

# Perspective and Coplanar Cockpit Displays of Traffic Information: Implications for Maneuver Choice, Flight Safety, and Mental Workload

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In 3 experiments, we examined maneuver choice, flight safety, and mental workload across 3-dimensional (3D) perspective and 2-dimensional coplanar cockpit displays of traffic information in a free-flight simulation. In Experiment 1 (30 pilots), we examined dimensionality issues; in Experiments 2 and 3 (18 pilots each), we examined the effects of traffic density, dimensionality, and vertical profile orientation. Collectively, these data may be modeled by trade-offs between the display types: The coplanar suite suffers from scanning-related integration that increases with conflict density; the 3D display suffers from perceptual ambiguity. This research informs our understanding of how displays modulate performance in free-flight environments.

The cockpit display of traffic information (CDTI) is a tool that is designed to support the pilots' traffic awareness (Johnson, Battiste, & Bochow, 1999; Kreifeldt, 1980; Wickens, Helleberg, & Xu, 2002). In its most radical conception, it is intended to support the pilots' tactical and strategic maneuvers to avoid conflicts in a "free-flight" airspace, thereby replacing the air traffic controller's responsibility in directing traffic. In a less radical conception, it is designed

merely to provide the pilot with shared awareness of traffic to that possessed by the controller and thereby to aid the two agents in collaborative problem solving and decision making (Wickens, Mavor, Parasuraman, & McGee, 1998). In current airspace, those more radical goals are achieved through the traffic alert and collision avoidance system (TCAS), which commands the pilots to make tactical emergency maneuvers in the vertical axis should a collision be imminent. The less radical goals are achieved typically through pilot requests to alter routes.

A relatively extensive body of research has explored the ideal symbology for a CDTI (e.g., Hart & Loomis, 1980; Johnson et al., 1999; Wickens, Gempfer, & Morphew, 2000). Other research has examined the effectiveness of the CDTI in supporting the pilots' task of traffic detection and avoidance when this support has been contrasted with that of air traffic control (ATC; Battiste & Ashford, 2000; Prinzo, 2001; Wickens, Goh, Horrey, Helleberg, & Talleur, 2003; Wickens et al., 2002). Still other research has examined the effectiveness of the CDTI in supporting the more radical versions of free flight (Hoekstra & Bussink, 2002). In the research we report here, we examined one very specific aspect of the format question in three low-fidelity simulations: What is the optimum viewpoint of the CDTI image generator to represent the three-dimensional (3D) volume of space through which the pilot's ownship and surrounding aircraft fly? In these experiments, we contrasted two viewpoint configurations: an exocentric 3D viewpoint looking down on the ownship from behind, and a two-dimensional (2D) coplanar viewpoint presenting a top (map or "God's eye") view and a side (or rear) 2D vertical situation display.

The rationale for choosing a 2D view is that it closely mimics the pilot's conventional navigational display coupled with a vertical profile display that has been long advocated in the cockpit (see Fadden, Braune, & Wiedemann, 1993). The rationale for considering a 3D viewpoint is simply that the airspace through which a pilot may need to maneuver for either tactical or strategic conflict avoidance is a 3D one. Indeed, the seeds for considering a 3D CDTI were planted in a study by Ellis, McGreevy, and Hitchcock (1987) who contrasted a 3D CDTI with a conventional uniplanar 2D map display. Ellis et al. found that the former view not only provided safer conflict avoidance maneuvers but also encouraged more vertical maneuvers, consistent with the logic offered by TCAS. Vertical maneuvers have the advantage in conflict avoidance of being more effective in time-critical situations (Krozel & Peters, 1997; Wickens et al., 2002). However Ellis et al. did not couple their plan view display with a vertical situation display (VSD), and so it is possible that the experimental differences observed between the two could have resulted from the absence of analog vertical information in the 2D view rather than from its inherent 2D format.

The relative costs and benefits of 3D displays and their coplanar counterparts have been evaluated elsewhere for tasks of flight path guidance (Haskell & Wickens, 1993), terrain representation (Hickox & Wickens, 1999; Olmos, Liang,

& Wickens, 1997; St. John, Cowen, Smallman, & Oonk, 2001; Wickens, Liang, Prevett, & Olmos, 1996; Wickens & Prevett, 1995), and generic data representation (McCormick & Wickens, 1995; St. John et al., 2001; Wickens, Merwin, & Lin, 1994). A general conclusion that has emerged from a synthesis of this research (Wickens, 2000a, 2000b, 2003) is the existence of task-display dependencies. The 3D display tends to invite poorer judgments of relative and absolute distance and motion along the orthogonal horizontal and vertical planes because of the presence of ambiguity whenever a 3D volume of space is mapped to a 2D viewing surface (Gregory, 1977; McGreevy & Ellis, 1986; Wickens, Todd, & Seidler, 1989). For example, Wickens, Miller, and Tham (1996) observed that the costs of a 3D ATC display only emerged when aircraft trajectories were simultaneously transitioning all three axes of space, thereby creating greater opportunities for such ambiguity. (One may note a slight paradox here in that the problems with the 3D display are observed precisely when aircraft motion is in three dimensions.)

At the same time, however, a 3D display is found to have greater “pictorial realism” (Roscoe, 1968) and present a more intuitive picture of the airspace. Such realism is particularly helpful when the picture presented on the display may need to be compared with the actual world scene (Hickox & Wickens, 1999). Furthermore, by integrating lateral and vertical planes into a single picture, the 3D display mitigates the visual scanning and “cognitive work” that may be required to integrate the various axes of motion and appreciate the general orientation of a 3D vector of motion (even if it may disrupt the precise evaluation of that motion). Only one study (Vierra & Wickens, 1996) was conducted to contrast the effectiveness of the two display formats in a traffic avoidance task. However, the authors displayed both traffic and weather, thereby creating a cluttered display.

Whereas 3D displays yield both costs and benefits to *performance* (here defined as safety and efficiency) in aerospace tasks, they may also impose another effect in a free-flight environment by qualitatively influencing the kind of maneuver that a pilot may choose to avoid a conflict. Several investigators have noted a variety of influences on the decision to maneuver laterally, vertically, or by adjusting airspeed in conflict avoidance choices (for a summary, see Alexander & Wickens, 2002; Wickens et al., 2002). Furthermore, as noted, Ellis et al. (1987) found that the analog representation of altitude present in the 3D display but absent in their plan view map display induced a greater preference for engaging in vertical maneuvers. Such format-induced choices have not, however, been examined in a contrast between 3D and coplanar 2D displays. One might expect that a coplanar display presenting an unambiguous representation of the vertical axis might induce an even stronger preference for maneuvering on this axis. Thus, in this article, we ask four primary research questions.

1. Does the format of the CDTI (coplanar vs. 3D) invite maneuver preferences, perhaps favoring vertical maneuvers with a coplanar display?

2. Does the format influence the safety of whatever maneuvers are chosen in which *safety* is defined, operationally, as the ability to avoid close passage to or loss of separation with a traffic aircraft?

3. If displays are found to differ in safety (as in Number 2), then does the display type induce pilots to choose maneuvers for which those displays are particularly safe? This question asks whether users will choose the maneuver that is shown to be particularly safe with a given display format even though it may not be the safest maneuver overall.

4. Does the orientation of the VSD (rear view vs. side view) influence the types of maneuvers chosen in avoiding conflicts as well as their relative safety?

We asked these research questions in three experiments. In Experiment 1, we varied the elevation angle of the 3D display and kept traffic problems quite simple, with only a single conflict aircraft. In Experiments 2 and 3, we increased traffic density of nonconflict aircraft (Experiment 2) and conflict aircraft (Experiment 3). In both Experiments 2 and 3 we also incorporated an additional experimental manipulation defined by the orientation of the plan view VSD. Most VSDs that are currently being considered for altitude representation present a view from beside the ownship, integrating vertical and longitudinal (i.e., along-path) information (Oman, Kendra, Hayashi, Stearns, & Burke-Cohen, 2001). However, some evaluations have considered a VSD pictured from behind the ownship, providing the same forward-looking viewpoint as the attitude indicator (e.g., Scallen, Smith, & Hancock, 1996). This difference too is hypothesized to influence both the choice of maneuvers as well as their safety.

## EXPERIMENT 1

### Method: Experiment 1

In Experiment 1, 30 certified flight instructors flew a series of conflict avoidance maneuvers on a low fidelity Silicon Graphics (Silicon Graphic, Inc., Mountain View, CA) based flight simulator with one of three display types. A coplanar display (Figure 1a) presents a plan view above and a profile view below, the latter represented from a viewpoint behind the ownship. The 3D perspective display (Figure 1b) was presented with either a 60° or 30° elevation angle.

On any given trial, there was a 67% chance that an “intruder” aircraft would penetrate the protected zone around the ownship (5 nautical miles [nm], 1,000 ft) if an avoidance maneuver was not undertaken. The conflict geometry involved a random mix of intruder overtaking, crossing, or approaching from the left or right and climbing, descending, or level. Each pilot participated in two sessions of 60 trials each, with each conflict trial lasting approximately 120 sec. During the first session only, a single intruder was present. During the second session, a second traffic

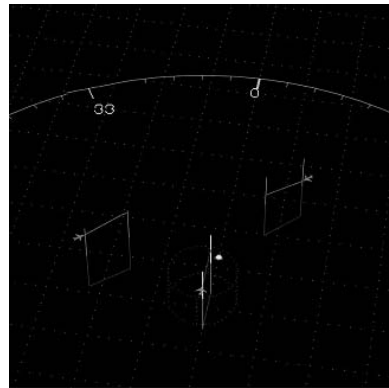
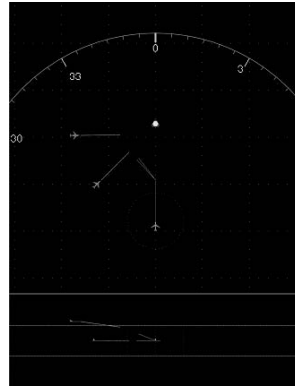


FIGURE 1 (a) Representation of the two-dimensional coplanar display with a rear-view vertical situation display panel; (b) three-dimensional perspective display. The text on the displays was not present for the pilots' viewing.

intruder was present. The second intruder was not initially on a conflict course, but maneuvers around the primary intruder needed to consider the geometry of the second. Airspeed was fixed at 325 knots (kt), but pilots could control heading and altitude via roll and pitch through conventional flight dynamics.

*Displays.* In all displays (Figure 1), predictor vectors on all traffic portrayed a 45-sec predictor span. A vector was drawn extending from the ownship's predictor in the direction of the intruder at the anticipated time of closest passage. The length of this "threat vector" was equal to the size of the protected zone. Thus, if the threat vector touched the intruder's predictor line, this event signaled that the ownship was projected to penetrate the protected zone of the traffic in the near future. This condition was highlighted on the display by a change in coloration of the symbology and was designated as a *predicted conflict*. An actual loss of separation resulted when the threat vector of the ownship touched the traffic. Identical symbology (predictor and threat vectors) was replicated on the lateral and vertical views of the coplanar display. The perspective (3D) display presented analogous

symbology but integrated this into a single view, placing aircraft atop “droplines” to a common base altitude (Ellis et al., 1987; St. John et al., 2001). The displays depict a region of approximately 25 nm ahead of the ownship.

*Task.* Pilots were cautioned to fly as directly as possible to a way point located on the far side of the traffic at 10,000 ft but to avoid creating actual or predicted conflicts. In a free-flight regime, the latter event, for example, might signal the required intervention by the ATC, a circumstance that would defeat the purpose of free flight.

*Design.* Each of the 30 pilots were randomly assigned to one of the three display conditions. Pilots encountered 36 conflicts presenting the various conflict geometries in random orders without replacement.

## Results and Discussion: Experiment 1

Full results of Experiment 1 are described in Merwin and Wickens (1996). In this writing, we highlight the most important significant differences relating to maneuver choice, flight safety, and subjective mental workload.

*Maneuver choice.* In general, across all displays and conflict geometries, pilots chose to maneuver vertically more than laterally as indicated by the difference in mean vertical (greater) and lateral (less) trajectories around the conflict. This preference may reflect the fact that control dynamics are of lower order (and hence, easier) in the vertical axis, the fact that vertical maneuvers are the most time efficient (Krozel & Peters, 1997), or the fact that there was no ATC simulation in this paradigm, freeing pilots from responsibility of obtaining clearance for the necessary change in flight level. The coplanar display significantly enhanced the tendency to choose vertical over lateral maneuvers, although this difference was not as marked in the perspective displays. Furthermore, there appeared to be an overall preference for climbs in the coplanar and 60° perspective displays, whereas descents were generally preferred with the 30° perspective display. Also, pilots who used the coplanar display tended to maneuver vertically in the opposite direction to the traffic’s vertical behavior, whereas those who used the perspective displays tended to maneuver in the same direction (i.e., climb if the traffic was climbing, descend if it was descending).

*Flight safety.* The operational definition of safety used in this research was inversely related to the time spent in predicted conflict (loss of separation within 45 sec if no maneuver was taken). The results generally indicated that the coplanar display supported safer conflict resolution. Pilots who flew with the coplanar display showed 20% fewer predicted conflicts with the primary traffic,  $F(2, 27) = 3.06, p <$

.06, and 8.5% fewer actual conflicts with the secondary traffic,  $F(2, 27) = 6.55, p < .01$  (see Table 1). An important characteristic of the latter differences is that the greater rate of conflicts for pilots with the perspective display was only shown when the primary traffic was nonlevel (descending or ascending), a more difficult perceptual problem and similar to the finding of selective 3D display costs observed for air traffic controllers by Wickens, Miller, and Tham (1996). Differences between the 30° and 60° perspectives are discussed in Merwin and Wickens (1996), although in general, the 60° perspective supported better performance.

The intruder geometry also influenced flight safety. Thus, there were more conflicts when the intruder approached from the left,  $F(1, 28) = 6.35, p < .02$ ; when the intruder approached from the front,  $F(2, 27) = 3.61, p < .04$ ; and when the intruder passed ahead rather than behind the ownship,  $F(1, 28) = 3.78, p = .06$ .

*Subjective mental workload.* After completion of each experimental session, pilots provided ratings on the level of subjective mental workload experienced performing the task using the National Aeronautic and Space Administration (NASA) Task Load Index (TLX) scale (Hart & Staveland, 1988). A nonsignificant trend in the ordering of the means for the three display types, with the lowest workload ratings associated with the coplanar display, matched the ordering revealed in the proportion of predicted conflict data discussed previously (see Table 1). Comparing the coplanar display workload to the combined mean of the perspective displays indicated a marginally significant lower level of workload for the former,  $F(1, 28) = 3.64, p = .067$ .

### EXPERIMENTS 2 AND 3

Realistic applications of a CDTI with a broad range of coverage could yield a considerably greater density of traffic than the one or two intruders in Experi-

TABLE 1  
 Predicted and Actual Conflict Rate(Proportion of Trials) by Display Type and Relative Altitude of Traffic

	Coplanar (%)	Perspective (%)	
		60°	30°
Primary traffic			
Predicted conflicts	56	83	70
Secondary traffic			
Total	6	10	17
Actual conflicts			
Level	0	0	0
Nonlevel	8	13	24

ment 1. With this in mind, we hypothesized that to the extent that conflict avoidance judgments are hindered by the clutter of irrelevant items on a display, this cost of clutter with increasing traffic load may be amplified in the 2D coplanar display because the number of displayed elements will grow with traffic load at twice the rate as with the integrated 3D display. Thus, coplanar costs may emerge at high workload levels relative to the 3D display, which have only a single element representing each aircraft.

A second issue examined in Experiments 2 and 3 involves the vertical profile orientation of the 2D VSD. A forward-looking view represents the ownship from behind such that each traffic symbol in its vertical depiction on the bottom panel can be directly positioned below its counterpart on the lateral display (see Figure 1a). The side-looking view (Figure 2), in contrast, shows a longitudinal depiction of the flight path that does not allow for a consistent vertical alignment of the two traffic symbols representing each intruder. Side-view displays are being developed and are available in advanced commercial aircraft to represent distance from terrain and profile descents (Jacobsen, Chen, & Wiedemann, 2002), and they already exist in static form on approach plates. It is therefore logical to explore the implications of representing traffic on these displays.

## EXPERIMENT 2

### Method: Experiment 2

The general procedures in Experiment 2 were quite similar to those in Experiment 1. In Experiment 2, 18 certified flight instructors flew a sequence of flight scenarios to compare the effects of traffic load, dimensionality, and a vertical profile orientation. Two coplanar displays, one with a rear view and one with a

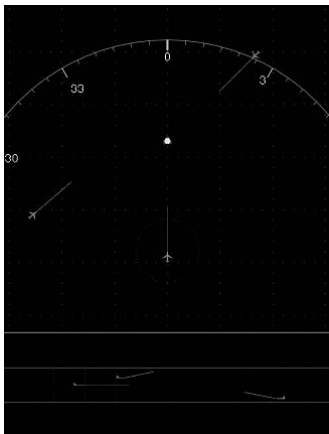


FIGURE 2 Representation of the two-dimensional coplanar display with a side-view vertical situation display panel. The text on the display was not present for the pilots' viewing.

side view vertical profile orientation as well as a 3D perspective display with a 45° elevation angle, were employed in this experiment. The rear-view display was presented as in the bottom panel of Figure 1a. The side-view display presented the same vertical extent but portrayed a distance ahead of the ownship of 24 nm (as shown in Figure 2). Every trial was designed to put the pilot in predicted conflict with one aircraft and an actual conflict with another aircraft (penetration of the ownship's protected zone: 6 nm, 3,000 ft) if an avoidance maneuver was not employed. The total number of aircraft was systemically increased across trials (2, 6, or 10 planes) to induce increased workload levels and determine how this increased load modulated differences in display format effects on maneuver choice and safety. Pilots were instructed to fly to a predetermined way point as directly as possible at an altitude of 12,000 ft and an airspeed of 350 kt.

## Results and Discussion: Experiment 2

As in Experiment 1, performance measures reported here include maneuver choice, flight safety, and subjective mental workload ratings. Refer to Alexander and Wickens (2001) for the full results of Experiment 2.

*Maneuver choice.* Figure 3 presents the distribution of maneuver frequencies chosen by pilots as a function of display type. The figure illustrates the clear dominance of vertical over lateral maneuvers,  $\chi^2(1, N = 324) = 97.8, p < .01$  with a slight preference for climbs over descents,  $\chi^2(1, N = 251) = 2.9, p < .10$ . Both of these trends replicate the effects observed by Wickens et al. (2002) in a full mission simulation with the rear-view coplanar CDTI and were also representative of the majority of participants (16 out of 18: 3 pilots showed a preference at  $p < .01$ , 6 at  $p < .05$ , 2 at  $p < .10$ , and 5 at  $p > .10$ ). Furthermore, pilots chose to climb with both the 2D coplanar and 3D displays when the intruding traffic descended,  $\chi^2(1, N = 31) = 17.1, p < .01$ ,  $\chi^2(1, N = 17) = 4.76, p < .05$ , respectively. However, pilots who used the 3D display tended to descend when traffic climbed,  $\chi^2(1, N = 39) = 11.3, p < .01$ , whereas pilots who used the 2D displays did not. The finding that pilots maneuvered in the opposite direction of the intruding traffic with the 3D display was in conflict with the finding in Experiment 1 that pilots tended to maneuver in the same direction as the intruding traffic.

Vertical maneuvers were further explored by examining whether display dimensionality modulated maneuver preferences as had been observed by both Ellis et al. (1987) and in Experiment 1. This issue was examined by several contrasts. First, vertical maneuvers were equally preferred across all displays ( $M = 26\%$ ), although this finding was inconsistent with the finding in Experiment 1 that the coplanar display enhanced the tendency to maneuver vertically more so than the 3D display. Second, within the vertical maneuvers, it appeared that display

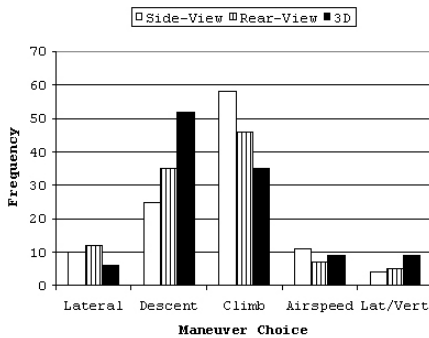


FIGURE 3 Maneuver frequencies by display type. 3D = three dimensional; Lat = lateral; Vert = vertical.

dimensionality influenced the tendency to climb versus descend. These comparisons showed that the side-view display elicited significantly more climbing than descending maneuvers,  $\chi^2(1, N = 83) = 13.1, p < .01$ . The rear-view display showed the same trend, although it was not significant,  $\chi^2(1, N = 81) = 1.49, p > .10$ . In contrast, the 3D display supported more descending (60%) than climbing (40%) maneuvers,  $\chi^2(1, N = 87) = 3.32, p < .10$ . Stated in other terms, the 3D display induced a marginally significant descent preference and climb aversion that was not only absent with the rear view coplanar display but reversed with the side view coplanar display.

**Flight safety.** The time spent in an actual conflict was not analyzed because although it was highly correlated with predicted conflicts, it occurred very rarely. Figure 4 presents the mean time in predicted conflict as a function of display type and traffic density. These data were analyzed in two repeated measures analyses of variance (ANOVAs) that corresponded to the two separate display issues addressed. One ANOVA examined display dimensionality including the 3D and rear-view display, which replicated the conditions compared in Experiment 1, and the second examined the effect of vertical view orientation that 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. For the dimensionality analysis, a 2 (display type: rear view and 3D)  $\times$  3 (traffic load: 2, 6, and 10) repeated measures ANOVA revealed no significant main effects (all  $ps > .10$ ). For the orientation analysis, a 2 (display type: rear view and side view)  $\times$  3 (traffic load: 2, 6, and 10) repeated measures ANOVA revealed only a marginally significant effect of workload,  $F(2, 34) = 2.7, p < .08$ .

Interestingly, increasing workload had only a marginally significant effect on performance with the coplanar display and no effect with the 3D display. We infer that this effect was observed because of the manner in which workload was manipulated in this particular paradigm. Specifically, the number of predicted conflicts did not increase with the manipulation designed to increase workload (total num-

ber of aircraft); therefore, it is possible that pilots were able to search rapidly for the single, relevant, potentially threatening intruder and perceptually filter all those that were not in the immediate area of concern to the ownship. This interpretation is consistent with the observation that increasing the number of nonconflict traffic did not monotonically effect our primary task performance measure, as shown in Figure 4, showing instead a “V-shaped” function.

Figure 5 presents the distribution of mean times spent in predicted conflicts as a function of maneuver choice collapsed over display type. The frequency with which each maneuver was chosen is shown above each bar. Figure 5 illustrates that the safety of maneuvers differed significantly from each other,  $F(3, 15) = 6.49, p < .01$ , most prominently with both directions of vertical maneuvers much safer than lateral maneuvers and with those that involved airspeed and combined (lateral and vertical) maneuvers falling in between (combined maneuvers were removed from the ANOVA analysis, however, as there were too few cases). It is important to note here that vertical maneuvers were also the most prevalent, which suggested that pilots were seen as “optimal” when they most frequently selected the maneuver that yielded the smallest time in a state of predicted conflict.

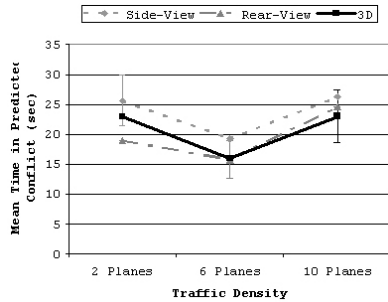


FIGURE 4 Predicted conflict avoidance rate by display type and traffic density. 3D = three dimensional.

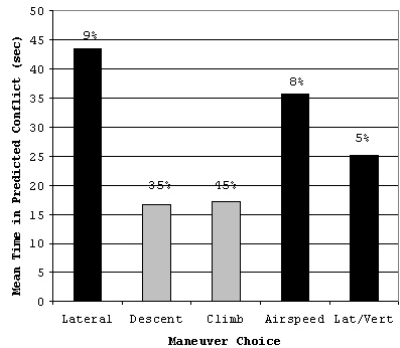


FIGURE 5 Mean time in predicted conflict by maneuver choice. The percentage time each maneuver was chosen is indicated above each bar. Lat = lateral; Vert = vertical.

*Subjective mental workload.* Analysis of the NASA-TLX scale data revealed that the rear view coplanar display yielded significantly lower workload than the 3D display,  $t(17) = -3.9, p < .01$ , and also marginally significantly lower workload than the coplanar side-view display,  $t(17) = -2.0, p < .07$ . Mental workload was rated highest with the 3D display ( $M = 11.8$ ), intermediate with the side-view display ( $M = 8.5$ ), and lowest with the rear-view display ( $M = 7.0$ ).

## EXPERIMENT 3

### Method: Experiment 3

Experiment 3 was designed with two goals in mind: (a) to explore further the hypothesis that traffic load would moderate the relative costs/benefits of display dimensionality when load was imposed by the number of potentially conflicting traffic aircraft and (b) to provide added data and therefore more statistical power regarding the influence of display on maneuver preferences to resolve some of the inconsistencies between Experiments 1 and 2.

The general procedures in Experiment 3 were similar to those in Experiments 1 and 2. Traffic load, dimensionality, and vertical profile orientation were again examined, as in Experiment 2; however, traffic load was manipulated in Experiment 3 by increasing the number of predicted conflicts as well as the number of total aircraft. As discussed previously, workload did not significantly disrupt performance in Experiment 2; therefore, trials in Experiment 3 were designed to include either one, two, or three predicted conflicts, which would result if the pilot made no avoidance maneuver. These were characterized by two, four, and six total traffic aircraft, respectively.

### Results and Discussion: Experiment 3

As in the previous experiments, performance measures included maneuver choice, flight safety, and subjective mental workload ratings. Full results for Experiment 3 are described in Alexander and Wickens (2002).

*Maneuver choice.* Figure 6 presents maneuver frequencies as a function of display type. The figure illustrates the clear dominance of vertical over other maneuvers,  $\chi^2(1, N = 323) = 82.3, p < .01$ . This trend replicated the effects observed by Wickens et al. (2002) and the results of both Experiments 1 and 2. Furthermore, the collective trend was representative of individual pilots within the sample. That is, the majority of participants chose vertical over other maneuver types (15 out of 18 pilots: 5 at  $p < .01$ , 3 at  $p < .05$ , 1 at  $p < .10$ , and 6 at  $p > .10$ ).

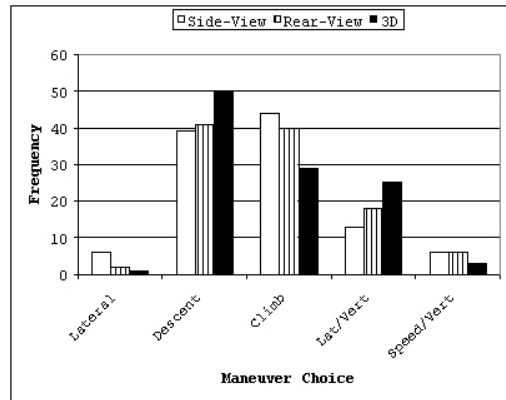


FIGURE 6 Maneuver frequencies by display type. 3D = three dimensional; Lat = lateral; Vert = vertical.

Vertical maneuvers were further explored by examining whether display dimensionality modulated maneuver preferences as had been observed by Ellis et al. (1987) as well as in Experiments 1 and 2. First, there was no overall difference in vertical maneuver choice preference for the 3D versus the coplanar displays (rear view,  $F < 1$ ; side view,  $F < 1$ ). Second, within vertical maneuvers, it appears that dimensionality did influence the tendency to climb versus descend. In this regard, pilots chose to descend more than climb with the 3D display,  $\chi^2(1, N = 79) = 5.58, p < .05$ . In support of this, a majority of the participants preferred descents over climbs when they used the 3D display (10 out of the 16 pilots who chose vertical maneuvers). The analysis also revealed that the side view 2D coplanar display marginally supported more climbing maneuvers than did the 3D display,  $\chi^2(1, N = 73) = 3.08, p < .10$ , thereby reversing the trend within descending maneuvers. In contrast to Experiment 2, however, coplanar displays did not themselves invite significantly more climbs (51%) than descents (49%). Also, there was a tendency to climb with the coplanar displays when traffic descended versus climbed,  $\chi^2(1, N = 19) = 11.8, p < .01$ , whereas pilots tended to choose descending maneuvers with the 3D display when traffic climbed versus descended,  $\chi^2(1, N = 11) = 4.45, p < .05$ .

*Flight safety.* As in Experiment 2, the time spent in an actual conflict was not used because although it was highly correlated with predicted conflicts, it occurred very rarely. Figure 7 shows the mean time spent in a state of predicted conflict as a function of display type and workload level. As in Experiment 2, these data were analyzed in two ANOVAs, one that examined display dimensionality including the 3D and rear-view displays and the second one that examined the effect of vertical profile orientation, which included only the two coplanar displays. No significant difference ( $p > .10$ ) of display type was revealed in either ANOVA. There was a main effect of workload, however, in the vertical profile orientation ANOVA, which indicated that the mean time spent in a predicted conflict increased with in-

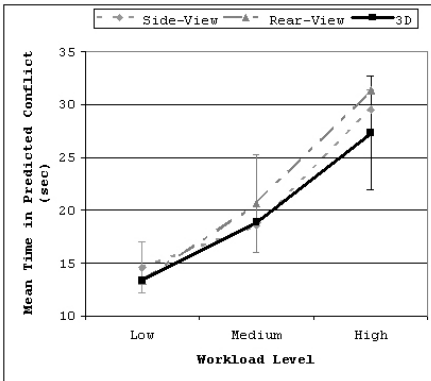


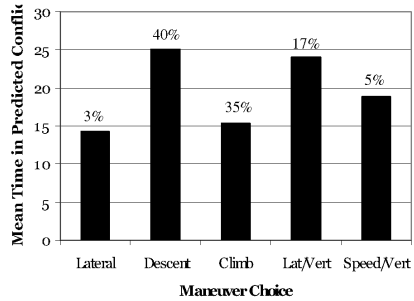
FIGURE 7 Predicted conflict avoidance rate by display type and workload level. 3D = three dimensional.

creasing workload for the two coplanar displays that were included in the ANOVA,  $F(2, 34) = 3.66, p < .04$ .

A workload effect was not found in the dimensionality ANOVA ( $p = .15$ ). Therefore, when only 2D coplanar displays were examined, increasing workload hurt performance, but when 3D displays were included, there was no evidence that 3D displays hurt performance at higher workload levels. This finding was surprising when examining Figure 7, as the lines for all three display formats appear to be roughly parallel. A one-way ANOVA across workload for only the 3D data revealed that safety was not affected by workload in the 3D display,  $F(2, 34) = 1.07, p = .36$ . Therefore, we assumed that this nonsignificance was a result of high between-subject variability across workload within the 3D display condition. This evidence was consistent with the original hypothesis that increasing workload levels would be detrimental to performance on the coplanar display but not necessarily with the 3D display. However, because of the high variance in the 3D condition, we cannot reject the hypothesis that workload may have affected performance in this condition as well (i.e., confirm the null hypothesis). The conclusion of no effect was drawn with caution because of the lower statistical power resulting from the higher between-subject variability in the effect.

We also assessed the overall safety of each maneuver type collapsed over display, as shown in Figure 8. Figure 8 illustrates that the safety of maneuvers differed from each other,  $F(4, 16) = 3.24, p < .02$ , most prominently with lateral and climbing maneuvers much safer than descending or combined maneuvers. Descents were found to be particularly less safe than the other maneuvers, an effect we hypothesized to be due to the fact that descending by naturally increasing airspeed will (if airspeed is not corrected by throttling back) allow the pilot less time to effectively adjust the maneuver as needed. We also infer that the combined maneuvers were less safe simply because they were chosen (out of necessity) on the more difficult conflict trials.

FIGURE 8 Mean time in predicted conflict by maneuver choice. The percentage of time each maneuver was chosen is indicated above each bar. Lat = lateral; Vert = vertical.



*Subjective mental workload.* Analysis of the NASA–TLX scale data revealed that the rear view coplanar display yielded significantly lower workload than the 3D display,  $t(17) = -5.7, p < .001$ , and also marginally significantly lower workload than the coplanar side-view display,  $t(17) = -2.2, p < .05$ . Subjective mental workload was rated highest with the 3D ( $M = 13.1$ ), intermediate with the side view ( $M = 8.8$ ), and lowest with the rear-view display ( $M = 6.6$ ). Because ratings were collected at the end of each block of trials on the separate displays, it was not possible to ascertain the extent to which higher 3D workload was manifest across all three levels of traffic load.

## GENERAL DISCUSSION

These data were examined from four interrelated perspectives: (a) what types of avoidance maneuvers pilots used, (b) how each of the display types influenced maneuver choice, (c) the relative merits of 2D coplanar versus 3D CDTI displays for flight safety, and (d) how the orientation of a plan view display in the coplanar suite influenced performance.

### Display Modulation of Maneuver Choice

Regarding the overall choices of conflict avoidance maneuvers, the results of all three experiments generally replicated findings of the other literature (for a summary, see Alexander & Wickens, 2002; Wickens et al., 2002) that there is an overall preference to maneuver in the vertical rather than the lateral dimension. This preference can be attributed to the fact that vertical maneuvers are of lower control order and therefore both cognitively less complex (Wickens, 1986) and temporally more efficient (Krozel & Peters, 1997). These results also generally replicated the paucity of joint, two-axis maneuvers (due to the greater cognitive complexity of these) and, in Experiments 2 and 3 in which speed control was allowed, the paucity of using this control to avoid conflict. In considering the vertical preference and, in particular, the climbing preference discussed in the fol-

lowing, we note that all vertical maneuvers were safer than lateral maneuvers, as found in Experiment 2 and reported also by Scallen et al. (1996), and that vertical climbing maneuvers in particular were safer than descents in Experiment 3.

The results of the three experiments were also consistent in revealing that the dimensional format of the display modulated the nature of the maneuver choice, although the precise form of that modulation was less consistent. In Experiment 1, the coplanar display was found to enhance the tendency to choose vertical (vs. lateral) maneuvers but not the direction (climb/descend) of those maneuvers, whereas in Experiments 2 and 3, dimensional changes did not affect axis choice but influenced the direction of choice within the vertical axis with the coplanar display having invited more climbs. This latter effect was consistent with the observations of Wickens et al. (2002) using a full mission simulation with only a coplanar display who also found that climbing maneuvers were favored over descents. One way of expressing the consistent message of all three experiments is that coplanar displays invited more climbing maneuvers than did the 3D display, an important conclusion in light of the safety implications of descents versus climbs described as follows.

Alexander and Wickens (2002) suggested that the reason why 3D displays appear to invite descents relates to the manner in which the 3D ambiguity (inherent in collapsing the volume of airspace onto the 2D viewing surface) is resolved. Given the “look-down” viewpoint, shown in Figure 1, the ownship will be seen as lower in the visual field than traffic ahead at the same true altitude as the ownship. To the extent that perceived display location is interpreted as signaling the true relative altitude (Wickens, 2002), then forward traffic will be biased to be seen as higher and ownship lower, thereby more likely inviting descents as the most efficient conflict avoidance maneuver.

Coupling the findings of different safety implications with those of dimensionality induced maneuver choices yields a potentially important conclusion: The 3D CDTI tended to invite maneuvers that were inherently less safe (as safety is operationally defined by the time in actual or predicted conflict). This conclusion has two manifestations in the results. Most direct, in Experiments 2 and 3, we noted that the descents, invited by the 3D display, yielded substantially more time in predicted conflict. In Experiment 1, we noted that the tendency to maneuver in the same vertical direction as the traffic, invited by the 3D display, was a tendency that prolonged the duration of potential conflict.

### Dimensionality Effects on Performance

The collective results of the three experiments were somewhat equivocal regarding the relative merits of the 2D coplanar versus the 3D perspective display, an equivocation that was indeed consistent with the multiplicity of factors influencing the two formats (Wickens, 2000b, 2003). In Experiment 1, with little traffic,

the 3D format supported lower levels of conflict avoidance safety. However, this was only observed with nonlevel traffic when the ambiguity of the 3D representation becomes most pronounced (Wickens, Miller, et al., 1996). In Experiments 2 and 3, with generally higher traffic load, the 3D display supported conflict avoidance performance that was no worse than the coplanar and might even have been considered to be superior in the sense that performance with this display was not further disrupted by an increase in traffic load, whereas that load increase disrupted performance with the coplanar displays.

As such, these data may be modeled by the cost–benefit trade-offs between the two display types: The coplanar suite suffered from scanning-related integration, which grows in magnitude with the number of elements on a display; the 3D display suffered from ambiguity, a cost that grows in magnitude with the loss of constraints of trajectories to lie along a horizontal plane (and therefore with the increase in the potential for ambiguity). We note, however, that the balance of this trade-off in this data was tipped slightly to favor the coplanar displays given that across all three experiments, these displays generated lower subjective workload than did the 3D display. Apparently, the cost of trying to resolve ambiguity outweighed the cost of added clutter.

In placing these results in the context of prior findings, they were consistent with those of Vierra and Wickens (1996) but, at first glance, only partially consistent with those of Ellis et al. (1987) who observed a clear advantage for the 3D display. Any inconsistencies however can be resolved by realizing that the 3D display used by Ellis et al. was contrasted with a uniplanar (i.e., electronic map) and not a coplanar 2D display (with a VSD) so that the resolution of vertical ambiguity was actually more difficult in the 2D than the 3D format.

### VSD Orientation

If, as described previously, the results generally speak as to the costs of the 3D display (except potentially at high traffic load), then one may ask which VSD within the coplanar suite is best: one from behind looking forward, such as a pictorial attitude indicator, or one presented from the side as seen on some flight deck display concepts (Jacobsen et al., 2002). The evidence on this issue offered by the data of Experiments 2 and 3 was more ambivalent (for more details, see Alexander & Wickens, 2001, 2002). The rear-view display consistently yielded lower subjective workload. There was no difference between the two displays in terms of safety (although there was a hint in Experiment 2 that the side-view display invited more of the safer climbs than did the rear-view display).

An additional aspect of the analysis, reported in detail in Alexander and Wickens (2002), suggested that the side-view display supported more efficient vertical maneuvers than did the rear-view display (i.e., less deviation from the assigned flight altitude) without sacrificing safety. Such a finding is consistent with

the fact that coordinating efficient vertical maneuvers requires a cognitive integration of altitude with along-track position (speed), and it is this side-view display that presents those two axes of the airspace in an integrated pictorial form (Haskell & Wickens, 1993). The role of display integration in supporting better information integration (Wickens & Carswell, 1995) was supported further by the observation of Alexander and Wickens (2002) that the rear-view display supported the most efficient lateral maneuvers. This latter finding, however, should probably have less impact on the choice of the optimal VSD orientation simply because these lateral maneuvers were rarely chosen.

### Constraints and Future Research

The conclusions of this research are constrained to the extent that there are limitations in generalizing these results to real cockpit flight due to the relatively homogeneous sample of general aviation pilots and the low fidelity of the flight environment. However, despite the low fidelity of our simulation, the maneuver tendencies observed here with the coplanar, rear-view display were consistent with those observed in the higher fidelity (full-cockpit) simulation carried out by Wickens et al. (2002).

It is important to note that the overall preference for vertical maneuvers in all experiments was inconsistent with current aviation recommendations (i.e., lateral maneuvers in the right-of-way rules, Federal Aviation Regulations, 91.113). Vertical maneuvers are normally not considered (without the aid of a CDTI) because the altitude of surrounding aircraft relative to the ownship is inherently difficult to determine through out-the-window visual inspection. Perhaps the regulation to make lateral maneuvers in avoiding traffic will need to be revised in the case that CDTIs are adopted for general aviation. This idea has in fact been utilized in the TCAS, which advises that vertical maneuvers be employed in tactically avoiding traffic in large part because of the greater speed of those maneuvers as already noted.

The most interesting future research questions raised by the experiments we described deal with two different issues. The first issue involves the finding that conflict avoidance maneuvers are influenced by the format with which the traffic situation is displayed. Specifically, exploring the 3D induced descent bias in light of the finding that descents were less safe (more time spent in predicted conflict) relative to climbs would be of interest to the extent that a 3D CDTI is considered for actual implementation.

A second issue explores another possible source of superiority for the 3D displays. All comparative evaluations of 2D–3D differences have been carried out in essentially instrument flight rules/instrument meteorological conditions with no outside representation of traffic. Yet recent research in our laboratory has indicated that the coplanar CDTI does not do a terribly effective job of providing guid-

ance on where to look in the outside world in visual meteorological conditions (Wickens et al., 2003). At the same time, 3D exocentric displays have been proven more effective in image comparison tasks (between the display and the forward view; Hickox & Wickens, 1999). Thus, it may be that the 3D CDTI could enhance the pilots' ability to spot traffic (visual callout) even if it was not as successful in guiding the avoidance maneuver as the coplanar display.

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