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Effects of CDTI Display Dimensionality and Conflict Geometry on Conflict Resolution Performance

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With the presence of a CDTI that provides graphical airspace information, pilots can use a variety of conflict resolution maneuvers in response to how they perceive the configuration of the conflict. However, across previous studies on conflict resolution using CDTIs, there has been little apparent consistency in maneuver safety, flight axis preferences (lateral or vertical), or turning direction within a flight axis. These inconsistencies may be due to a limited range of conflict geometries and/or display frames of reference. This article describes a study that incorporates three displays with different frames of reference and a wide range of conflict geometries to determine their specific effects on maneuver preferences. Results indicated that the designs of the two 3-D displays, which included features to reduce spatial ambiguities, produced performance levels nearly equivalent to the 2-D coplanar display in almost all conflict geometry conditions. Overall, display dimensionality had no effect on success or response times and only a limited effect on direction preference within the lateral axis. Conflict geometry, especially lateral approach angle, affected success, response times, and preferences for maneuvering along different flight axes.

Introduction

The move towards Free Flight will require that the pilot have access to displays that will accurately support his/her understanding of the airspace (RTCA, 1995). This understanding will contribute to the pilot's ability to navigate through the airspace, maintain self-separation, and resolve potentially risky flight situations (conflicts) as they arise. In support of these proposed new responsibilities, cockpit displays of traffic information (CDTIs) are being developed to support pilot awareness and understanding of the airspace and the traffic within it (e.g. Johnson, Battiste, & Bochow, 1999). Currently, FAA-certified CDTIs do not contain any features for directly interacting with the flight plan to (for example) resolve conflicts, but there has been research to investigate the effectiveness of such a feature.

A conflict is defined as the loss of the minimum required separation distance between two aircraft, defined in this study as 5 nautical miles lateral and ± 1000 ft vertical; a resolution involves creating a new flight path that ensures that the two aircraft do not lose minimum separation. Although the Federal Aviation Regulations (FAR 91.113) recommend that conflicts be resolved by making lateral changes only, it is not mandatory and in fact the on-board Traffic Collision Avoidance System only provides vertical resolution recommendations when a conflict is detected. With the presence of a cockpit-based display that provides more detailed 3-D airspace information, pilots have more opportunities to use a wide variety of conflict resolution maneuvers (airspeed, altitude, and/or heading changes) in response to how they perceive the configuration of the conflict. Thus, it is also important to establish the extent to which the CDTI induces resolution maneuvers that are consistent or inconsistent with either TCAS resolution advisories (vertical only), or FAA "rules of the road" (lateral only).

Display Dimensionality

A CDTI is designed to show air traffic from the perspective of the pilot's own aircraft ("ownship;" Johnson, Battiste, & Bochow, 1999). Understanding of the airspace is supported to varying degrees by the dimensional frame of reference of the CDTI. The frame of reference dictates how the spatial information is depicted, whether it is two- or three-dimensional. It has been well established that for each frame of reference, there are benefits as well as costs (see Wickens, 2002, 2003 for review). Thus, selecting the most appropriate CDTI frame of reference depends on identifying the benefits and costs of each type of display for the particular tasks facing the pilot (e.g. conflict detection, resolution).

For example, in a 2-D coplanar display, there are two orthographic views of the airspace (from above and from the side or behind ownship) showing only two dimensions each. Each view in this format shows absolute spatial information in two dimensions without ambiguity, but requires effortful cognitive integration across both views for a full understanding of the 3-D environment (Wickens, 2002, 2003).

In a 3-D perspective display, all three dimensions are integrated and displayed in a manner analogous to the environment being depicted, but the particular viewpoint will cause some distortion in at least one, and possibly all three, spatial dimensions. Line-of-sight ambiguity is a result of the projection of the 3-D environment onto a 2-D screen, and can produce biases in estimating distances, such as foreshortening, along the compressed axes (Wickens, 2002).

One potential solution to the problem of viewpoint-related foreshortening is to allow the viewpoint to be positioned in a variety of angles so that the 3-D spatial environment may be viewed from different directions that disambiguate the relevant spatial information. This can be accomplished by either providing several pre-set viewpoints, which the pilot may choose between, or by allowing the pilot to freely and continuously reposition the viewpoint as desired (e.g. Wickens & Helleberg, 1999). Determining the feasibility of resolving this ambiguity through viewpoint rotation is one of the objectives of the current study.

Conflict Geometry

The conflict geometry between two planes (ownship and "intruder") can be defined by three parameters: **altitude** of intruder (both absolute and relative to ownship), **airspeed** of intruder (both absolute and relative to ownship), and the **angle** formed by the intersection of the trajectories of the two aircraft. Conflict geometry has been found to affect the type of conflict avoidance maneuver chosen by the pilot and the safety of those maneuvers (e.g. Scallen, Smith, & Hancock, 1997; Johnson, Bilimoria, Thomas, Lee, & Battiste, 2003).

Maneuver Choice Summary

The collective findings of the influences of conflict geometry and display dimensionality on maneuver choice and maneuver safety are somewhat inconsistent, but do allow a few conclusions to emerge, with varying degrees of certainty, as summarized in papers by Wickens, Helleberg, & Xu (2002), Alexander, Wickens, & Merwin (2005), and Thomas & Wickens (2005, in preparation).

Regarding maneuver choice, there is a general tendency to choose vertical over lateral maneuvers, at least when light (e.g., GA) aircraft simulations are involved. Furthermore there appears to be a tendency for the vertical preference to be enhanced to the extent that the linear vertical representation of the co-planar display is present. That is, the coplanar display enhances the vertical preference, while the 3D display diminishes it.

Within the vertical dimension, there appears to be a climbing preference that emerges with, and is consistently shown by, the co-planar display (Wickens & Helleberg, 1999; Alexander et al, 2005, Experiments 1 and 2; O'Brien & Wickens, 1997). However this preference is reduced, and sometimes reversed, with a 3D display which sometimes invites more descents than climbs (Alexander et al, 2005, Experiments 1 and 3).

The pattern of climb-descent preference is somewhat complicated by the influence of conflict geometry. With the coplanar display, pilots generally chose to maneuver in the opposite direction of the vertical behavior of non-level traffic. That is, they climb when it descends and vice-versa. However, with the 3D display this "vertical opposite tendency" appears to be less consistently manifest, and is sometimes replaced by a tendency to maneuver vertically in the same direction as the traffic (O'Brien & Wickens, 1997; Alexander et al, 2005, Experiment 1). Finally, at least within the coplanar display, the overall climbing tendency appears to be amplified to the extent that traffic approaches from the front (head-on conflicts).

Maneuver Safety Summary

Regarding maneuver safety, as typically measured by the amount of time during which there is a predicted loss of separation, whenever safety differed between display formats, this measure favored the coplanar display. Such a difference may be attributable to the ambiguity of the 3D display because such 3D costs tended only to emerge when the traffic was non-level (climbing or descending), a circumstance that will leave its vertical trajectory ambiguous on the 3D but not the 2D display (Alexander et al, 2005, Experiment 1; O'Brien & Wickens, 1997). This effect is replicated on Air Traffic Control displays as well (Wickens, Miller, & Tham, 1996).

Our study was specifically designed to contrast a 2D co-planar display with two versions of a multi-viewpoint 3D CDTI that were both designed to address the 3D ambiguity problems that have plagued single viewpoint 3D displays in the past (Alexander et al, 2005; Wickens & Helleberg, 1999). Both 3D CDTI versions allow for pilot control over the viewpoint and provide continuous motion between viewpoint rotations, producing motion parallax and different perspectives which may reduce the spatial ambiguities of any one perspective.

Hypotheses

H1. 3D ambiguity will be manifest as a drop in the success rate for resolving conflicts using the two 3-D CDTIs compared to the 2-D coplanar.

H2. However, the fact that alternative viewpoints are provided for each of the two 3-D CDTIs may be sufficient to reduce, and perhaps eliminate, the 3D costs relative to previous experiments.

H3. There will be a general preference for vertical maneuvering over lateral.

H4. Further, the better (more precise) rendering of the vertical axis in the 2-D co-planar CDTI may amplify this preference. That is, the 2-D co-planar CDTI will cause more vertical maneuvering than either 3D CDTI.

H5. Within the vertical axis, climbs will be preferred over descents, and vertical maneuvering will be opposite the traffic maneuvering, at least [particularly] with the coplanar displays.

H6. Vertical geometry (climbing-descending traffic) will present more difficult conflicts to resolve because this involves 3 simultaneous axes of change, and may lead to less accurate resolutions and/or longer response times in creating resolutions.

Methods

Participants. Thirty student pilots from the University of Illinois participated in this study and were reimbursed for their participation.

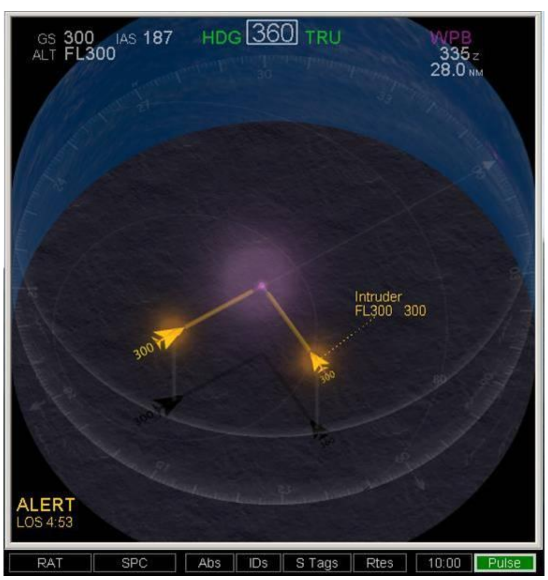

Figure 1. *Cockpit display of traffic information. Image shows Toggle condition View 1, conflict with an intruder in a crossing conflict from the left and traveling at the same speed and same altitude as Ownship.*

Displays. There were three different CDTI formats. The Coplanar display consisted of two side-by side views of the airspace, one top-down (showing the horizontal plane) and one from the side (showing vertical information). The Toggle display consisted of one display with two 3D viewpoint options that could be switched by pressing the "View 1/View 2" button on the CDTI button bar (see Figure 1). View 1 was set to 60 degrees elevation and 330 degrees azimuth (above and slightly to the left of ownship), and View 2 was set to 30 degrees elevation and 60 degrees azimuth (slightly above and far to the right of ownship). The Manipulable display consisted of one display with a viewpoint that could be set anywhere in the vertical range of 0°-90° or laterally from 0°-360° when moved around by the participant using the mouse.

Design. Table 1 outlines 54 (or 3 x 3 x 3 x 2) unique conflict geometries (the within subject variables) which were used as the conflict trials. The total number of experimental trials was tripled by choosing three angles within each subset of conflict angles so that the three sets of conflicts were similar but not identical. The conflict geometries were defined by the intruder's position relative to ownship and covered the spectrum of conflicts that may occur in real flight. The same set of 162 trials were presented in a randomized orders to different pilots in each of the three display conditions. All conflicts were direct collision courses between ownship and intruder.

Between	**Within**		
Display	**Angle**	**Altitude Change**	**Relative Speed**
Coplanar	Head-on (150º-210º)	Ascending to OS's alt.	Faster than ownship
Toggle	Crossing (70º-110º, 250º-290º)	Level, same altitude as ownship	Same as ownship
Manipu-lable	Overtake (20º-50º, 310º-340º)	Descending to OS's alt.	Slower than ownship

Table 1. Each level of each variable in this study.

Procedure and Tasks. At the beginning of the experiment, the pilots were quasi-randomly placed into one of the three display conditions. After signing consent forms, reading instructions, and performing practice trials, each pilot viewed 162 experimental trials consisting of a conflict between ownship and an intruder. Each trial was constructed so that the conflict was predicted to occur in 5 minutes from the start of the trial. Hence, head-on conflicts started with larger separation, and closed at a faster speed. Pilots were instructed to resolve each of the conflicts by making one of the following resolution maneuvers: lateral (by using the mouse to click and drag ownship's flight path into a new configuration), vertical (by using the mouse to click up/down arrows in a pop-up altitude change menu), or both in combination. Feedback from the alerting color changes indicated whether a proposed resolution was successful: if it was, the color of the aircraft changed away from yellow. Once a successful resolution was entered, pilots clicked an Enter and an Execute button, and after 5 seconds the next trial began.

Results

Resolution Success

Success data were first calculated by the percentage of the 18 trials within each category of display condition x conflict angle x relative speed (collapsed across altitude, after it was determined that altitude had no main effect or interactions with other variables) where participants entered a successful resolution. The data were skewed, and therefore transformed using the arcsine transformation A repeated measures ANOVA was conducted on the data, using the three levels of conflict angle and three levels of relative speed as the repeated measures, and display condition as the between subjects variable.

There was no significant main effect of display type on success of resolution. The significant main effect of conflict angle on resolution success ($F_{2, 54}$ =5.70, p<0.006) shows a decrease in performance as the conflict angle gets smaller: conflicts with intruders approaching at head-on conflict angles are easier to resolve (96%) than crossing angles (93%) or overtake angles (93%).

The significant interaction between display condition and conflict angle shown in figure 2 ($F_{4, 54}$ = 3.01, p<0.026) reflects the fact that only in the Manipulable condition were crossing and overtaking conflicts more difficult to resolve.

A significant main effect of relative speed of the Intruder compared to ownship ($F_{2, 54}$ = 6.18, p<0.004) reflects the fact that the best resolution performance occurs when the Intruder aircraft is faster (96%) than Ownship (no difference between same [93%] and slower [94%] speed performance).

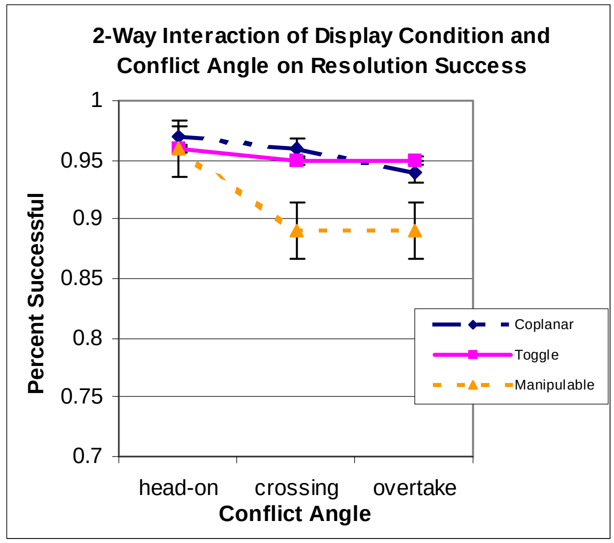

Figure 2. *Resolution success as a function of display condition and conflict angle.*

Response Times

There was no significant main effect of display on response times nor was there any interaction between display and any parameter of conflict geometry.

There was a significant main effect of conflict angle on response times ($F_{1.6, 44.1}$ =36.32, p<0.001. Head-on (16.3 s) conflicts were the fastest to resolve (and also the most successful; refer to Figure 2), then crossing (18.1 s), and overtake (19.8 s) were the slowest (and least successful) to resolve. This is likely due to the fact that in head-on conflicts, the perceived time pressure from the faster closure rate may encourage faster maneuver selection.

Maneuver Axis Preference

Maneuver axis type for each successful resolution was categorized as one of three types: lateral (i.e. turn toward or away), vertical (i.e. climb or descend), or dual-axis combination (e.g. climbing left turn) maneuvers. Frequency of maneuver axis types was determined by calculating proportion of each type of maneuver across successful trials in each conflict geometry category for each pilot. These frequencies were then analyzed to determine whether pilots demonstrated a preference for one maneuver axis type over another.

An initial analysis revealed a slight but statistically non-significant (p=0.14) preference between the three maneuver categories (vertical: 40%, lateral 29%, combined 30%). To determine how other aspects of the conflict geometry might have moderated this preference profile, the three categories of maneuvers were then classified as a second independent variable in an ANOVA, so that the profile modification would be revealed as a statistical interaction between axis choice, and other display/geometry variables.

The analysis revealed that there was a significant interaction between conflict angle and maneuver axis preference ($F_{4, 104} = 13.06$, $p<0.001$; refer to Figure 3, left graphs). Vertical maneuvers were preferred over both lateral and combination in crossing conflicts, and over lateral in overtake angle conflicts. There was a significant interaction between altitude change and maneuver axis preference ($F_{4, 104} = 3.36$, $p<0.012$; Fig 3, center graphs). Vertical maneuvers were preferred over lateral and combination when the intruder was flying level. There was a significant interaction between relative speed and maneuver axis preference ($F_{4, 104} = 8.49$, $p<0.001$; Fig 3, right graphs). Vertical maneuvers were preferred over lateral and combination when the intruder was flying faster or at the same speed as ownship.

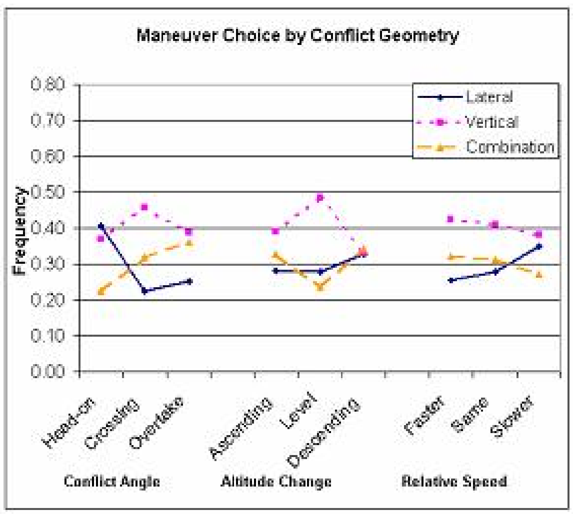

Figure 3. *Main effects of each parameter of conflict geometry on maneuver flight axis preference.*

Within-Axis Direction Preference

Maneuver axis preferences were further analyzed to determine whether there were preferences for turning one direction or the other within an axis.

Single-axis vertical direction preferences (ascents vs. descents) were evaluated on the basis of the intruder's vertical behavior (ascending or descending only; cases where intruder was flying level were analyzed separately). The vertical choice was significant ($F1, 26 = 50.4$, $p<0.001$), and shows a strong preference to maneuver vertically away from the intruder across all display conditions. This is consistent with the pattern of prior research using the 2-D coplanar CDTI research, but is less consistent with the pattern using the 3D display.

Vertical direction preferences when the intruder was flying level were then evaluated. There was a marginally significant effect of vertical direction preference ($F_{2, 52} = 2.84$, $p<0.07$), where ascents were most preferred, followed by level flight and then by descents, consistent with the results in Wickens et al (2002). Neither the display condition nor any dimension of conflict geometry had a significant effect on vertical direction preference.

Discussion

There appeared to be some support for H1, in that the Manipulable display produced the poorest performance overall and specifically in cases where the conflict was in a crossing over overtake configuration. However, there was also support for H2: there was no performance difference between the 2-D Coplanar and 3-D Toggle conditions, and even the 3D costs of the Manipulable display were attenuated, only manifest in two of the three conflict angle conditions, and then only in a 6% loss of accuracy (Figure 2).

There was marginal support for H3: overall, there was a slight preferences for vertical maneuvers, and in particular, vertical maneuvers were preferred over lateral and combination in both crossing and overtake angle conflicts, when the intruder was flying level, or when the intruder was flying faster or at the same speed as ownship. There were no circumstances in which lateral maneuvers were preferred.

Display dimensionality had no significant effect on maneuver axis preference; contrary to H4, the three-dimensional nature of the displays did not appear to significantly alter maneuver flight axis preferences compared to the 2-D coplanar display, and again, as with Hypothesis 2, suggesting that the interactivity of the viewpoints attenuated the previously-observed influences of the 3D display..

There was limited support for H5 in the data indicating that ascents were preferred over descents when the intruder was flying level. Furthermore, the preference to maneuver vertically away from the intruder (choosing descents significantly more often than ascents when the Intruder was descending) was stronger than the general preference for ascending maneuvers over descending. There was no support for H6: neither success rate nor response time was affected by whether the Intruder was flying level or making a vertical change in either direction.

One possible reason why our results did not replicate some previous findings of differences between 2-D and 3-D CDTIs is that the multi-viewpoint designs of the 3-D CDTIs used in this study reduced the ambiguities associated with single-viewpoint 3-D CDTIs, and thus reduced the decrements in performance attributed to those ambiguities. In addition, in our experimental paradigm pilots were asked to plan a resolution maneuver with interactive tools that provided safety feedback, but were not required to carry it out. Previous studies had pilots actually fly their resolution maneuvers, and it is unclear what differences, if any, may exist for maneuver flight axis preferences between planning a theoretical resolution and using a flight simulator to carry one out.

Conclusions

The interactive features of the two 3-D displays (multiple set viewpoints, continuously manipulable viewpoint) appeared to reduce ambiguity and produced success and response time performance levels more or less equivalent to the non-interactive 2-D coplanar condition, with a limited time cost associated with the Toggle feature. So far, analysis of the results indicates that there are limited main effects of display dimensionality and conflict geometry on conflict resolution characteristics.

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