demands and simultaneously improved performance, a key goal of cognitive engineering (Rasmussen et al., 1995) and its closely associated field of ecological interface design (Vicente and Rasmussen, 1992).

Considering the implications of the current results for performance in the broader context of the flight task, the data did not suggest that the reduced workload (resource demand) of the higher information levels actually provided any spare visual capacity for monitoring the far domain, since RT to the secondary task of event monitoring was delayed equally across all three display conditions. At the same time, it is important to observe that greater interference was NOT observed with the higher information level displays. Such interference might have been predicted had the greater (but more useful) information of the PI and TV required a greater time cost and effort expenditure to process (Yeh and Wickens, 1988; Herron, 1980). That such a cost was not imposed here may be attributable to the careful design of the display features based upon pilot input (Merwin and Wickens, 1996).

With regard to the impact of displays on control performance, we found less general evidence for display X maneuver interactions than were observed in the previous studies in this project (Merwin, O'Brien, and Wickens, 1997). In particular, although pilots here were given the opportunity to use airspeed control in the current study, we did not observe that its use was modulated by the nature of the displayed information.

In conclusion, the current results appear to validate the adequacy of the 2D coplanar display for traffic information, which could be used in a free flight scenario or, alternatively, used to support pilot traffic awareness in a more conventional ATC-based airspace, although they also point to the substantial head-down cost of using such displays for traffic avoidance maneuvers. Our results do not speak to the many additional issues associated with the choice between ground and air-based control. Adequate traffic displays are a necessary, but only small piece of the free flight puzzle. Furthermore, the current results strongly urge the conduct of additional higher fidelity flight simulations.

Acknowledgments

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Appendix X.

Free Flight Experiment:
Instructions for Participants

Introduction

The FAA and NASA have recently undertaken research efforts towards examining specific ways to improve the efficiency of the National Airspace System. These efforts have resulted in the development of a program known as *Free Flight.*

Arising from the need to employ innovative solutions to safely and efficiently maintain air traffic separation in increasingly denser skyways, the concept of *free flight* **involves shifting air traffic management responsibilities from air traffic control** (ATC) **to in-flight pilots.** Under *free flight* conditions, pilots will have the capability, and the responsibility, of selecting and implementing their own flight parameters to their destinations including route, speed, and altitude. The responsibility of maintaining air traffic separation will be redirected from Air Traffic Control (ATC) to pilots, with ATC imposing restrictions only to resolve conflicts, preclude exceeding airport capacity, prevent unauthorized flight through Special Use Airspace, and ensure ultimate flight safety (RTCA, 1995). The goal is to provide each pilot with the flexibility to optimize their flightpath while maintaining the safety and efficiency of the overall system (Planzer & Jenny, 1995), as doing so can afford a variety of ATM benefits.

Significant human factors challenges arise with the implementation of *free flight*. Such challenges include the design and implementation of displays to support traffic and hazard awareness in the cockpit, and the assessment of pilot performance in relation to such displays.

The purpose of this experiment is to examine flight performance, workload, attentional demands and the effectiveness of certain display aids (predictors and threat vectors) in response to an airborne traffic display and associated air traffic management responsibilities that come with it. Your participation will help us complete our research which will contribute to NASA and the FAA's understanding of pilot and system performance in relation to airborne traffic management displays.

Task Overview (experimenter read to pilot)

In this study, you will be asked to fly a desktop flight simulator which includes a traffic display such as would be used in a cockpit equipped with *free flight* capabilities. Accordingly, your task will be to not only fly to your waypoint (VOR) destination, but also to effectively avoid the traffic in your airspace using the *free flight* display. You will be asked to complete 2 separate sessions (approximately 1.25 hours each). In each session, you will fly 3 "missions". Each mission is comprised of a series of 10 short (1-2 minute) trials. You will complete a total of six (6) missions.

Your task is to fly (adhering as closely as possible to a prescribed altitude of 10,000 feet, speed of 325 knots, and a heading aimed at the VOR) towards a designated waypoint (VOR) while monitoring the traffic display for potential conflicts and engaging in avoidance maneuvers if necessary. *Traffic conflicts* are defined as penetrations of the protected zone around your aircraft (+/- 1500 feet vertically, 3 mile horizontal radius). **The primary goal of your task is to reach the designated waypoint while maintaining the prescribed flight parameters and avoiding any predicted or actual traffic conflicts.** You must also monitor the horizontal gray strip extending across the top of the display for the occurrence of FFOV indicators (see Figure 1) *(experimenter: please show the subject the color picture of the display, along with Figure 1 and point out all information discussed in this preceding paragraph).*

As an overview, you will have 3 tasks to perform:

1. Fly the aircraft as smoothly and efficiently as possible to the waypoint (i.e., minimizing changes in flight parameters (325 knots, 10,000 ft, VOR heading).

2. Monitor your traffic display and use it to guide your maneuvers around any conflicting traffic if necessary.

3. Monitor the simulated view out the windshield for visual sightings of traffic.

Your task will now be described in greater detail:

1. Fly the prescribed heading and altitude toward the navigational waypoint (VOR). **Maintain the prescribed flight parameters (altitude = 10,000 ft, speed = 325 knots, heading = towards waypoint (VOR)) to the extent possible (when not maneuvering to avoid intruder aircraft)!**

2. Remember to monitor the gray horizontal strip extending across the top of the display for FFOV (forward field of view) indicator ellipses to appear. Faint flashes of light appearing as an ellipse will appear at random times and locations across the panel throughout each trial. These simulate the demands of out of the cockpit traffic monitoring, and you should ***indicate their appearance as soon as you notice them by pressing the space bar on the keyboard***. The percentage that you identify, in addition to the time it took you to identify them in will be recorded

and incorporated into performance scores. **It is vital that you monitor this bar for the occurrence of indicator dots an press the space bar each time you identify one.** To help facilitate this, please rest your left hand on the pad in front of the keyboard.

3. Monitor the traffic display for anticipated conflicts. There will always be only one other aircraft in your airspace, which may or may not pose a traffic threat. The "intruder" aircraft will always maintain its heading, speed, and pre-determined altitude. In other words, the other aircraft will not act in response to your own aircraft's behavior, or change it's speed, heading or altitude. It will continue to do what it is doing at the beginning of the trial.

4. If you assess the current and predicted situation and feel that a conflict will occur, maneuver so as to avoid the conflict but remember to return as soon as possible to a heading and altitude that will intersect the navigational waypoint on the display (towards the VOR, at 10,000 feet), and to the 325 knot airspeed prescribed. Maneuvers should be as "efficient" as possible without compromising separation between your aircraft and the other aircraft. That is, you should try to deviate as little as possible from your prescribed heading, altitude and airspeed, while safely maneuvering around the conflict. **You may use ANY means you wish in maneuvering (changing your altitude, speed or heading)** so as to maintain separation. **No one way of maneuvering is preferred**. Your choice for maintaining separation should be based on what you would actually do in the cockpit were you involved in the same situation. No one means is more desirable than any other, and there are no restrictions on the method you choose for maintaining adequate separation between aircraft.

5. The trial will end when you reach within 3 miles of the waypoint and are at an altitude between 9,000 and 11,000 feet (resulting in successful trial completion) **or** when you pass the waypoint outside of the specified parameters (resulting in unsuccessful trial completion).

6. Remember that ***your primary objective is to reach the navigational waypoint without coming into conflict with the other traffic***. The threat vector line (see figure 2c) indicates where the nearest threat is predicted to be when you reach the threat vector, so you can use the vector to determine how close other aircraft will come to your protected zone. The threat vector will move toward your aircraft symbol as the time until the threat is closest decreases. Also, the end of the threat vector indicates the edge of your protected zone. Therefore, *if the threat vector reaches another aircraft's predictor line, a conflict is predicted to occur* (at the time that the threat vector reaches your aircraft symbol), unless you deviate from your current course. You will know that this has occurred because your aircraft and the intruder aircraft will highlight (as will their corresponding predictor lines). Said again, if the threat vector touches the intruder's predictor line, you are in a predicted conflict. If the threat vector touches the intruder's aircraft symbol, you are in an actual conflict. ***You should avoid triggering predicted conflicts*** (this is when ATC would intervene to resolve the situation), ***as well as actual conflicts!*** Experimenter: show and discuss Figure 3 illustrations to your pilot: (a) no conflict, (b) predicted conflict, and (c) actual conflict situations.

Any questions so far?

Displays, Symbology and Conflicts

In addition to the schematic drawing in Figure 1, you have been provided with a picture of the actual display that you will be flying in order to familiarize yourself with the display's various components, including the display symbology and coding, and an example of a type of traffic conflict you may encounter.

Display Components (Experimenter illustrate each of the below components on the color picture of display)

- ADI
- HSI (coplanar: top down and forward-looking)
- airspeed indicator
- altimeter
- FFOV or "out-the-window" horizontal bar

The 3 Display Conditions

Throughout the simulation, you will be using three different types of displays (experimenter: show and illustrate the following with Figure 2). The three display types differ only with respect to the following parameters: in one display condition, only ownship had a predictor vector. In the second condition included predictor vectors on both ownship and intruder. In the third condition, predictors appeared on both ownship and the intruder aircraft, in addition to the display of a threat vector.

Display Symbology (experimenter: use color display picture to accompany explanation of the following symbologies):

1. **Grid**: the dots comprising the grid are separated by one mile increments. One grid block is five miles by five miles. The grid is always 5000 feet below ownship's current position. In the display conditions when there is no threat vector indicating ownship's protected zone, you can use the grid to help you in estimating where your protected zone is. For example, the threat vector length is the radius of ownship's protected airspace. It extends the approximately 4 miles into the future, which equals the distance represented by 4 dots on the grid.

2. **Waypoint**: the waypoint will always be at an altitude of 10,000 feet, directly in front of ownship at the beginning of each scenario. Its horizontal position is depicted on the grid.

3. **Ownship**: your aircraft (referred to as ownship) is magenta and begins at an altitude of 10,000 feet.

4. **Traffic (intruder aircraft)**: the intruder aircraft is colored gray under non-conflict conditions. When in a predicted or actual conflict occurs with the intruder, both planes highlight and intruder turns bright yellow.

5. **Predictor lines**: extend from the nose of the aircraft and represent the predicted flight path 45 seconds (4 miles) into the future.

6. **Threat vector**: threat vectors are orange and point in the direction at which you would see the other aircraft pass closest to ownship. The threat vector moves closer to ownship's actual aircraft symbol as time to conflict decreases. The end point of the threat vector moves closer to the intruder aircraft's predictor line as your predicted separation decreases. Therefore avoid contact between the threat vector's endpoint and the intruder's predictor line at all times. Even though this condition does not indicate an actual conflict (loss of separation), it is a condition in which a conflict is predicted to occur if no one maneuvers. Hence ATC would be alerted and would be likely to assume positive control for traffic separation. This is a circumstance you would like to avoid, as it defeats the rules of *free flight*.

7. The distinction between the display symbology for a *predicted conflict*, and for an *actual conflict* are depicted in Figure 3. As demonstrated in Figure 3a, when ownship's threat vector is not

touching intruder's predictor line or aircraft symbol, no conflict is predicted. As illustrated in Figure 3b, a conflict *is* predicted when ownship's threat vector is touching the intruder's predictor or aircraft symbol. In this case, ownship is in a predicted conflict with the intruder. Figure 3c depicts ownship in an *actual* conflict. ***Remember that your task is to avoid engaging in predicted and actual conflicts!***

8. In the display conditions where the threat vector and intruder's predictor line are absent (see fig 2a), you must use your best judgment to avoid predicted and actual conflicts.

9. Solid yellow lines on the forward-looking (bottom panel) view of the HSI: the solid yellow lines represent **current** vertical protected zone boundaries (1500 feet above and below ownship) while dashed yellow lines represent **predicted** protected zone boundaries. (illustrate with figure 4). **Ephi expand on this.**

10. Forward field of view (FFOV) indicator: this horizontal bar across the top of the display represents the visual attentional demands of the "out-the-window" view. An ellipse (visible in figure 1) appears randomly several times throughout each scenario. Assume that you are flying VFR, in which case, your task is to direct your attention to this FFOV representation as often as possible so as to notice the appearance of all ellipses. **How quickly you notice the appearance of each ellipse, in addition to the percentage that you notice, will be used in performance scores. It is very important to notice them and press the spacebar as quickly as possible after the occurrence of one!** When you see each FFOV indicator, press the space bar on the keyboard in front of you. Please position your hand on the pad in front of the keyboard at all times so that the space bar is close at hand.

If you have any questions, please discuss them with your experimenter.

Schedule:

Day 1:

Session 1:
- Statement of Consent
- 9 practice scenarios (3 per display type)
- short break (you may stand up, rest, go to the restroom etc. during this time)
- Mission 1 (10 scenarios)
- short break
- Mission 2 (10 scenarios)
- short break
- Mission 3 (10 scenarios)

Day 2:

Session 2:
- 6 practice scenarios (2 per display type)
- short break
- Mission 4 (10 scenarios)
  - ***NASA TLX Workload scale**
- short break
- Mission 5 (10 scenarios)
  - ***NASA TLX Workload scale**
- short break
- Mission 6 (10 scenarios)
  - ***NASA TLX Workload scale**

- Post-experiment questionnaire
- Payment form/payment
- Thank you!