Proceedings of the 45th Annual Meeting of the Human Factors and Ergonomics Society.
Santa Monica, CA: Human Factors & Ergonomics Society. 2001.

COCKPIT DISPLAY OF TRAFFIC INFORMATION: THE EFFECTS OF TRAFFIC LOAD, DIMENSIONALITY, AND VERTICAL PROFILE ORIENTATION

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Eighteen certified flight instructors from the University of Illinois Institute of Aviation participated in an experiment exploring the design of the Cockpit Display of Traffic Information (CDTI) for free flight. Pilots flew a sequence of flight scenarios to compare the effects of traffic load, dimensionality, and a vertical profile orientation on maneuver frequency, safety, and maneuver efficiency. Climbs and descents were found to be more frequent than other maneuvers. Both the rear-view and 3D displays were safer in terms of predicted conflict avoidance than the side-view display. Climbing maneuvers were more safely implemented with the rear-view and 3D displays than with the side-view display. The lateral efficiency of climbing maneuvers was highest with the rear-view display. Altitude maintenance of lateral/vertical maneuvers was highest with the side-view, then the rear-view, and then lowest with the 3D display. Airspeed efficiency of airspeed maneuvers was highest with the rear-view display. These findings suggest that a rear-view coplanar CDTI may be preferable to either a side-view coplanar or 3D display.

INTRODUCTION

Designers of the national airspace are considering a concept called Free Flight, defined as “a safe and efficient flight operation capability under instrument flight rules in which the operators have the freedom to select their path and speed in real time” (Wickens, Mavor, Parasuraman, & McGee, 1998). Free Flight aims to change the current standards of using analog voice communications and ground-based radar surveillance, to placing more responsibility for air traffic separation in the hands of the pilots themselves monitoring the automated Free Flight system. Several issues have been raised concerning the safety and effectiveness of Free Flight. One main issue involves how the information needed to provide separation from other traffic, should be displayed to the pilots in a manner that provides safe and efficient means to evaluate those hazards and decide upon avoidance maneuvers (Kreifeldt, 1980; Ellis, McGreevy, & Hitchcock, 1987). Such information is to be presented on the Cockpit Display of Traffic Information or CDTI.

The CDTI is an expected evolutionary aspect of Free Flight (Sheldon & Belcher, 1999; Johnson Battiste and Bochow, 2000), but at this time, there is no firm consensus on its appropriate format. One important design issue is the dimensionality of representing the traffic around the aircraft. A 3D perspective CDTI (Ellis et al., 1987, Merwin, Wickens, & O’Brien, 1997) provides an advantage of integrating all three axes of the airspace in a single panel. However, a 3D view can be somewhat ambiguous in representing the precise location and trajectory of aircraft (Wickens, 2000). Coplanar displays which present a map view and a vertical view, on the other hand, allow for ease and precision in making both horizontal and vertical judgments. Potential disadvantages of the coplanar view, however, include the cost of visually scanning between the two panels, the greater demand placed on working memory in retaining values from each panel to be compared or integrated with the other panel, and the cognitive demands required to integrate or reconstruct the 3D environment from the 2D displays (Wickens, Merwin, & Lin, 1994).

In comparing traffic detection and avoidance performance between the 3D display and the 2D coplanar display, such as those shown in figure 1a and 1b, researchers have found that overall performance advantages in avoiding pre-defined protected zone conflicts were supported by the coplanar format relative to the 3D format (Merwin *et al*., 1997). Furthermore, the coplanar format fostered more flexible maneuvering strategies, providing greater separation between ownship and other traffic. In this case, integrating across the two panels of the coplanar display was less detrimental to performance, than was the ambiguity of the 3D view. However, only a limited number of aircraft were used throughout the experiment while the potential number of aircraft on a display has increased dramatically (Johnson, Battiste, & Bochow, 1999). Increasing the number of aircraft, resulting in a more complex, cluttered traffic environment might require more integration or visual scanning between the two panels of the coplanar display, therefore reducing, and possibly reversing the advantage seen by Merwin *et al*., for the coplanar over the 3D format.

In addition to traffic density, and display dimensionality, a third issue addressed in the current study concerns the orientation of the vertical view in the coplanar display. Figure 1b shows the “behind” vertical view used by Merwin *et al*. in which both the plan view and the profile view represent “left” of the aircraft to the left of the display. Thus each traffic symbol in its vertical depiction on the bottom, is directly positioned under its counterpart on the lateral display. In contrast, the side view in figure 1c shows a longitudinal depiction of the flight path; therefore, aircraft are not matched on a one-to-one basis across the two panels. This representation would appear to be disadvantageous for understanding the 3D locations of multiple traffic aircraft because it amplifies the visual search/scanning cost associated with 2D coplanar displays. However, it is examined because such a view appears to be relatively popular, as aviation designers are considering the implementation of “vertical situation displays” in the cockpit (e.g., DeJonge, 2000; Oman, Kendra, Hayashi, Stearns, & Burki-Cohen, 2001). No study has directly compared these two views in a single experiment; however, a between-experiment comparison did reveal the apparent advantage of the “behind view” of figure 1b. (Olmos, Wickens, & Chudy, 2000). This research, however, did not involve traffic maneuvering.

In contrasting display formats to support conflict avoidance maneuvers, an important issue is the type of maneuver chosen (e.g., climbs, turns), and how these might be influenced by the display format (Wickens et al., in press). For example, Ellis et al. (1987) reported that the incorporation of the vertical depiction in the 3D display led to more frequent vertical maneuvering.

Thus, the current study was designed to assess how differences in the format of the display (3D, rear-view, side-view) affected the safety and efficiency of traffic avoidance, different maneuver choices, and whether these effects were moderated by traffic density.

METHODS

Eighteen certified flight instructors from the University of Illinois Institute of Aviation flew a sequence of flight scenarios designed to compare the three formats of the CDTI. The mean number of flight hours was 1206 hours, with a mean of 237 instrument flight hours. The experiment was conducted on a low fidelity flight simulator consisting of a Silicon Graphics Iris Octane workstation, a Silicon Graphics 20-in. color display screen, and a flight stick controlling pitch, roll, and throttle.

Traffic Symbology

The CDTI presented ownship and traffic, each with 45-second predictor lines. Symbology developed by Merwin *et al*. (1997) was employed to graphically present information regarding the degree of conflict and time until the loss of separation with any traffic aircraft converging on ownship. This loss of separation was defined as penetration of a cylindrical protected zone around ownship, 1500 feet above and below and 3 miles in radius.

Displays

*3D Format***.** The 3D display shown in figure 1a depicted an integrated view of the three spatial dimensions viewed from an exocentric position above and behind ownship, with an elevation angle of 45°, and an azimuth offset of 10°. This azimuth offset was used so that ownship’s predictor line would not lie on the line-of-sight projection. The display showed the previously described symbology along with droplines to unambiguously show the horizontal positions and relative altitudes of the aircraft icons and the ends of the predictive lines.

Coplanar Formats. The coplanar displays shown in figures 1b and c consisted of two windows offering a horizontal, top-down (X-Z axes) view and either a vertical, forward-looking (X-Y axes) or vertical, side-looking (Y-Z axes) view projected orthogonally (without perspective information). The horizontal display showed the previously

a)

b)

c)

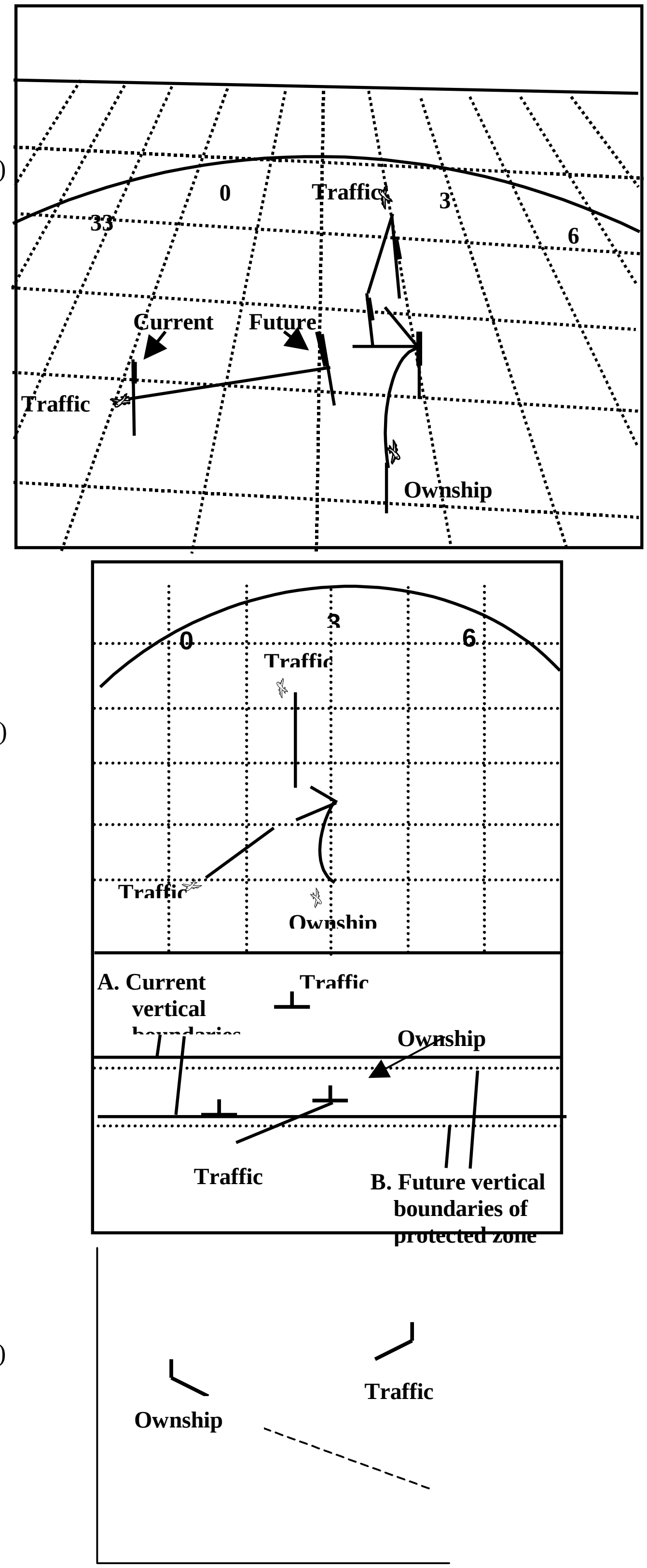


Figure 1. Three display versions of the CDTI: (a) 3D, (b) 2D coplanar rear-view, (c) 2D coplanar side-view. The rendering of the side view profile in (c) is not what participants actually saw, but is a schematic designed to highlight the different orientation from figure (b).

described symbology overlaid on a grid of equi-spaced lines representing 5 mile increments. Both vertical displays contained two sets of horizontal lines indicating the altitude boundaries of ownship's protected zone.

Task

The task involved flying direct routes to predetermined waypoints while encountering other aircraft. The pilot determined what maneuvers were necessary to avoid conflict with the other aircraft, while minimizing deviations in speed, heading, and altitude from pre-specified target values. After determining that the conflict had been resolved, the pilot returned to the flight path to intercept the predetermined waypoint. Two independent variables were manipulated within subjects. Display type was manipulated by providing the coplanar forward-looking, coplanar side-looking, or 3D display (figure 1). Traffic level was manipulated by including 2, 6, or 10 aircraft besides ownship.

Each trial, regardless of traffic level, contained one primary (actual) and one secondary (predicted) conflict. The actual conflict traffic required maneuvering to be avoided. The predicted conflict traffic was on such a trajectory that a careless maneuver to avoid the actual traffic conflict could produce a loss of separation with the predicted conflict. Thus, its trajectory needed to be considered in implementing the avoidance maneuver. Conflict aircraft randomly approached from six different horizontal angles: 45°, 90°, and 135°, from both the left and the right. Conflict aircraft also approached at the same altitude, from below, or from above. Randomly varying the geometry of the traffic encounters both horizontally and vertically without replacement, as indicated above, allowed testing to occur across a variety of possible situations. All other traffic was of sufficient lateral or vertical separation so that it was very unlikely to conflict. However, pilots could not determine this without carefully attending to the altitude of this traffic.

Design

Pilots flew a series of 18 trials according to instrument flight rules. Each pilot flew two replications of the 9 trials, formed by the 3x3 combination of traffic load (low, medium, high) and display format. Full counterbalancing was completed across the 18 subjects.

RESULTS

Maneuver Frequency

The raw data was used to create graphs which were examined to determine the types of maneuvers chosen by pilots for each trial. Maneuvers were categorized as being lateral, descents, climbs, airspeed, or lateral/vertical according to the pilot's control inputs and flight parameters Figure 2 presents maneuver frequencies by display type. The figure illustrates the clear dominance of vertical over lateral maneuvers, with a slight preference for climbs over descents. This replicates the effects observed by Wickens, Helleberg, and Xu (2001).

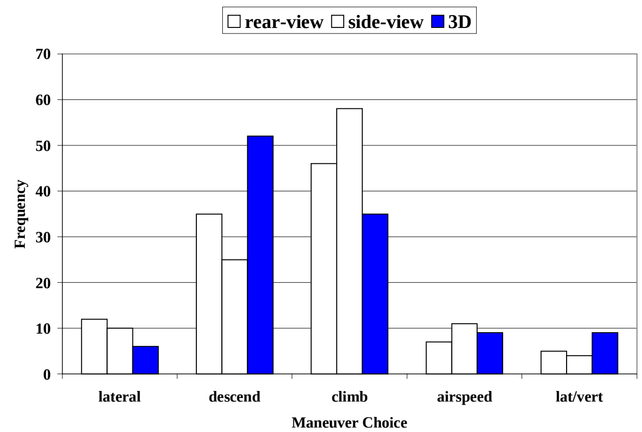


Figure 2. Maneuver frequencies by display type.

Safety

The time spent in a "predicted conflict" (loss of separation within 45 seconds if no maneuver was taken) was the primary measure of safety. The time spent in an "actual conflict" was not used because such occurrences, while highly correlated with predicted conflicts, occurred very rarely. These data were analyzed in two ANOVA's, one examining display dimensionality including the 3D and rear-view display, replicating the study of Merwin et al. The second, examining the effect of vertical view, included only the two coplanar displays. A log transformation of the mean seconds per trial spent in predicted conflict was performed to normalize the data. A 2(display type: rear-view/3D) x 3(traffic load: 2/6/10) ANOVA revealed no significant differences. A 2(display type: rear-view/side-view) x 3(traffic load: 2/6/10) ANOVA revealed that the rear-view display supported marginally significant superior conflict avoidance performance over the side-view display, $F(2, 175) = 2.843$, $p < .10$.

Safety was further explored by looking at the amount of time spent in a predicted conflict across display type as a consequence of making certain avoidance maneuvers. ANOVA results revealed a marginally significant effect within climbing maneuvers such that climbs were more safely implemented while using the 3D or rear-view display than when using the side-view display, $F(2, 114) = 2.62$, $p < .10$.

Maneuver Efficiency

How display format affected maneuver efficiency was examined as a function of the type of maneuver chosen, focusing separately on climbs, combined lateral/vertical, and airspeed maneuvers (no significant differences were found for lateral maneuvers or descents). Efficiency was assumed to be greatest if pilots deviated the smallest amount from the target altitude, airspeed and heading values.

A series of ANOVA's were conducted to determine the effects of these specific maneuvers on efficiency across the three display types. Workload was not included because it had no significant effects across all maneuver types. Figure 3 presents the mean absolute heading deviation of climbing maneuvers by display type. A log transformation was performed to normalize the data. The lateral efficiency of climbing maneuvers was significantly affected by display type, $F(2, 125) = 4.33$, $p < .05$, such that efficiency was highest with the rear-view display, somewhat lower with the side-view display, and lowest with the 3D display. No other significant effects were found for lateral efficiency.

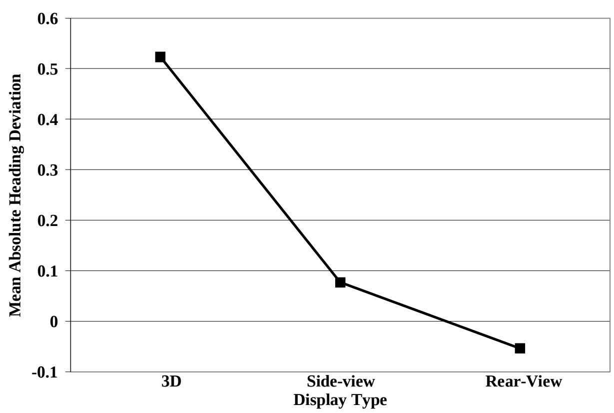


Figure 3. Mean absolute heading deviation of climbing maneuvers by display type.

Figure 4 presents the mean absolute altitude deviation of combined lateral/vertical maneuvers by display type. Workload was not included because it had no significant effects across all maneuver types. Altitude maintenance of combined lateral/vertical maneuvers was best with the side-view display, then the rear-view, and worst with the 3D display, $F(2,11) = 8.76$, $p < .01$.

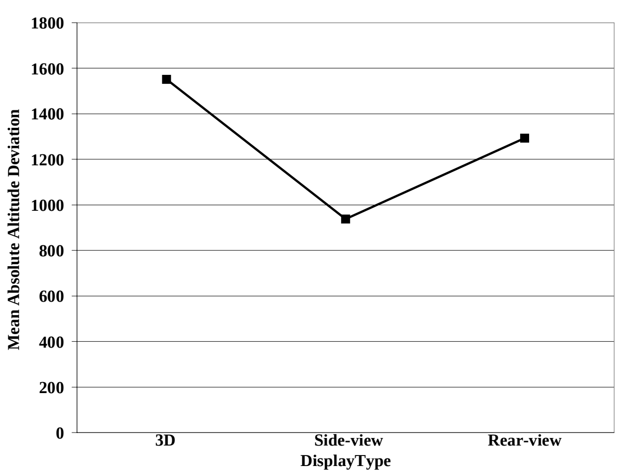
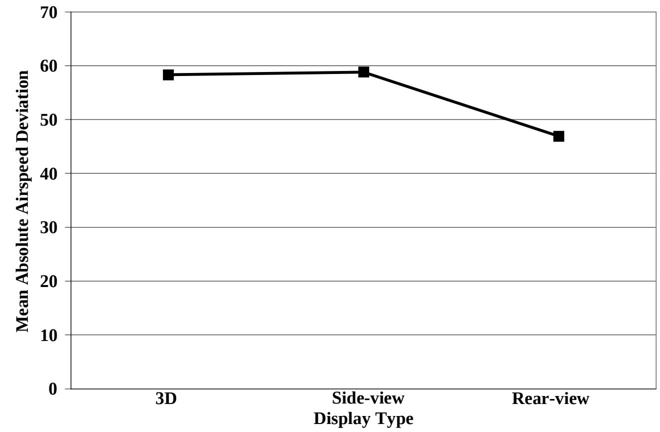


Figure 4. Mean absolute altitude deviation of combined lateral/vertical maneuvers by display type.

Figure 5 presents the mean absolute airspeed deviation of airspeed maneuvers by display type. Airspeed



efficiency was affected by airspeed maneuvers in that efficiency was greatest with the rear-view display, $F(2,23) = 3.93$, $p < .05$. Also, a 3(display type) x 3(traffic load) ANOVA revealed a marginally significant effect of traffic load, $F(2, 315) = 2.82$, $p < .10$.

Figure 5. Mean absolute airspeed deviation of airspeed maneuvers by display type.

DISCUSSION

The purpose of this study was to examine the effects of dimensionality and traffic load on safety, in terms of conflict avoidance performance, maneuver choice, and maneuver efficiency. The results reveal the superior conflict avoidance performance of the rear-view and 3D displays over the side-view display. This was shown by the finding that the mean time spent in predicted conflict was of marginally higher for the side-view display than the rear-view display. Performance with the rear-view display was not significantly different than the 3D display; therefore, the 3D display also supported superior performance than the side-view display. These results were expected according to the idea that the side-view display did not utilize a one-to-one matching of aircraft across the two display panels, and therefore invoked a more demanding visual scan process. The results also show superior conflict avoidance performance on the rear-view and 3D displays compared to the side-view display when implementing climbing maneuvers.

The rear-view display supported the highest lateral efficiency when implementing climbing maneuvers. This was shown in that the mean absolute heading deviation was greater for the side-view and 3D displays than the rear-view display. An explanation for this could be that pilots had redundant heading information between the two panels when using the rear-view display, while only the top-down panel contained heading information for the side-view display, and the 3D display only had one representation of heading information within its single panel. This means that pilots had to scan between panels to gauge heading and altitude concurrently while using the side-view display, and only had one source of heading information with the 3D display.

Altitude maintenance of combined lateral and vertical maneuvers was best with the side-view display, then the rear-view, and then worst with the 3D display. The side-view display allowed pilots to integrate altitude and position along the flight path on a longitudinal scale. Neither the rear-view nor the 3D display depicted this information as clearly as the side-view display. It is important to note, however, that the rear-view display supported superior altitude maintenance to the 3D display. This could have been due to how altitude was coded in the different displays, in that maintaining altitude with the unambiguous horizontal lines across the vertical profile of the rear-view display was easier than comparing relative altitudes depicted ambiguously on drop-lines in the 3D display. This finding clearly shows that complex maneuvers exacerbate the problem of ambiguity associated with 3D displays.

The finding that lateral and vertical efficiency is better with the rear-view than the 3D display replicates several previous findings. For instance, Boyer, Campbell, May, Merwin, and Wickens (1995) found that avoidance paths were slightly longer and farther away from hazards with a 3D display compared to a 2D display. May, Campbell, and Wickens (1996) also found that maneuvers were less efficient with the 3D display. In particular, Wickens, Miller, and Tham (1996) found an efficiency cost associated with 3D displays for complex maneuvers.

The effects of workload in the current study were surprisingly small. In particular, we did not find that increasing workload significantly disrupted performance with the coplanar displays relative to the 3D display. However, workload did exert at least one important effect, in terms of airspeed deviation. Increasing the number of aircraft caused the mean absolute airspeed deviation to increase marginally across all displays. This means that the primary tasks of avoiding predicted conflicts and maneuvering efficiently kept pilots from monitoring their airspeed under high workload conditions.

The following table summarizes the overall findings according to display type and dependent measure.

	Rear-view	Side-view	3D
Safety	+	-	+
Lat. Eff.	+	**0**	-
Vert. Eff.	**0**	+	-
Air Spd. Eff.	+	**0**	**0**
	3	**0**	**-1**

Table 1. Summary.

A plus score means that the display supported the best performance on that dependent measure. A score of 0 means that the display supported neutral, or second-best, performance, while a minus score means the display revealed the worst performance on that measure. Instances in which performance levels are the same for different display types are indicated by the same table scores. For example, the rear-view and 3D displays supported similar high-safety performance ratings, as indicated by the two plus scores; therefore, there was no "second-best" display and the side-view received a minus score for showing the worst performance. These findings suggest that a rear-view coplanar CDTI may be preferable to either a side-view coplanar or a 3D display.

ACKNOWLEDGMENTS

This research was supported by contract NASA-NAG-2-1120 from the NASA Ames Research Center, for which David Foyle was the technical monitor. The authors wish to thank Ron Carbonari for his software development and post-processing contributions.

REFERENCES

Boyer, B., Campbell, M., May, P., Merwin, D. & Wickens, C.D. (1995). Three-dimensional displays for terrain and weather awareness in the national airspace system. *Proceedings of the Human Factors and Ergonomics Society 39th Annual Meeting* (pp. 6-10). Santa Monica, CA: HFES.

DeJonge, M. (2000). Displaying the FMS vertical profile. In *Proceedings of the 2000 World Aviation Conference* (2000-01-5615). Anaheim, CA.

Ellis, S.R., McGreevy, M.W., & Hitchcock, R.J. (1987). Perspective traffic display format and airline pilot traffic avoidance. *Human Factors, 29,* 371-382.

Johnson, W.W., Battiste, V., & Bochow, S.H. (1999). A cockpit display designed to enable limited flight deck separation responsibility. In *Proceedings of the 1999 World Aviation Conference* (1999-01-5567). Anaheim, CA.

Kreifeldt, J.G. (1980). Cockpit displayed traffic information and distributed management in air traffic control. *Human Factors, 22*(6), 671-691).

May, P.A., Campbell, M., & Wickens, C.D. (1995). Perspective displays for air traffic control: Display of terrain and weather. *Air Traffic Quarterly,3,* 1-17.

McGreevy, M.W. & Ellis, S.R. (1986). The effect of perspective geometry on judged direction in spatial information instruments. *Human Factors, 28,* 439-456.

Merwin, D.H., Wickens, C.D., & O'Brien, J.V. (1997). Display format-induced biases in air traffic avoidance behavior. *Proceedings of the World Aviation Congress* (98WAC-71). Warrendale, PA: Society of Automotive Engineers, Inc.

Olmos, O., Wickens, C.D., & Chudy, A. (2000). Tactical displays for combat awareness: An examination of dimensionality and frame of reference concepts and the application of cognitive engineering. *The International Journal of Aviation Psychology, 10,* 247-271.

Oman, C., Kendra, A., Hayashi, M., Stearns, M., & Burki-Cohen, J. (2001). Vertical navigation displays: Pilot performance and workload during simulated constant angle descent GPS approaches. *International Journal of Aviation Psychology, 11,* 15-32.

Shelden, S. & Belcher, S. (1999). Cockpit traffic displays of tomorrow. *Ergonomics in Design, 7,* 4-9.

Wickens, C.D., Helleberg, J., & Xu, X. (1999). Maneuver choice in free flight. *Proceedings of the 1999 World Aviation Conference* (1999-01-5591). Anaheim, CA.

Wickens, C.D., Mavor, A.S., Parasuraman, R., & McGee, P. (1998). Airspace system integration: The concept of free flight. In *The future of air traffic control.* Washington DC: National Academy Press.

Wickens, C.D., Merwin, D.H., & Lin, E. (1994). Implications of graphics enhancements for the visualization of scientific data: Dimensional integrality, stereopsis, motion, and mesh. *Human Factors, 36*, 44-61.

Wickens, C.D., Miller, S., & Tham, M. (1996). The implications of data-link for representing pilot request information on 2D and 3D air traffic control displays. *International Journal of Industrial Ergonomics, 18*, 283-293.