

DOES WORKLOAD MODULATE THE DIFFERENCE BETWEEN COCKPIT TRAFFIC DISPLAY FORMATS?

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Eighteen certified flight instructors from the University of Illinois Institute of Aviation participated in an experiment exploring the format of the Cockpit Display of Traffic Information for free flight traffic avoidance maneuvers. Pilots flew a sequence of flight scenarios to compare the effects of traffic load, display dimensionality (3D vs. 2D coplanar), and a vertical profile orientation on maneuver choice, conflict avoidance performance, and maneuver efficiency. The highest levels of workload induced more combined lateral/vertical maneuvers, degraded safety on the 2D coplanar displays, and degraded efficiency regardless of display type. In the context of an overwhelming preference for vertical maneuvers, the 3D display increased the frequency of the less-safe descent maneuvers (relative to climbs) and increased subjective workload, while the 2D rear-view display decreased the vertical efficiency of all maneuvers, relative to its side-view counterpart.

INTRODUCTION

The Cockpit Display of Traffic Information (CDTI) is being developed for the display of information needed by the pilot in order to safely and efficiently evaluate hazards and decide upon avoidance maneuvers in a Free Flight context (Kreifeldt, 1980; Ellis, McGreevy, & Hitchcock, 1987; Johson, Battiste, & Bochow, 1999). Two important design issues have been raised concerning the appropriate format of the CDTI. The first of these concerns the dimensionality of the display representing traffic around ownship. Two-dimensional coplanar displays (map view plus vertical situation display) allow for ease and precision in making both horizontal and vertical judgments through the presentation of both map and vertical views (Wickens, 2000), but may induce a cost of scanning between the two panels, placing a greater demand on retaining attributes of each panel for comparison or integration (Wickens, Merwin, & Lin, 1994). A 3D perspective display, however, provides the advantage of integrating all three axes of the airspace in a single panel (Ellis et al., 1987; Merwin, Wickens, & O'Brien, 1997), but may be ambiguous in representing the precise location and trajectory of aircraft (Wickens, 2000). Indeed, Merwin et al. found a 3D safety cost when compared with a rear-view display, related to the ambiguity of the 3D view. However, traffic workload was very low with a maximum of two aircraft.

A second design issue involves the vertical profile orientation of the 2D vertical situation display (VSD). A forward-looking view represents ownship from behind such that each traffic symbol in its vertical depiction on the bottom panel is directly positioned below its counterpart on the lateral display. The side-looking view, in contrast, shows a longitudinal depiction of the flight path which does not allow for a one-to-one matching of traffic symbols. The side-view representation is examined because it is being considered by designers in the implementation of "vertical situation displays" in the cockpit (e.g., DeJonge, 2000; Oman, Kendra, Hayashi, Stearns, & Burki-Cohen, 2001). Side-view displays are being developed to represent distance from terrain and profile descents, and they already exist in static form on

approach plates. It is therefore logical to explore the implications of representing traffic on these displays.

Alexander and Wickens (2001) examined the effects of dimensionality, profile view orientation, and traffic density on conflict avoidance, maneuver choice, efficiency, and maneuver separation (safety). Pilots flew a sequence of flight scenarios containing two conflict aircraft among two, six, or ten aircraft besides ownship. Replicating previous studies (Merwin & Wickens, 1996; Wickens, Helleberg, & Xu, 1999), vertical maneuvers were preferred over other maneuvers on all display types, with a preference for descents on the 3D display and climbs on the coplanar displays. The side-view display, in particular, amplified the preference for climbing maneuvers due to the improved visualization of altitude in its along-track representation. Interestingly, climbing maneuvers were the least safe with the side-view display because they appeared to invite pilots to "cut corners," or level off prematurely, which increased efficiency but decreased safety.

Maneuver efficiency and subjective mental workload ratings favored the rear-view coplanar display overall (Alexander & Wickens, 2001). It was expected that the 3D display would support progressively better conflict avoidance performance as traffic density (workload) increased due to the increased scanning costs associated with the coplanar display. That is, that the 3D cost observed by Merwin et al. at low levels of workload (one aircraft) would be eliminated. This interaction was not found and there was no overall effect of dimensionality (coplanar vs. 3D) on safety or efficiency, however, we hypothesized because of the pilots' abilities to attentionally filter the added traffic at higher workload levels which did not pose an immediate threat (i.e., at all workload levels, only two traffic aircraft posed conflicts).

One objective of the current study was to explore this null effect of workload found in Alexander and Wickens (2001) by increasing the number of predicted conflicts as well as the number of aircraft. This workload manipulation would prevent pilots from disregarding all but the two conflict aircraft, regardless of the number of aircraft total, as possibly occurred in the previously discussed study. We hypothesized that the enhanced benefits of the 3D display would be borne out under the increased workload conditions. A second

objective was to further investigate the safety/efficiency tradeoff found with the different orientation of the VSD in the side-view display. A third objective was to gain further understanding of the influences on pilot maneuver choice.

METHODS

Eighteen certified flight instructors (experience, $\bar{M} = 459$ flight hours, $\bar{M} = 91$ instrument flight hours) flew a sequence of flight scenarios designed to compare the three CDTI formats. The experiment was conducted on a low fidelity personal computer flight simulator with a flight stick controlling pitch, roll, and throttle.

Displays

The CDTI presented ownship and traffic, each with 45-second predictor lines. Symbology developed by Merwin, Wickens, and O'Brien (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.

Coplanar Formats. The coplanar display 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) vertical situation display (VSD) projected orthogonally (without perspective information). Both VSDs contained two sets of horizontal lines indicating the altitude boundaries of ownship's protected zone.

3D Format. The 3D display shown in Figure 1a depicted an integrated view of the airspace from a perspective above and behind ownship, with an elevation angle of 45° , and an azimuth offset of 10° . The display showed the previously described symbology along with droplines to unambiguously show the horizontal positions of the aircraft icons and the ends of the predictive lines.

Task

Pilots flew direct routes to predetermined waypoints while encountering other aircraft, and maneuvered to avoid conflicts with traffic, while minimizing deviations in speed, heading, and altitude from target values. After determining that the conflict had been resolved, the pilot returned to the flight path to intercept the waypoint.

Display type was manipulated by providing the three viewpoints (Figure 1). Traffic level was manipulated by including 2, 4, or 6 aircraft besides ownship with 1, 2, or 3 predicted conflicts, respectively. 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 aircraft. Thus, its trajectory needed to be considered in implementing the avoidance maneuver. 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

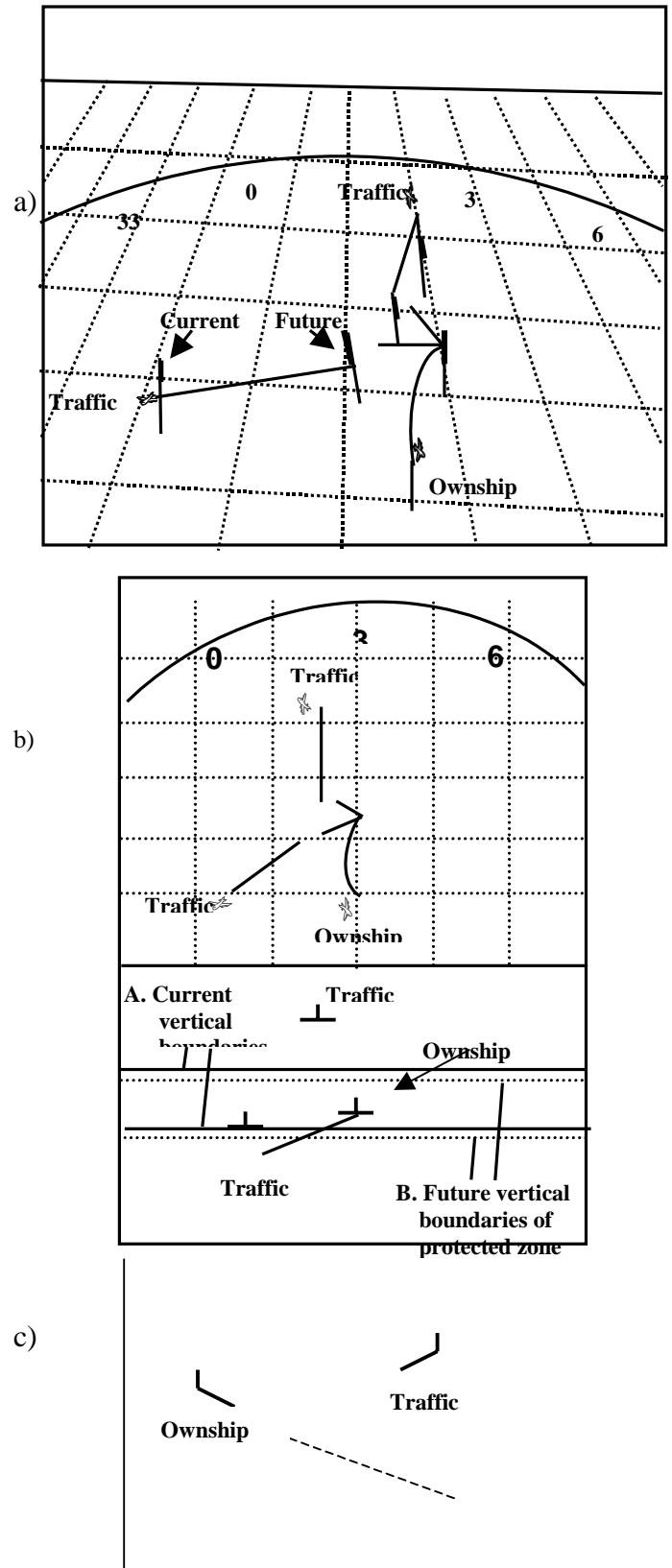


Figure 1. Three display versions of the CDTI: (a) 3D, (b) 2D coplanar rear-view, (c) 2D coplanar side-view. The rendering of the side view profile in (c) is not what participants actually saw, but is a schematic designed to highlight the different orientation of the VSD from figure (b).

this traffic.

Pilots performed two replications of the 9 trials in counterbalanced order, formed by the 3x3 combination of traffic load (low, medium, high) and display format.

RESULTS

Maneuver Frequency

Maneuvers were categorized according to timelines created from the raw data as lateral, descents, climbs, lateral/vertical, and airspeed/vertical based on the pilot's control inputs and flight parameters for each trial. Figure 2 presents maneuver frequencies by display type. The figure illustrates the clear dominance of vertical over other maneuvers, $\chi^2(1, N = 323) = 82.26, p < .01$, as well as a preference for descents over climbs for the 3D display, $\chi^2(1, N = 79) = 5.58, p < .05$.

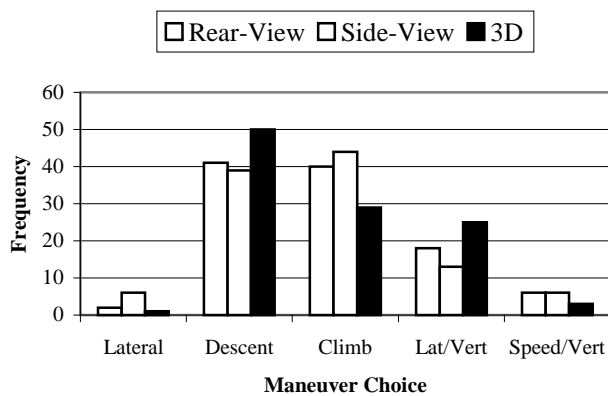


Figure 2. Maneuver frequencies by display type.

Examining maneuver frequencies by workload level revealed that combined maneuvers (lateral/vertical and speed/vertical) were more commonly used under high than medium workload levels, $\chi^2(1, N = 44) = 7.36, p < .01$.

Safety

The primary measure of safety was the time spent in a state of predicted conflict (loss of separation within 45 seconds if no maneuver was taken). The time spent in an actual conflict was not used because such occurrences, while highly correlated with predicted conflicts, occurred very rarely. ANOVA's revealed that safety was compromised at higher workload with the two coplanar displays, $F(2,162) = 4.62, p < .02$, but not with the 3D display, $F(2, 86) = 0.09, p = .91$. This nonsignificance was a result of high between subject variability across workload within the 3D display condition.

Safety was further explored by examining the amount of time spent in predicted conflict across display type as a consequence of making certain avoidance maneuvers. Planned comparisons revealed a significant effect such that lateral maneuvers were more safely implemented when using the side-view than when using the rear-view display, $t(4.1) = -4.61, p < .01$.

Maneuver Efficiency

Figure 3 presents the mean absolute altitude deviation (vertical efficiency) by display type and workload (traffic density). Two analyses, one on the top two lines examining display dimensionality, and one on the bottom two examining orientation, both revealed the significant effect of increasing workload on increasing altitude deviation ($p < .01$). The dimensionality analysis also revealed that the 3D display was less efficient than the 2D rear on climbs and lateral/vertical maneuvers, $t(51.9) = 2.08, p < .05$ and $t(28.1) = 2.06, p < .05$, respectively, and the orientation analysis revealed that the 2D rear view was less vertically efficient than the 2D side-view on all maneuvers, $F(1, 210) = 3.53, p < .07$.

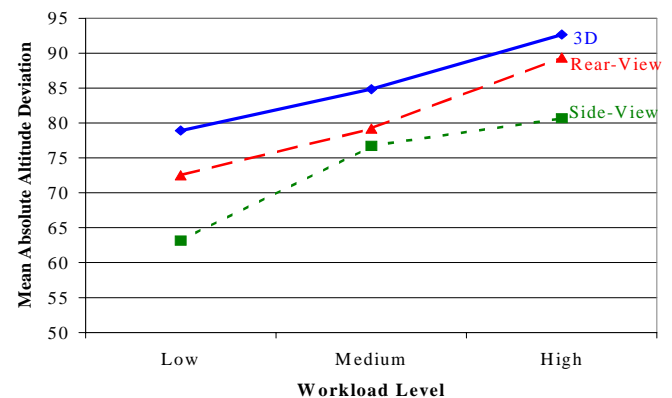


Figure 3. Mean absolute altitude deviation by display type and workload level.

Lateral efficiency was affected in lateral maneuvers in that efficiency was greater with the rear-view than the side-view display, $t(2.7) = 8.45, p < .01$. Combined lateral/vertical maneuvers were more laterally efficient with the 3D display than with the rear-view display, $t(29) = -2.11, p < .05$.

Subjective Mental Workload

Separate tests revealed that the 2D rear-view display (6.6) had substantially lower workload than the 3D (13.1), $t(34) = 4.9, p < .01$, and a non-significant trend for lower workload than the side-view (8.8), $t(33) = 1.5, p = .13$, both effects replicating those observed by Alexander and Wickens (2001).

DISCUSSION

In the following, we first discuss the general maneuver tendencies that were observed, and then describe how these were modulated by the two important display manipulations incorporated in the experimental design: the dimensionality and the orientation of a coplanar view.

Maneuver Choice

There was a strong preference for vertical over other maneuvers for all display formats ($p < .01$). This finding replicates the effects observed by Wickens, Helleberg, and Xu

(2001) and Alexander and Wickens (2001). There are several reasons why this strong vertical preference has been repeatedly found. First, vertical maneuvers are less complex cognitively due to their lower control order (second) compared to lateral maneuvers (third; Wickens, 1986). Second, as a function of this lower control order, vertical maneuvers are more efficient because they result in more rapid deviations from and return to the intended flight path (Krozel & Peters, 1997). Because of this greater efficiency, vertical maneuvers are more effective under high time pressure because they take less time to implement than lateral maneuvers, also a consequence of their respective control orders.

In contrast to previous studies (Helleberg, Wickens, & Xu, 2000 and Alexander & Wickens, 2001), climbs were equally preferred to descents. The previous finding of an overall climb preference was offset in the current results by the overwhelming number of descending maneuvers chosen at medium workload levels for reasons that cannot be fully explained.

Dimensionality Effects

While the highest level of workload had a more robust effect than in the previous experiment (Alexander & Wickens, 2001), inducing more combined maneuvers and degrading both safety and efficiency, these workload effects were further moderated by the predicted effect of display format (e.g. less workload disruption on the 3D display). In particular, safety of maneuvers suffered with increasing workload for the two coplanar displays ($p < .02$), whereas it did not with the 3D display ($p = .91$). However, we cannot fully accept the hypothesis that increasing workload had no effect on the 3D display, because high between-subject variance reduced the power of the test.

Overall, the effects of display representation were relatively muted. In general, pilots were able to extract the necessary information with equal precision out of all three display formats, and in particular, use each set of information to engage in equally safe conflict avoidance behavior. However, there were differences between displays in the types of vertical maneuvers selected. Essentially, the 3D display induced a descent preference and climb aversion ($p < .10$) which was not seen in the coplanar displays. The descent preference with the 3D display replicates the findings of Merwin et al. (1997) and Alexander and Wickens (2001).

The safety of performance with the rear-view coplanar display was not significantly different from that with the 3D display, replicating the null effects observed by Alexander and Wickens (2001). It was expected that safety would be influenced in favor of the 3D display at high levels of workload because the visual search induced by matching an increased number of aircraft representations would be more demanding with the coplanar display. This expected difference between the rear-view 2D coplanar and 3D display was somewhat supported by the finding that performance was hurt at increasing workload levels for the coplanar display, but not for the 3D display. But as we discussed above, while safety was NOT degraded with more traffic in the 3D display, the

statistical power to confirm this null effect was limited because of high variance.

In another sense, the collective results of this study, along with Alexander and Wickens (2001) and Merwin et al. (1997), are consistent with the overall workload-dimensionality hypothesis offered at the outset: both of the two experiments reported by Merwin et al. had low workload (1 or 2 planes) and found a 3D cost, while both of the experiments of Alexander and Wickens had much higher traffic load and the 3D cost was eliminated.

Subjective mental workload ratings revealed that participants felt their workload was highest with the 3D display. We hypothesize that pilots successfully compensated for whatever ambiguity the 3D display might have imposed by mentally rotating vectors between ownship and traffic for more precise resolution (Boeckman & Wickens, 2001), but this rotation imposed added mental demands. Merwin et al. (1997) and Alexander and Wickens (2001) also found similar mental workload differences between 2D and 3D displays.

Orientation Effects

The orientation effects tended to be even more muted than the dimensionality effects in the current study and in comparison to the Alexander and Wickens (2001) study. The results of this study, in terms of safety, did not replicate the findings of Alexander and Wickens (2001) that the rear-view display exhibited superior conflict avoidance performance compared to the side-view display.

The most pronounced effect of profile view orientation (but possibly the least important because it occurred on the lateral avoidance trials which were chosen so rarely) was the safety-efficiency tradeoff on lateral maneuvers. Specifically for lateral maneuvers, a safety benefit for the side-view over the rear-view display was offset by an efficiency benefit for the rear-view display. While the safety benefit for the side-view display is not easily explainable, the efficiency benefit with the rear-view display was inferred to be due to the redundant coding of heading and lateral deviation information across the two panels in the rear-view display, while only the top-down panel contained heading information for the side-view display. This means that pilots had to scan between panels to access and integrate heading and altitude information while using the side-view display.

In the current study, the weighted average of vertical efficiency with the rear-view display was marginally significantly lower than with the side-view display. We hypothesized that this effect resulted because the side-view display allowed pilots to integrate altitude and position along the flight path on a longitudinal scale, allowing for easily visualized predictor line slopes, whereas the rear-view display did not depict this time dimension as clearly and relied on the displacement of solid and dashed lines for altitude information. The side-view display would naturally support better altitude maintenance performance (greater vertical efficiency) than the rear-view display since both climbs and descents were more easily visualized with the side-view than with the rear-view display. This finding reinforces the display effect, that vertical efficiency was better with the side-view

than with the rear-view display, found for combined lateral/vertical maneuvers in the Alexander and Wickens (2001) study.

Table 1 summarizes the overall findings regarding the influence of display type and the significance of differences between them on each dependent measure, as categorized by maneuver type. The table reveals that the rear-view is superior to the 3D display, and that performance aggregated across all dependent measures was found to be equivalent for the two coplanar displays.

Measure	Maneuver	Rear	Side	Rear	3D
Safety	Lateral	-	+	0	0
Lat Eff	Lateral	+	-	0	0
	Lat/Vert	0	0	-	+
Vert Eff	All	-	+	+	-
	Climbs	0	0	+	-
	Lat/Vert	0	0	+	-
Speed Eff		0	0	0	0
Workload		+	-	+	-
Total		0	0	3	-3

Table 1. Summary table. A plus score means that the display supported the best performance on that dependent measure. A score of zero reveals equivalent performance, while a minus score means the display supported the worst performance on that measure.

In conclusion, differences or changes in display format may have two separate effects on pilot information: (1) They may invite or inhibit certain types of maneuvers by making certain features of the airspace more or less salient (e.g. 3D invitation of descending maneuvers). Also, some of the maneuvers “invited” by a display may actually be inherently less safe or less efficient than desired (e.g. lateral maneuvers when using the rear-view display). (2) They may influence the quality of the chosen maneuver, by hiding or degrading the nature of certain information (e.g. the line-of-sight ambiguity of the 3D display) or by increasing the processing demands of accessing and combining that information (e.g. requiring integration across separate panels as in the decrease in safety found with the side-view compared to the 3D display in Alexander and Wickens (2001)).

Again, the findings summarized in Table 1 reveal the superiority of the rear-view coplanar display over the 3D display. Whether a rear-view or side-view coplanar display should be implemented would depend on the relative importance of the different dependent measures. If an airline places the greatest weight on safety, then a side-view display may be preferred to the rear-view. If fuel and time efficiency is of utmost importance, then the rear-view display may be preferred due to the superior lateral efficiency maintained while using the rear-view display. Weights may also be placed through the table according to the significance or power associated with each finding.

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