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Display Dimensionality, Conflict Geometry, and Time Pressure Effects on Conflict Detection and Resolution Performance Using Cockpit Displays of Traffic Information

Lisa C. Thomas
Boeing PhantomWorks
Seattle, Washington

Christopher D. Wickens
University of Illinois at Urbana–Champaign

Cockpit displays of traffic information are designed to support pilots' abilities to perform conflict detection and resolution tasks. Three experiments investigated the effects of display dimensionality, conflict geometry, and time pressure of in-flight conflicts on performance. The results indicated that interactive viewpoints in 2 3–D displays eliminated ambiguity costs, resulting in performance on both tasks comparable to a 2–D coplanar display. Viewpoint interactivity in the 3–D displays was vulnerable to increased workload, although corresponding performance was no worse than the 2–D coplanar. All 3 display formats showed performance decrements for nonlevel conflict geometries and increased time pressure.

Currently, cockpit displays of traffic information (CDTIs) provide airspace information to the pilot in an ownship-centric format, enabling the pilot to understand the relative positions of other aircraft in the airspace and perform self-separation tasks. As part of an effort to assign more enroute responsibility from air traffic control to the individual pilots, the Federal Aviation Administration (FAA) is developing human factors certification criteria for the use of

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Correspondence should be sent to Lisa C. Thomas, 2100 Lake Washington Boulevard North, Apartment E102, Renton, WA 98056. Email: lcthoma1@yahoo.com

CDTIs for use in enroute conflict detection and, when applicable, resolution of a detected conflict (RTCA, 1995; Thomas & Rantanen, in press). In support of this effort, the Distributed Air/Ground Traffic Management team at NASA Ames Research Center has developed concepts for maneuvering "rules of the road" along with displays designed to support future free flight activities (Granada, Dao, Wong, Johnson, & Battiste, 2005; Johnson, Canton, Battiste, & Johnson, 2005).

Traditionally, CDTIs have been designed as 2–D displays akin to radar screens, where the pilot's own aircraft (ownship) is located in the center, all traffic and air hazards are depicted relative to ownship, and altitudes are depicted numerically (refer to Figure 1, Johnson, Battiste, & Bochow, 1999). However, as airspace is inherently 3–D, it has been proposed that a display that graphically depicts all three dimensions may better support pilots' conceptions of the airspace. In this context, we note the emergence of 3–D displays for flight path guidance and terrain representation in aviation (Prinzel et al., 2004; Schnell, Kwon, Merchant, & Etherington, 2004). It is reasonable to assume that these displays may also be asked to host traffic information. One proposed display concept, the 3–D volumetric cockpit situation display, designed at NASA Ames Research Center (Granada et al., 2005), forms the basis of this study.

A 3–D representation is typically accomplished in one of two ways, either by providing a vertical situation display along with the traditional 2–D planar view (producing a 2–D coplanar display; Hughes, 2004; Prinzel, Kramer, & Arthur, 2005), or by providing a viewpoint that is set to a perspective angle and shows all three dimensions integrated in a single view (3–D displays). Previous research has shown that each format has associated costs and benefits that are typically

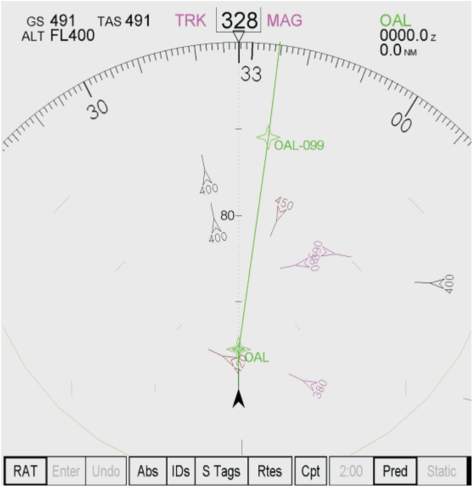


FIGURE 1 The CDTI used in Johnson, Battiste, & Bochow (1999); colors are inverted for clarity of reproduction.

task-dependent (Wickens, 2003), discussed later in the context of conflict detection and resolution tasks.

The tasks of conflict detection and resolution involve extrapolating future positions of all aircraft involved, adding a fourth dimension for consideration. Flight paths may be extrapolated from information about current positions and flight plans of surrounding aircraft, and depicted as predictor lines extending from the front of the aircraft. Altogether the ownship and each surrounding aircraft with its associated predictor line create a particular configuration, or conflict geometry, that is perceived and analyzed by the pilot for conflict potential. Conflict geometries are defined by three components, reflecting the three spatial dimensions: lateral approach angle, relative altitude and vertical speed changes, and relative airspeed. The headings, altitudes, and relative velocities of the aircraft involved dictate the closest point of approach (CPA), which is compared against the dimensions of the cylinder of airspace, called the protected zone, surrounding ownship (see Figure 2).

A conflict, or loss of separation, occurs when the CPA falls within the protected zone. Conflict detection is the process of detecting a predicted loss of separation. Conflict resolution involves creating a new flight path that moves the CPA safely outside the protected zone by changing one or more of the parameters of heading, altitude, or airspeed. Both of these tasks require accurate depiction of the airspace to support the pilot's situation awareness of perceiving where every aircraft is, understanding their positions relative to ownship, and extrapolating their predicted future locations (Endsley, 1995).

DISPLAY DIMENSIONALITY

Both of the display options mentioned earlier (2–D coplanar, 3–D display) have inherent perceptual or cognitive limitations that produce display–task trade-offs. For example, the 2–D coplanar display provides absolute information for all three dimensions, but because this information is distributed across two views there is a cognitive cost associated with mentally integrating the two views to fully understand a 3–D airspace. In addition, if display size is held constant, the two views of a 2–D coplanar display can take up twice as much display as a single-view 3–D display, which is undesirable when display space is limited. To preserve cockpit real estate (reduce the amount of space taken by a new display), the 2–D coplanar display views can be minimized, but at the cost of losing display resolution (Kroft & Wickens, 2003). A 3–D display presents spatial information in an integrated graphical format and allows the observer to perceive information about spatial relations quickly. However, the particular viewpoint angle and resultant presentation of 3–D information on a flat 2–D screen create spatial ambiguities due to different degrees of compression in one or more axes

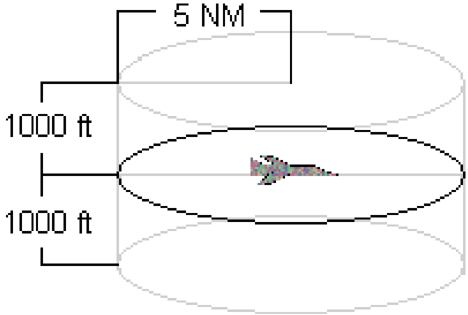


FIGURE 2 Depiction of the protected zone of an aircraft.

along the line of sight (McGreevy & Ellis, 1986; St. John, Cowen, Smallman, & Oonk, 2001; Wickens, 2002, 2003; Wickens & Hollands, 2000; Wickens, Vincow, & Yeh, 2005).

Overall, the research on display dimensionality has so far been unable to reveal consistent support for the benefits of one frame of reference over another for all tasks (e.g., Alexander, Wickens, & Merwin, 2004, observed a slight 2–D coplanar benefit for traffic conflict resolution, whereas Prinzel et al., 2005, observed a 3–D display benefit for terrain awareness); the successes (and failures) have been task dependent.

Conflict Resolution

In previous studies, whenever conflict resolution performance has differed between display formats, this measure favored the 2–D coplanar display, although not the 2–D plan view display (without the VSD). Such a difference may be attributable to the ambiguity of the 3–D display because such 3–D costs tended only to emerge when the traffic was making a vertical maneuver (climbing or descending), a circumstance that may result in an ambiguous vertical trajectory on the 3–D but not the 2–D coplanar display (Alexander et al., 2004, Experiment 1; O'Brien & Wickens, 1997). This effect has been replicated on air traffic control displays as well (Wickens, Miller, & Tham, 1996).

Merwin, Wickens, and O'Brien (1998) found that pilots were better able to avoid predicted conflicts using a 2–D coplanar display (compared to a 3–D perspective display). Results from the study by Wickens and Helleberg (1999) showed that pilots using the 3–D perspective display spent more time in actual conflicts (when loss of separation has already occurred), and created less safe resolution maneuvers, than pilots using a 2–D coplanar display. In two studies, Alexander et al. (2004) found a safety cost for 3–D displays, but only for nonlevel maneuvers (Experiment 2), and also found that this cost disappeared when workload increased (Experiment 3). Generally, then, 2–D coplanar displays support safer conflict avoidance maneuvers than 3–D displays.

Conflict Detection

There is only a small amount of information on detection performance in the literature. Most studies use the term *conflict avoidance* to encompass both tasks of conflict detection and resolution and do not always parse out each task segment. Merwin and Wickens (1996) found that a 2–D coplanar CDTI supported better conflict detection than either of two 3–D displays with different viewpoints (30° and 60°).

Alternative Viewpoints

In sum, previous research tends to slightly favor the 2–D coplanar display. However, if it is true that the viewpoint angle of a 3–D perspective display produces poorer conflict detection and resolution performance due to spatial ambiguities, then incorporating a feature to reduce those viewpoint-specific ambiguities might improve performance to a level equal to or perhaps greater than the 2–D coplanar display. A potential solution is to allow the viewpoint to be positioned by the pilot in a variety of angles so that the 3–D spatial environment may be viewed from different directions that disambiguate the relevant spatial information, a technique proven quite effective in supporting terrain awareness (Prinzel et al., 2005).

One method of providing multiple perspectives is to allow observers to switch between two different perspective viewpoints by clicking on the interface. The two perspective viewpoints are predetermined by the display designer to provide optimal perspective information that, combined, reduces the ambiguity inherent to either of the views. There will be an associated cognitive cost of integrating across two serially presented frames of reference.

A second method is to allow the observer to manually rotate the viewpoint through a continuous and fluid range of possible viewpoint positions (e.g., Wickens & Helleberg, 1999). The viewpoint rotation provides motion-related depth cues (motion parallax) as well as the alternate viewpoints that may work to resolve spatial ambiguities and provide a more intuitive picture of the spatial environment (Woods, 1984). However, because the observer is selecting the viewpoint, there is a risk that the perspectives chosen are not effective in reducing ambiguity to the greatest extent possible.

Although a host of literature in basic 3–D perception supports the dominance of motion parallax as a valuable depth cue (see Wickens, Todd, & Seidler, 1989), only two applied studies have investigated the usefulness of variable-viewpoint perspective displays in resolving spatial ambiguities to solve spatial reasoning problems (Sollenberger & Milgram, 1993; Wickens & Helleberg, 1999). Sollenberger and Milgram (1993) found that an angiogram path tracing task was best supported by a continuously rotating-viewpoint 3–D display, then by a multiple-angle 3–D display, and least supported by the static 2–D display. Using a CDTI, Wickens and Helleberg (1999) found that pilot performance on nonlevel conflicts was aided by their use of an interactive vertical axis viewpoint to reduce ambiguities for nonlevel conflicts although the level of performance never exceeded that of the 2–D coplanar display.

This Study

The three experiments comprising this study were designed to evaluate performance on simple conflict detection (Experiment 3) and both simple and complex conflict resolution (Experiments 1 and 2) using either a 2–D coplanar display, a 3–D display with two different perspective views, or a 3–D display with a continuously manipulable viewpoint (summarized in Table 1). Our primary research question was this: Given a set of two-plane conflicts from a wide range of possible conflict geometries, could pilots effectively use the alternative viewpoints provided in the two 3–D displays to reduce ambiguity and produce detection and resolution performances equivalent to (or perhaps better than) that of the 2–D coplanar display? In addition, we investigated the effects of increased task load (in the forms of a concurrent tracking task and added nonconflicting traffic aircraft) and increased time pressure (reducing the time to conflict from 5 min to 2 min) on conflict resolution performance in the high task load resolution experiment.

TABLE 1
Comparison of the Three Experiments Conducted in This Study

	Three CDTI Experiments	
	Task(s)	*Independent Variables*
Experiment 1	Conflict resolution with alerting, RAT	• Display dimensionality • Conflict geometry
Experiment 2	Conflict resolution with alerting, RAT, five distracter aircraft Concurrent tracking task on separate screen	• Display dimensionality • Conflict geometry • Time pressure
Experiment 3	Conflict detection, no alerting or RAT	• Display dimensionality • Conflict geometry

Note. CDTI = cockpit display of travel information; RAT = route altering tool.

We hypothesized that performance (both detection and resolution) would be worse for the two 3–D displays compared to the 2–D coplanar display due to the inherent ambiguities of 3–D displays, to the extent that the interactive viewpoint features were not used. However, we predicted that if pilots used the interactive viewpoints, then any performance differences attributed to spatial ambiguities would be reduced or eliminated to the extent that pilots could use the provided alternative viewpoints to reduce those ambiguities.

In addition, we hypothesized that conflict geometries involving vertical changes made by the intruder would be more difficult to detect and to resolve because they involve simultaneous changes in three spatial axes. This drop in performance would be manifested by a lower resolution success rate and longer response times.

Finally we hypothesized that increased workload, in the form of increased time pressure and task load from a concurrent task, would reduce performance and, to the extent that it reduced viewpoint interactivity, would be a greater detriment to the two 3–D displays.

METHOD: EXPERIMENTS 1 AND 2

Because Experiments 1 and 2 used the same displays, procedures, and tasks, we describe the common methods for those two experiments and then the differences between them prior to reporting the results for each experiment.

Displays

Each of the three experiments used the following three displays, created from the 3–D volumetric cockpit situation display developed at NASA Ames Research Center (see Granada et al., 2005). The 2–D coplanar display, shown in Figure 3, was composed of a top-down view and a side view of the same airspace presented next to each other on a 21-in. monitor.

The 3–D toggle display consisted of two serially presented perspective views, shown in Figure 4. Pilots could choose which perspective to view by pressing a button labeled View 1 or View 2 on the button bar along the bottom of the CDTI. When the View button was clicked, the display rotated smoothly from one perspective to the other, providing motion parallax and continuity between the two views.

The 3–D manipulable display initially presented the pilots with a 2–D top-down view (the left view in Figure 3); pilots could manipulate the viewpoint by holding down the right mouse button and moving the mouse up or down to change the vertical angle between 0° and 90° vertical, or moving it left or right to change the lateral position anywhere in the range of 0° to 359° lateral. The display rotated smoothly according to the mouse movements, again providing motion parallax and continuity between possible viewpoints.

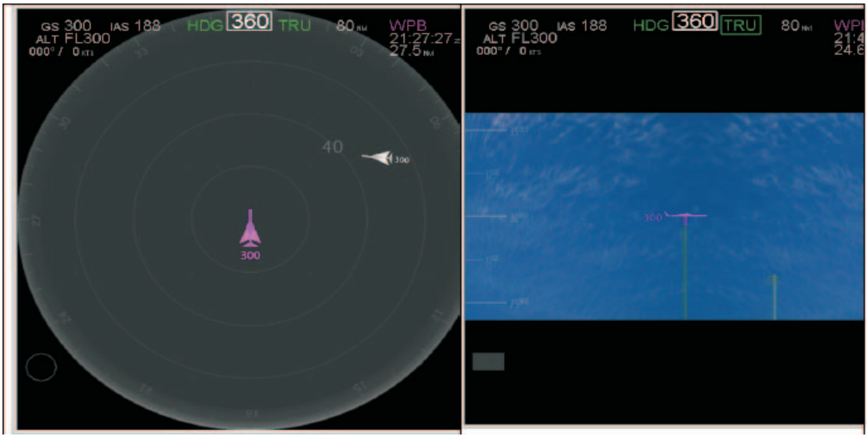
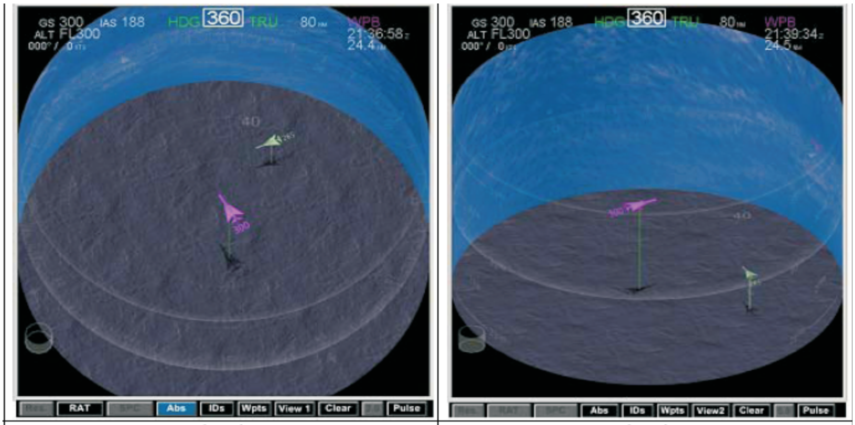


FIGURE 3 The top-down and side views of the airspace, comprising the 2–D coplanar display.



Toggle View 1

Toggle View 2

FIGURE 4 Two possible perspective views provided in the 3–D toggle display condition. View 1's viewpoint was set at 60° vertical and 30° to the left of ownship. View 2's viewpoint was set at 30° vertical and 60° to the right of ownship.

Participants

Thirty student pilots from the University of Illinois participated in each of the two experiments and were paid $8 per hour for their participation. Across Experiments 1 and 2, the average age was 22 years and the average number of flight hours was 400.

General Tasks and Procedure

Participants in Experiments 1 and 2 were to perform conflict resolutions by using the Route Altering Tool (RAT; see Thomas & Johnson, 2001), a graphical interface provided within the CDTI, to adjust the current flight path and provide a new flight path (resolution) that would avoid the existing conflict. To create a resolution, the participant used the left mouse button to click on the ownship's flight path to create a maneuver-start waypoint, and clicked on a second point on the flight path to create a new waypoint that could be positioned laterally by holding the left button down and dragging the waypoint horizontally (left or right) or positioned vertically by mouse-clicking on the up or down arrows in the pop-up menu's Altitude line. The flight path of ownship changed graphically to illustrate the vertical change. Although all aircraft icons had 5-min flight path predictor lines associated with them, only ownship's flight path could be altered.

The participant needed to decide whether the conflict would be avoided by the new flight path he or she has created, cued by a dynamic color change (the flight paths and intruder icon turned from yellow to white if the path was conflict free). If the conflict was not resolved, the participant could continue making alterations to the new flight path. In the current paradigm, failures did not represent actual losses of separation, but rather that the resolution path as entered would still result in a predicted conflict. In actual flight usage, pilots would have a chance to correct the unsafe resolution before any loss of separation occurred. Once the desired changes had been made, the participant left-clicked on the Enter button (located next to the RAT button on the display), then confirmed it by clicking on the Execute button that would pop up. After Execute had been selected, the trial ran for another 5 sec, and then the next trial began.

Design: Experiment 1

Experiment 1 (E1) investigated the effects of display format on conflict resolution for conflict scenarios involving two aircraft: ownship and intruder. At the beginning of the experiment, the participants were randomly assigned to one of the three display conditions. Table 2 outlines 27 (or 3 × 3 × 3) unique conflict geometries (the within-subject variables) that were used as the conflict trials. All trajectories were designed so that an actual collision would result if no maneuver were undertaken.

The total number of experimental trials was increased to 162 by choosing six angles (three from the right and three from the left) within each subset of the 27 unique geometry classes, so that the six conflicts within each subset were similar but not identical (e.g., not entirely predictable). Ownship was always flying a straight and level trajectory at flight level 300 (or 30,000 ft) with heading 0° and airspeed 300 kt. The same set of 162 trials was presented in a randomized order in each of the three display conditions.

In E1, each trial was constructed so that the conflict was predicted to occur 5 min from the start of the trial. The conflict was highlighted by the use of alerting color (both ownship and intruder symbols and flight paths were depicted in yellow) and a pulse predictor (Thomas & Johnson, 2001), which traveled along the predicted flight path lines to illustrate the planes' estimated trajectories in speeded-up time.

Design: Experiment 2

Experiment 2 (E2) used the same display conditions (coplanar, toggle, manipulable) and a subset of the same conflict geometries (three levels each of angle, altitude, and relative speed) as those described in E1. In addition, another independent variable was the time pressure of each conflict, In E2, half of the trials included 5-min conflicts (low time pressure), whereas the other half included conflicts that were predicted to occur 2 min from the start of the trial (high time pressure condition). Barring an ideal response, the penalties for any delay, such as a reduction in possible maneuver choices, would quickly become harsher in the 2-min trials.

To increase the realism of the simulation, a second change in E2 was to increase the pilot's task load by adding a concurrent tracking task (presented on an adjacent monitor) that pilots performed continuously while also resolving conflicts on the CDTI. A delay of 18 sec from the start of the trial before the intruder aircraft appeared and a conflict between ownship was added so that conflicts were not continuously presented, and the conflict was signaled by the onset of intruder, color change of ownship's icon and flight path from white to yellow, and a single aural tone. Pilots were instructed that they should feel free to observe the configuration of traffic in the airspace and, in the toggle and manipulable conditions, to manipulate the viewpoint if desired prior to the presentation of a conflict, as long as the tracking task did not suffer as a result.

In addition, five traffic aircraft that were not in conflict with each other or with the ownship or intruder were added to the CDTI airspace. These traffic aircraft were intended to increase the complexity of the airspace and limit the possible number or type of resolutions available to the pilot.

Finally, the number of trials in E2 was reduced from 164 to 60 (30 5-min conflicts and 30 2-min conflicts). The 30 5-min conflict trials were taken directly from

E1 (to be compared directly to those E1 trials) and represented a wide range of conflict geometries. The 30 2-min conflict trials were created by taking the first 30 trials and reducing the time to conflict from 5 min to 2 min, so that the geometries were kept consistent and only time pressure varied.

Tasks and Procedures

Pilots were instructed on how to use the RAT to perform the conflict resolution task. In addition, they were trained on the tracking task, which required them to use a joystick with their left hands to control a cursor laterally and vertically, through first order of control (velocity) dynamics, to keep it centered on the screen. The possibility of a cursor drifting off the screen ensured that pilots could not attend to the CDTI for too long before needing to return to the tracking task.

The 60 experimental trials were blocked into three sessions of 20 trials. Pilots were instructed to perform the tracking task as well as possible, but not to ignore the information on the CDTI, which could produce catastrophic consequences (a collision with another aircraft) if ignored. At the end of each session, pilots could either take a break or continue, until all three sessions were completed.

RESULTS: EXPERIMENTS 1 AND 2

Results from the data collected in E1 and E2 are presented together in the following section. For each subsection, results are presented first from E1, then from E2. To directly investigate the effects of the tracking task and extra traffic aircraft present in E2, we compared the performance (success rate, response times, maneuver preferences, and viewpoint interaction) in the 30 5-min look-ahead time (LAT) conflict trials in E2 with those 30 trials (also 5-min LAT) in E1 that had the same conflict geometries. These comparisons are presented last within each subsection where applicable. For each experiment, the effects of display variable, lateral conflict angle, and altitude change on resolution success, response time, and efficiency were analyzed using one-way analyses of variance (ANOVAs). In E2, time pressure effects were analyzed in repeated measures ANOVAs as the sole repeated variable and then in combination with each conflict geometry repeated variable (display condition was always the between-subject variable).

Resolution success data from E1 were collapsed across the relative speed variable and an arcsine transformation was used that reduced skew from –2.71 to –0.77. Data from E2 were not collapsed due to the limited number of trials in each conflict geometry category, and no transformation was performed (skew was –0.76). Results pertaining to relative speed are presented in Thomas and Wickens (2005).

Display Dimensionality

Display dimensionality had no effect on resolution success in either E1 or E2 ($p > .20$ in both cases). In E1 overall success rates were 96% for 2–D coplanar, 95% for 3–D toggle, and 91% for 3–D manipulable. In E2, overall success rates were 75% for 2–D coplanar, 81% for 3–D toggle, and 79% for 3–D manipulable. The success rate for the 5-min conflicts in E2 (82%) was significantly lower than for the comparable trials in E1 (92%), $F(1, 54) = 15.37$, $p < .01$; however, this did not vary by display type, suggesting that increased workload negatively impacted performance equally across the 2–D and 3–D displays.

Furthermore, display dimensionality had no effect on response times in either E1 or E2 ($p > .20$ in both cases). Average response time was 18 sec for E1 and 20 sec for E2. However, response time for the 30 5-min trials from E2 (18.8 sec) was marginally significantly faster than response time for the matching trials in E1 (21.2 sec), $F(1, 54) = 3.50$, $p = .07$.

The efficiency of the resolutions was evaluated by the amount of lateral and vertical deviation from the original (straight) flight path, as measured at the resolution's CPA to the intruder. Lateral deviation in the 2–D coplanar condition was significantly lower (2.7 nm greater deviation at CPA) than in the 3–D manipulable condition, $t(17) = 2.12$, $p < .05$, in E1, and was significantly lower (2.5 nm greater deviation at CPA) than in the 3–D toggle condition, $t(9) = 2.34$, $p < .05$, in E2. Vertical deviation did not differ by display condition.

Interactivity data revealed that pilots consistently used the interactive viewpoint features in both 3–D displays throughout both experiments, although this interactivity decreased from E1 to E2 for both toggling, $t(18) = 2.29$, $p < .05$, and viewpoint manipulation, $t(18) = 4.35$, $p < .01$.

Conflict Geometry

As the lateral conflict angle decreased (from head-on to overtake), resolution success in E1 decreased, although this effect was limited to the manipulable condition, $F(4, 54) = 3.01$, $p < .05$. Although lateral conflict angle had no significant overall effect on performance in E2, post hoc comparisons showed a significantly lower success rate for head-on conflicts using the 2–D coplanar display than the toggle, $t(18) = 3.43$, $p < .01$, or manipulable, $t(18) = 1.97$, $p = .06$, displays. As lateral conflict angle decreased, response times increased in E1, $F(1.7, 44.1) = 36.22$, $p < .01$, and E2, $F(1.75, 47.14) = 20.95$, $p < .01$, independently of format.

Altitude change had no effect on resolution success, and did not significantly interact with display condition for either experiment. Ascending conflicts were marginally faster to resolve than level or descending in E1, $F(2, 54) = 2.84$, $p = .06$, and E2, $F(2, 54) = 3.96, p < .05$; for 5-min conflicts only. In E2, the 2-min conflicts revealed a time cost for nonlevel conflicts, $F(2, 54) = 30.84, p < .01$.

Time Pressure

Time pressure analysis in E2 also revealed that resolution success rates were significantly lower (74%) in the 2-min conflicts than the 5-min conflicts (82%), $F(1, 27) = 21.33, p < .01$. There was no significant interaction between display condition and time pressure, $F(2, 27) = 0.65, p > .20$.

Time pressure had a significant main effect on response time, $F(1, 27) = 33.54, p < .01$. The pilots took an average of 2.5 sec longer to resolve the 2-min conflicts than the 5-min conflicts. Furthermore, as we noted earlier, the extra time in the 2-min conflicts was associated with a decrease in resolution performance on those trials when intruder speed was the same as ownship. The interaction between display condition and time pressure on response times was not significant, $F(2, 27) = 1.26, p > .20$. It appears that the response time cost to increasing time pressure is uniquely manifest in geometry involving nonlevel traffic and traffic traveling at faster speeds than ownship.

DISCUSSION: EXPERIMENTS 1 AND 2

Effects of Display Dimensionality

There was very little support for the hypothesis that performance would be worse for the two 3–D displays compared to the 2–D coplanar display due to the inherent ambiguities of 3–D displays. There were no consistent overall performance differences between the 2–D coplanar and 3–D toggle and manipulable conditions. In E1, there was a drop in success rate for the 3–D manipulable condition only, limited to resolving crossing and possibly overtake conflicts. Conversely, in E2, a benefit was observed for resolving head-on conflicts in both 3–D conditions over the 2–D coplanar display. However, both 3–D displays showed reduced lateral efficiency (larger flight path deviations) relative to the 2–D coplanar display. We infer that this lack of support for the first hypothesis is due to the presence of the viewpoint interactivity features in each of the two 3–D displays, which allow for alternate, pilot-controlled viewpoints that help resolve the spatial ambiguities associated with any one viewpoint (Sollenberger & Milgram, 1993). Even the significantly lower amounts of both toggling and viewpoint manipulations in E2 (compared to E1) were sufficient to reduce 3–D spatial ambiguities in most cases and produce performance comparable to that of the 2–D coplanar display.

Effects of Vertical Conflict Geometry

The hypothesis that conflicts would be harder to resolve when the intruder was making a vertical change (ascending or descending) than when the intruder was flying level was not supported by the results from either E1 or E2, which showed no differences in resolution success between level and nonlevel intruder flight, although there was a response time cost associated with nonlevel flights under increased time pressure. Furthermore, three benefits for nonlevel flight were actually observed: (a) in 5-min conflicts (all of E1 trials, half of E2 trials), ascending (i.e., nonlevel) conflicts resulted in the fastest response times with no drop in safety; (b) in E1, nonlevel conflicts invited less vertical maneuvering, and such maneuvering was found to be less safe (lower success rates) than the lateral maneuvers; and (c) in E1, when nonlevel conflict were resolved with vertical maneuvers, these had less deviation (were more efficient) than the vertical maneuvers used to resolve level conflicts.

The emergence of these benefits in this study, in contrast to the hypothesized costs, may be due to the fact that the previous studies cited earlier (e.g., Alexander et al., 2004; Merwin et al., 1998) dealt with experimental paradigms where pilots were actually flying the resolution maneuvers in a flight simulator (rather than creating maneuvers with a planning tool) and were also dealing with conflicts of much shorter LATs (45 sec) than the conflicts in E1 and E2. Perhaps one effect of the current planning paradigm was to eliminate cognitively or time-based differences between vertical (lower cognitive demand, faster implementation) and lateral (higher cognitive demand, slower implementation) maneuvers that were more prevalently observed under conditions of higher time pressure (Alexander & Wickens, 2002; Krozel & Peters, 1997).

Effects of Increased Workload (Time Pressure and Concurrent Task)

As anticipated, the increased workload from E1 to E2, specifically the presence of the concurrent tracking task, significantly decreased performance on the conflict resolution task compared to the matched trials in E1. The increased time pressure within E2 also lowered success rates on the conflict resolution task by 8% from the 5-min conflict trials to the 2-min conflict trials. The increased time pressure also resulted in longer response times; 2-min LAT trials took 2.5 sec longer to resolve than 5-min trials. This may reflect a dominance of the greater difficulty of resolving the short-LAT conflict geometries, offsetting the expected time pressure effects on response time (which would be to shorten this response time; Svenson & Maule, 1993). Collectively, these results indicate that the hypothesized workload cost to performance was amplified by time pressure, and the cost to response time was limited to high time pressure trials.

EXPERIMENT 3

Method

Experiment 3 examined the effects of display condition and conflict geometry on the task of conflict detection without the use of automated aids (RAT and dynamic color change). The same three display formats described earlier were used in this experiment. Thirty student pilot participants in this experiment and were paid $8 per hr for their efforts. The average age was 20.3 years and average number of flight hours was 183. Both planes retained their 5-min predictor lines, which emitted pulses at a frequency of about 18 pulses per minute. The pulses traveled the length of the predictor line at relative rates of speed (given the relative lengths of the predictor lines), which provided more information about the future location of the aircraft than the motion of the icons themselves across the screen, which was barely perceptible.

Four types of loss-of-separation scenarios were identified depending on whether a loss of separation was predicted in the lateral or the vertical dimension. True conflicts were defined as predicted losses of separation in both the lateral and vertical dimension. Nonconflicts could sustain a loss of separation in either the lateral or the vertical dimension, or neither dimension.

Total number of possible unique trials was 27 conflict (from E1) + (27 × 2 lateral CPAs) + (27 × 2 vertical CPAs) + (27 × 4 combination CPAs), or 216 possible nonconflict trials. Of these, we used all 27 conflict trials and 82 (out of the 216 possible) nonconflict trials, or 109 trials. In addition to the 109 trials where ownship was flying level, 53 trials were added where ownship made a vertical change, either ascending (26 trials, 9 of which were conflict trials) or descending (27 trials, 9 of which were conflict trials). In total, 162 trials were used in this experiment (45 conflict trials and 117 nonconflict trials) defined by parameters described in Table 2.

Pilots were asked to determine whether the two planes were on a course to lose separation in 5 min (conflict or nonconflict). They were given a time limit of 25 sec in which to make this decision, although they were able to respond more quickly if desired. Next they were asked to provide a confidence rating (very, somewhat, or not at all confident), make a decision as to whether they would maneuver in the given situation, and select the type of maneuver they would implement (from eight possible combinations of lateral, vertical, or dual-axis maneuvers).

Results

Because hit rate was constant and high across conditions, nearly all variance in sensitivity was reflected in false alarm rates (FAR), so the latter are the focus of analysis.

Overall the hit rate was 95% (pilots correctly identified 43 of 45 conflicts on average) and the FAR was 11% (pilots misidentified 13 of 117 nonconflicts as conflicts on average). Display dimensionality had no effect on hit rate, FAR, or sensitivity. Display condition did, however, have a significant effect on response time, $F(2, 29) = 4.91$, $p < .01$: The toggle condition (17 sec) had a significantly longer average response time than either the coplanar (12 sec) or manipulable (13.5 sec) condition.

Altitude change of the intruder had a significant effect on FAR, $F(2, 81) = 6.09$, $p < .01$; level conflicts had a significantly lower false alarm rate (7%) than nonlevel (14%) conflicts. Further investigation revealed that the high FAR for nonlevel flight was amplified in overtake conflicts, $F(2, 81) = 10.94$, $p < .01$. There was no significant interaction between altitude change and display condition on FAR, $F(4, 81) = 0.52$, $p > .20$.

There was a significant interaction between ownship and intruder vertical behavior on FAR, $F(4, 174) = 9.59$, $p < .01$, when both ownship and intruder were making vertical (altitude) changes, shown in Figure 5. When ownship was level, intruder behavior had little influence; however, when the ownship was making a vertical change, there were major costs to detection accuracy when the intruder was descending. Again, this pattern of interaction was not affected by display format.

Altitude change had a marginally significant effect on response times, $F(2, 81) = 2.65$, $p = .08$. Level configurations were responded to fastest (13 sec), then descending (14.4 sec), and finally ascending configurations took the longest to respond to (15.2 sec).

Discussion

The hypothesis that spatial ambiguities in the two 3–D displays would lead to poorer conflict detection performance compared to the 2–D coplanar display, as observed by Merwin and Wickens (1996) and Wickens et al. (1996), was not supported by the

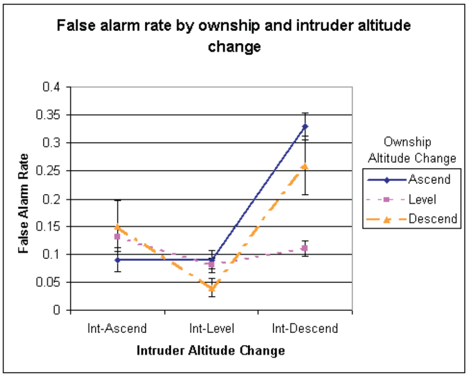


FIGURE 5 False alarm rate in conflict detection as a function of the altitude changes of both ownship and intruder.

results. The amount of viewpoint interactivity for both the toggle and the manipulable displays was even greater in E3 than in E1 (50% more toggling than in E1, almost 400% more viewpoint manipulation than in E1), and far more than in E2, and produced equivalent performance, in terms of sensitivity, between the two 3–D displays and the 2–D coplanar display. Furthermore, although nonlevel intruder behavior, especially when coupled with nonlevel ownship behavior, resulted in significantly poorer performance (higher FAR) than level conflicts, it was not found that 3–D displays suffered disproportionately on nonlevel trials, as had been observed in an air traffic control conflict detection experiment by Wickens et al. (1996).

GENERAL DISCUSSION

The collective performance results from Experiments 1, 2, and 3 indicate that pilots were able to use all three of the display conditions to produce exceptionally safe resolutions and correct detections of conflicts under low workload conditions. Although the safety of the resolutions was significantly affected by increased task load and time pressure, pilots still produced resolutions with a success rate of better than 75%. (Note that in this planning paradigm, pilots would be able to correct initially unsuccessful resolutions before a final flight decision was made.)

Overall these results can assist the choice of a designer to use a 2–D coplanar display or a 3–D perspective display (with the associated interactive support). This choice can be guided by the data in Table 3, which summarize the results of the current three experiments. Within the table, each cell represents a contrast between the 2–D coplanar display and either the toggle or the manipulable display, where the contrast is the presence (+ or –) or absence (0) of a main effect of the comparison between the 3–D and 2–D displays, with the | + | indicating a 3–D benefit, and the | – | a 3–D cost. This is done for each of the three important variables of display effectiveness: safety (predicted loss of separation), response time, and efficiency (deviation).

As the table indicates, the 2–D and 3–D displays produced comparable performance across most measures, with both 3–D decrements and benefits having qualified applicability (in that they only appear for certain conflict geometries and not uniformly across all scenarios). Neither 3–D display condition had a major detrimental effect on safety performance compared to the 2–D coplanar condition, and in some cases was even favored by better performance. Only the toggle display produced a response time decrement, and then only in the conflict detection task, which did not negatively affect the detection sensitivity. In terms of efficiency, each of the two 3–D displays produced greater deviations in some resolutions, although this effect was limited to lateral-only solutions. Although greater deviation translates to lower efficiency, the pilot is increasing the probability that the new

TABLE 3
Cost/Benefit Analysis of Each of the 3–D Displays Compared to the 2–D Coplanar on the Three Dependent Variables (Safety, Response Time, and Efficiency), Which Are Presented in the Order of Highest to Lowest Criticality to System Safety

	Safety			*Response Time*			*Efficiency*	
	E1	*E2*	*E3*	*E1*	*E2*	*E3*	*E1*	*E2*
3–D toggle	0	+ (for head-on)	0	0	0	—	0	– (lateral only)
3–D manipulable	– (for crossing and overtake angles)	+ (for head-on)	0	0	0	0	– (lateral only)	0

flight path will resolve the conflict by moving the ownship even further from the intruder, resulting in increased safety, which is a more critical system goal.

The lack of a clear-cut display dimensionality effect on performance on either conflict detection or resolution could be attributed to the presence of two viewpoint interactivity features that allow pilots to view the 3–D airspace from alternate viewpoints, reducing the spatial ambiguity associated with any one 3–D viewpoint (see also Sollenberger & Milgram, 1993; Wickens & Helleberg, 1999). In the conflict detection task, all three display conditions produced the same level of performance in terms of sensitivity to conflicts.

One potential vulnerability of the 3–D displays not captured by Table 3 is that viewpoint interactivity in both 3–D displays decreased significantly with increased dual-task workload (from E1 to E2), although the drop in interactivity was not additionally affected by increased time pressure. It should be noted, however, that overall performance between the 3–D and 2–D displays did not differ, which suggests that although these vulnerabilities may have contributed to the drop in performance from E1 to E2, they did not result in a greater penalty for the two 3–D displays compared to the 2–D coplanar. In fact, this may even suggest that because even a minimal amount of interaction is sufficient to eliminate ambiguity-induced performance decrements, with training pilots may become more effective in selecting optimal viewpoints with the minimum amount of time and effort.

In E1 and E2, the particular conflict geometries that were found to be the most difficult to resolve were those that involved intruder making a vertical change combined with small lateral angles of approach (overtake conflicts) between the two planes. In E3, when one or both aircraft was making vertical changes, producing a more spatially complex configuration than a level-flight conflict, pilots had to process spatial information in all three dimensions to detect the conflict and performance suffered as a result.

Increased time pressure resulted in longer conflict resolution response times, suggesting that the conflict geometries of the short-LAT conflict trials were sufficiently difficult that pilots felt they needed to invest extra time in resolving them, and despite this effort were still less successful than resolving the long-LAT conflicts. As anticipated, increased workload did significantly decrease performance on the conflict resolution task, although this effect was not amplified in the 3–D display formats.

Because this was a part-task low-fidelity simulation involving a novel CDTI display type, these results may only be generalizable in limited form to real flight situations. Nevertheless, some validity is preserved through the simulated demands of high pilot workload in E2, and many aspects of the results were consistent with Wickens, Helleberg, and Xu (2002), which was carried out in a relatively high-fidelity simulation and in which maneuvers selected actually needed subsequently to be flown, in contrast to the current simulation. Furthermore, on most advanced aircraft, “flying” a maneuver may be done as easily as varying a few parameters on a mode control panel or, potentially, downloading an automated solution from the RAT to an onboard flight management computer. It is our hope that these experiments provide the basis for future research that may investigate aspects of the CDTI and RAT tools that we were not able to address here, such as the effects of unreliable alerting and the potential solution of providing multilevel alerting or probability cues to the pilot, or the ability of the pilot to perform unaided conflict detection when the airspace is crowded.

APPLICATIONS

We continue to look at 3–D displays because they have the potential to offer integrated spatial information on a smaller display space than, say, coplanar displays, and display technology is getting to the point where generating high-resolution graphics with a rapid refresh rate is possible and cost effective. Rockwell Collins and Chelton Flight Systems, among others, are already flight-testing synthetic vision systems (SVSs) that produce integrated 3–D views of airspace, terrain, and weather for navigation and strategic flight planning (Ramsey, 2004). Although these SVS displays do not typically depict air traffic information, it is likely that integration of traffic information will be the next step in providing the pilot with all necessary information for optimal flight planning.

The main drive of the research discussed earlier was to determine whether the 3–D display could support conflict detection and resolution performance at least as well as the 2–D coplanar, by investigating different display interaction techniques designed to mitigate or eliminate previously found spatial-distortion problems of 3–D displays. What we have demonstrated here is that all the three display formats produce successful performance at nearly equivalent levels, suggesting that the choice to implement one over the others may be primarily based on the available flight deck space and potential limitations for display interaction rather than on the format's effect on performance.

CONCLUSIONS

Overall, the evidence suggests that the use of the interactive features in both of the 3–D displays produced performance that was almost equivalent to the coplanar display across most metrics. When the alternate viewpoints provided in both of the 3–D display conditions were used effectively, these conditions produced performance that was nearly as good for either task as that of the 2–D coplanar display, which is not without its few drawbacks. Furthermore, because both views in a coplanar display are possible to achieve in a manipulable-viewpoint 3–D display (although not displayed concurrently), the 3–D display may ultimately have an edge over the limited set of views in the coplanar. It is possible, then, that appropriate training in viewpoint selection may produce benefits to the 3–D display as workload increases to real flight deck levels.

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