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HORIZONTAL CONFLICT RESOLUTION MANEUVERS WITH A COCKPIT DISPLAY OF TRAFFIC INFORMATION

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PREFACE

This study investigated how pilots resolved potential conflicts in the horizontal plane when the only information available on the other aircraft was presented on a Cockpit Display of Traffic Information (CDTI). The intruder aircraft appeared on the CDTI with various programmed minimum miss distances, times to minimum miss distance, crossing angles, velocities, and turn rates. The pilot's task was to assess the situation and if necessary maneuver so as to avoid the other aircraft. No instructions were given on evasive strategy or on what was considered to be an acceptable minimum separation.

The results indicate that pilots had a strong bias of turning toward the intruder aircraft in order to pass behind it. In more than 50% of the encounters with a 90 degree crossing angle in which the intruder aircraft was programmed to pass either 2000 or 4000 feet behind ownship, the pilots maneuvered so as to pass behind the intruder. This bias was not as strong with the display which showed a prediction of the intruder's relative velocity. The average miss distance for all encounters was about 4500 feet.

INTRODUCTION

Two avionic systems are being developed which if implemented will provide pilots with information on other aircraft. One is the Cockpit Display of Traffic Information (CDTI) which shows the position and other information on nearby aircraft on an electronic map display. The second is the Collision Avoidance System (CAS) which in its simplest form provides warnings and maneuver commands to the pilot to avert possible midair collisions. In this latter system, to reduce the number of false alarms, commands are not issued until an immediate evasive maneuver is required to prevent physical contact between two aircraft. More complex collision avoidance systems also include an electronic display very similiar to a CDTI.

There are a number of potential advantages and disadvantages to presenting the pilot with situation information with a CDTI and command information with a CAS. The CDTI may interfere with the CAS by encouraging the pilot to assess the validity of alarms and commands and thereby exceed

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the pilot response times that have been assumed in the design of the CAS algorithms. An assessment of the situation displayed on the CDTI may also result in the pilot making a maneuver different from that commanded by the CAS. On the other hand, the CDTI may aid the CAS if it allows pilots to detect potential problems before they become serious and make small maneuvers which will eliminate the collision threat. The CDTI may help reduce pilot response time to CAS commands by alerting the pilot to the need for a possible evasive maneuver (reference 1). The CDTI may also help eliminate the startle factor that might accompany a CAS alarm.

Flight research on collision avoidance systems without a CDTI has shown that often when pilots visually acquired an intruder aircraft by looking out the window before a CAS alarm sounded, they made an evasive maneuver different than that recommended by the CAS (reference 2). These differences usually arose when the CAS algorithm chose a maneuver that would maximize the minimum miss distance and the pilot chose a maneuver that would keep the other aircraft in sight and/or would allow ownship to pass behind the other aircraft. Situations where the pilot does not follow the command can cause problems if the other aircraft is receiving a complementary maneuver command. A CDTI display provides information in a very different format than that provided by the pilots' out-the-window view and these conflicts might not arise with this display. One obvious difference is that the intruder aircraft is always equally visible when displayed on the CDTI irrespective of distance or bearing.

The objective of this part task simulation study was to determine what types of maneuvers pilots made when the only information that they had on the other aircraft was that presented on a CDTI. Later studies will investigate pilot behavior when both CAS commands and CDTI situation information are simultaneously available.

METHOD

Display Hardware: The CDTI was displayed on a 18 cm (7") by 18 cm (7") cathode ray tube (CRT) located directly below the attitude indicator in a fixed base cockpit simulator. The center of the display was 0.44 rad (25 deg) below the horizontal and 90 cm (35") from the subject's eye reference point. The display elements were generated by a general purpose stroke writing computer graphics system.

Display Symbology: The ownship was always displayed with a curved ground referenced predictor. This predictor curves during a turn to show the effect of turn rate on future aircraft position. Figure 1 shows the two types of intruder predictors. They were: 1) the curved ground referenced (CGR) predictor which shows the future position over the ground with the provision that the current velocity and turn rate of the aircraft remain constant; (2) Curved ownship referenced (COR) predictor which shows the intruder's future position relative to ownship assuming both aircraft maintain constant turn rates and velocities. The following display elements were not changed throughout the experiment: 1) present position of ownship was always indicated by a chevron symbol - the actual location of ownship was at the vertex of the symbol; 2) present position of the intruder was indicated by a dot in the center of a circular symbol; 3) RNAV route and runway symbols provided ground objects for background; 4) the width of the terrain displayed on the map was always 18.5 km (10 nm). With this map scale, 1.85 km (1 nm) on the ground equals 1.3 cm (0.5") on the display and 1.85 km on the map subtended a visual angle of 0.82 degrees; 5) the display was oriented with ownship track up; 6) track was updated every 0.1 seconds; 7) ownship position and all intruder information were updated every 4 seconds; and 8) ground referenced history which shows the past flight path of the aircraft over the ground was always present. No sensor noise or tracker lag was simulated.

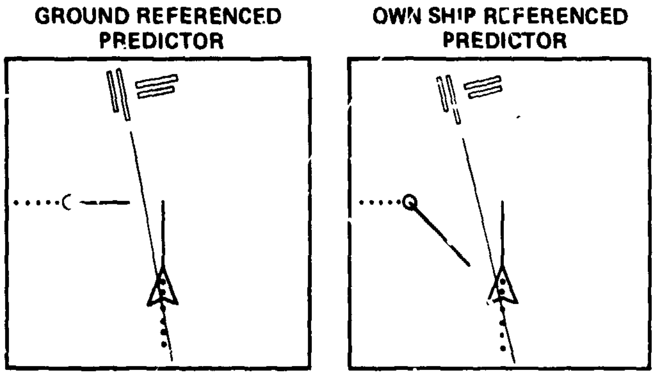

Figure 1. Two Experimental Display Formats

Encounter Variables: The experimental design incorporated a mixed factorial and star design. An encounter between the ownship and intruder ship was defined by the programmed miss distance (PMD), initial time to minimum miss distance (lead time), crossing angle of the intruder, speed of the intruder, and turn rate of both aircraft (see table 1). Ownship velocity was always 180 knots and both aircraft were always at the same altitude. An intruder with a positive programmed miss distance would pass ahead of ownship if ownship did not maneuver. The intruder was always initialized on the left side of ownship. With the intruder on the left, ownship actually had the right-of-way but the pilots were instructed that they should assume that the intruder had neither a CDTI nor a CAS and was not aware of ownships presence. On four of the encounters the intruder did maneuver 20 seconds after first appearing, but these turns were independent of ownships position.

Task: Subjects were asked to view the CDTI which depicted both ownship and the intruder. Subjects used the trim switch to turn ownship either right or left. Each "click" of the trim switch incremented the turn rate by 1.5 deg/sec.

Encounter No.	Programmed Miss Distance (feet)	Time to Programmed Miss Distance (sec)	Crossing Angle (deg)	Intruder Speed (knots)	Ownship Turn Rate (deg/s)	Intruder Turn Rate (deg/s)
1	+4000	30	90	180	0	0
2	+2000	30	90	180	0	0
3	0	30	90	180	0	0
4	-2000	30	90	180	0	0
5	-4000	30	90	180	0	0
6	+4000	60	90	180	0	0
7	+2000	60	90	180	0	0
8	0	60	90	180	0	0
9	-2000	60	90	180	0	0
10	-4000	60	90	180	0	0
11	+4000	90	90	180	0	0
12	+2000	90	90	180	0	0
13	0	90	90	180	0	0
14	-2000	90	90	180	0	0
15	-4000	90	90	180	0	0
16	+2000	60	90	120	0	0
17	-2000	60	90	120	0	0
18	+2000	60	90	240	0	0
19	-2000	60	90	240	0	0
20	+2000	60	45	180	0	0
21	-2000	60	45	180	0	0
22	+2000	60	135	180	0	0
23	-2000	60	135	180	0	0
24	+2000	60	90	180	+1.5	0
25	-2000	60	90	180	+1.5	0
26	+2000	60	90	180	-1.5	0
27	-2000	60	90	180	-1.5	0
28	+2000	60	90	180	0	+1.5
29	-2000	60	90	180	0	+1.5
30	+2000	60	90	180	0	-1.5
31	-2000	60	90	180	0	-1.5
32	+2000	60	90	180	0	+1.5*
33	-2000	60	90	180	0	+1.5*
34	+2000	60	90	180	0	-1.5*
35	-2000	60	90	180	0	-1.5*

* Intruder turned after 20 seconds

Table 1. Intruder parameters. In encounters 1 to 15, programmed miss instance and time to programmed miss distance were varied in a 3 by 5 factorial design. In the remaining encounters one parameter was varied at a time for PMD's of +2000 and -2000 feet.

Subjects: Eight current airline pilots served as paid subjects. They were selected from a pool of pilots who had volunteered to participate as test subjects.

Procedure: Pilots initially were given a brief description of basic CDTI concepts. A description of the predictors they would be using and instructions on how to use the trim switch to turn the ownship were given.

Pilots were instructed that they were to maneuver the ownship so that there were no collisions or near misses while keeping their deviation from course to a minimum. They were not instructed as to what was an acceptable miss distance or when or in which direction to maneuver. Pilots were instructed that the encounters would begin with different programmed minimum separations. It was explained that it was not mandatory to maneuver if it was thought that the current course was the best maneuver. The pilots were told that at the end of each encounter the CRT would display the minimum achieved separation. It was also explained that they would subjectively evaluate each encounter. Evaluation of encounters included ratings of how satisfied the pilot was with the overall maneuver.

Experimental Design: Pilots were presented with two blocks of all 35 encounters with one predictor type on the first day and one block of the same predictor on the second day. Four pilots saw each predictor condition in a between subject experimental design with subjects nested in predictor types. The order of the 35 encounters was random.

Objective data gathered included time and direction of the first turn, minimum achieved separation, maximum turn rate and maximum course deviation.

RESULTS

Analysis of the data from encounters 1 to 15, in which programmed miss distance and time to programmed miss distance varied while speed, crossing angle, and turn rate were held constant, was conducted by a four-way analysis of variance for repeated measures. Analysis of the data from the remaining encounters, in which the sign of the programmed miss distance, speed, crossing angle, and turn rate varied while the magnitude of the programmed miss distance and time to programmed miss distance was held constant, was conducted by a series of three-way analysis of variance for repeated measures.

Achieved Separation: Analysis of the data from all 35 encounters indicated that there was no significant difference in achieved separation between the two predictor types. Therefore, data from the two groups were combined.

The mean achieved separation over all programmed miss distances (PMD) and all times to minimum separation (lead times) in encounters 1 thru 15 was 4,410 ft. with a standard deviation of 1,560 ft. and a range of 300 ft. to 14,000 ft. This mean was fairly consistent regardless of the speed of the intruder (encounters 16-19; 4,470 ft.), the crossing angle of the intruder (encounters 20-23; 4,700 ft.) or the turn rate of the intruder (encounters 28-31; 4,780 ft.). However, the mean achieved separation did increase by approximately 1,600 ft. when (a) ownship was turning (encounters 24-27), or (b) intruder initiated a turn after 20 seconds (encounters 32-35).

In encounters 1-15 the ANOVA found that the main effects of PMD and lead time were both significant. The highest mean achieved separation for each lead time occurred at the PMD of +4000 ft., while the lowest mean achieved separation for each lead time occurred at the PMD of -2000 ft. or 0 ft. (figure 2). The highest mean achieved separation for all PMD (except +2000 ft.) was at the lead time of 90 seconds while the lowest mean achieved miss distance for all PMD was at 30 seconds. It appeared that a greater difference in mean separation was found between the lead times of 30 and 60 seconds than existed between the lead times of 60 and 90 seconds. In addition, over all lead times, +PMD had a higher mean separation than -PMD. This result was found in all other encounter blocks except where the intruder turned after 20 seconds. In this instance the results were reversed.

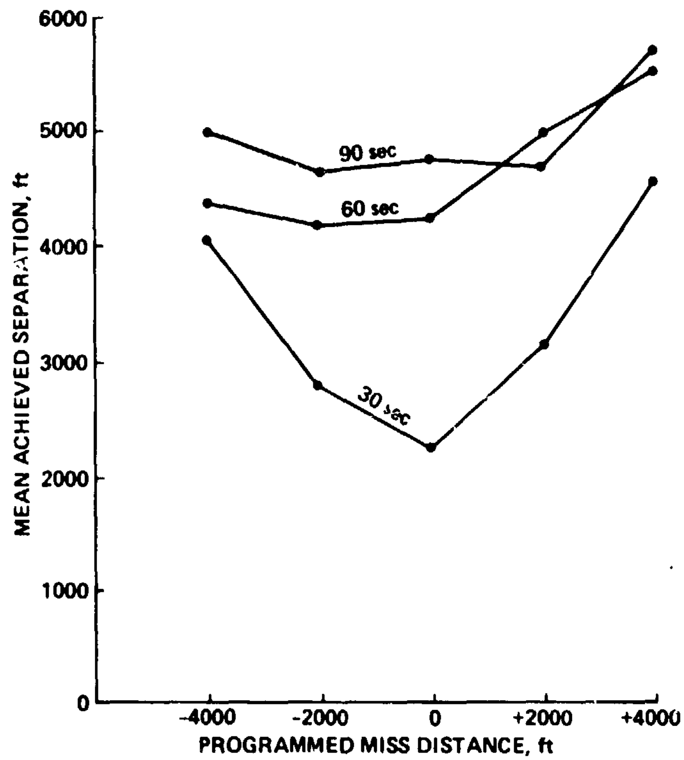

Figure 2. Mean Achieved Separation by Programmed Miss Distance for 30, 60, and 90 seconds to Programmed Miss Distance for Encounters 1 to 15.

Out of a total of 288 maneuvers in encounters 1-15, 31 maneuvers (10.7%) resulted in an achieved separation less than the programmed miss distance. These maneuvers will be referred to as "blunders". Over all lead times, the number of "blunders" was significantly higher for the -PMD (9%) than for the +PMD (1.7%) (figure 3). The number of blunders decreased as lead time increased but this effect was not significant. The CGR predictor group made significantly more "blunder" than the COR predictor group (figure 4).

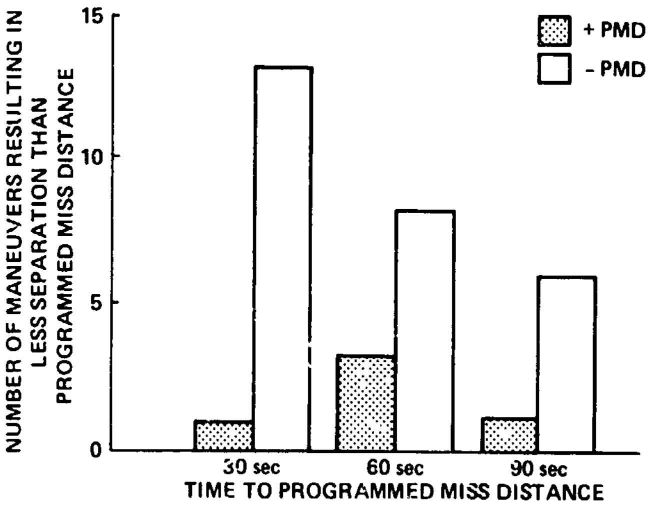

Figure 3. Number of Maneuvers Resulting in Less Separation than Programmed Miss Distance (blunders) by Position of Programmed Miss Distance (+PMD;-PMD) and Time to Programmed Miss Distance (lead time).

Latency Time Until First Maneuver: Data pertaining to this variable were obtained by recording the time from appearance of intruder on CDTI until pilots' initial maneuver. Trials in which no maneuvers were executed were not included in the analysis. Since analysis of data from all encounters except 16-19, in which intruder speed varied, showed no significant difference by predictor type, data for the two groups were combined in most instances. In encounters 1 to 15 the main effects of programmed miss distance and time to programmed miss distance were statistically significant ($p<.01$) and the interaction of programmed miss distance and time to programmed miss distance was significant ($p<.05$).

The latency time until first maneuver under the 30 second lead time condition (encounters 1-15) was 9.1 seconds with a standard deviation of 4.7 seconds. Thus, on the average, pilots made their first maneuver 9.1 seconds after the intruder appeared on the CDTI or after about 2 updates. The latency time until first maneuver increased as lead time increased.

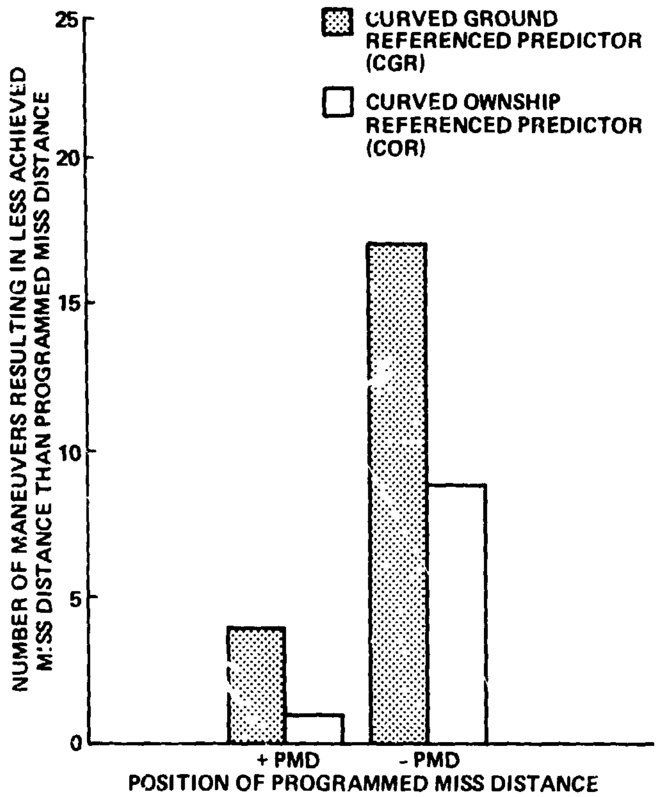

Figure 4. Number of Maneuvers Resulting in Less Separation than Programmed Miss Distance ("blunders") by Position of Programmed Miss Distance (+PMD; -PMD) and Predictor Type.

For each 30 second increase in lead time, pilots waited approximately an additional 10 seconds before maneuvering. This increase was fairly constant over all PMD.

In the encounters where lead time was held constant at 60 seconds but PMD, crossing angle, and initial turn rate were varied (encounters 7, 9, 20-31) the latency time until first maneuver ranged from 13.4 seconds to 19.9 seconds. However, when the speed of the intruder was varied (encounters 16-19) a significant difference ($p<.05$) was found by predictor type with the COR group, on the average, maneuvering approximately 10 seconds later than the CGR group.

Direction of First Turn: All pilots executed more left turns toward the intruder (67%) than right turns away from the intruder (17.5%) in encounters 1-15. Furthermore, seven out of eight pilots exhibited a statistically significant individual bias for turning left in the trials where there was a maneuver. This was consistent over all other encounters except where ownship was already turning. In this instance, 58% of the responses were "no turn"; however, where a maneuver was executed it was in most cases in the same direction that ownship was already turning.

Data from encounters 1-15 revealed that the CGR predictor group made a higher proportion of left turns than the COR predictor group (figure 5). This trend was also evident in most other encounter phases.

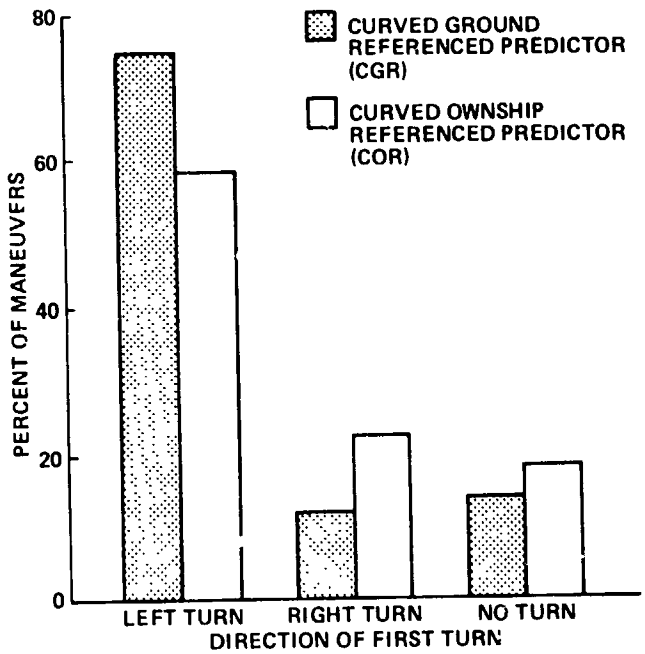

Figure 5. Percentage of Total Maneuvers which were "Left", "Right", or "No Maneuver" by Predictor Type.

Satisfaction Ratings: Analysis of data from the satisfaction ratings of each encounter (1=most satisfaction - 6=least satisfaction) revealed no significant difference in satisfaction by predictor type. Therefore, data from the two groups were combined. In encounters 1 to 15 the main effects of programmed miss distance and time to to programmed miss distance were significant ($p<.01$) as well as the interaction between programmed miss distance and time to programmed miss distance ($p<.01$).

The mean satisfaction rating for all lead time and PMD combinations for encounters 1-15 was 2.16 with a standard deviation of .52 and a range of 1.6 to 3.5. The pilots' lowest mean satisfaction occurred at the combination of 0 PMD and the lead time of 30 seconds. This was consistent with the point at which the lowest actual achieved miss distance occurred. The pilots' highest mean satisfaction occurred at the PMD of +4000 regardless of lead time.

Over all PMD, the pilots' mean satisfaction was lowest for the lead time of 30 seconds and about equal for the lead times of 60 and 90 seconds (figure 6). Once again, the mean satisfaction rating followed the pattern of the mean achieved separation.

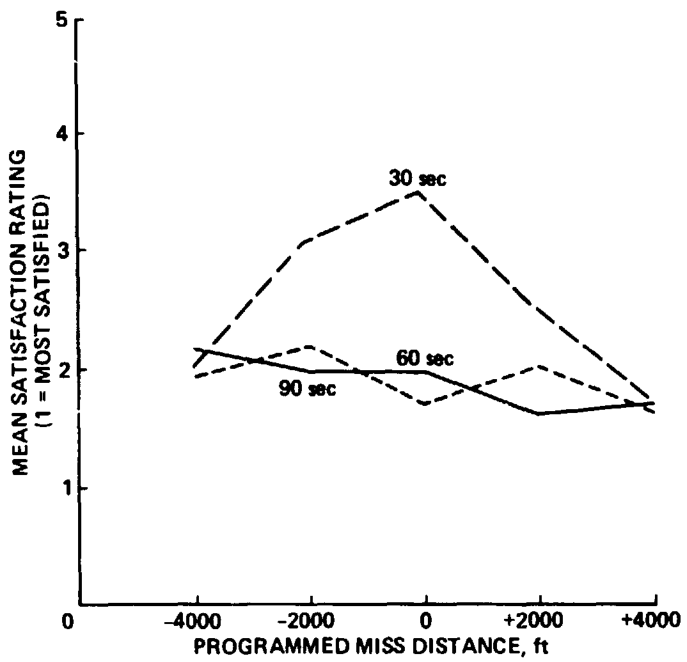

Figure 6. Mean Pilot Satisfaction Rating by Programmed Miss Distance and Time to Programmed Miss Distance (lead time).

This was evident for all encounter phases except where the intruder turned after 20 seconds. In this instance the results were reversed.

When the speed was varied (encounters 16-19), pilots were less satisfied at all speeds when the intruder passed behind ownship than when it passed in front of ownship. In addition, satisfaction decreased as speed increased. The lowest mean satisfaction occurred when the intruder was at 240 knots and passing behind ownship. No difference in satisfaction was associated with the crossing angle of intruder to ownship.

DISCUSSION

Seven of the eight pilots in this study had a bias toward turning so that they would pass behind the intruder aircraft. This bias existed even when the intruder aircraft was initially on a trajectory that would take it behind ownship if ownship did not change course. In these encounters, a turn toward the intruder caused ownship to actually turn through a collision course with the intruder. A CAS algorithm that attempts to just maximize the minimum separation between two aircraft would always command a turn away from the intruder in these situations. Apparently these pilots' maneuver decisions were influenced by objectives other than just maximizing the minimum miss distance.

One objective expressed by the pilots was a desire to keep the other aircraft in sight. This was expressed even though no external vision was provided in this simulation and the CDTI display allowed the pilot to "see" equally well in all directions. Pilots were apparently attempting to keep the intruder in a position so that if they could look out the window, they would be able to see the other aircraft.

A second possible objective, though not volunteered by the pilots, was to minimize the amount of time it took to resolve the conflict. A turn toward the intruder allowed the pilot to more quickly resolve the problem and to return to the original course. Since speed and altitude maneuvers were not possible in this experiment, a horizontal maneuver that turned away from the intruder would sometimes place ownship on a course parallel to the intruder with the intruder effectively blocking ownship from returning to its original course.

A third consideration was that when a turn was made toward the intruder, it was perceptually easier to judge when the conflict was resolved. A typical maneuver was to turn toward the intruder until the intruder was directly ahead of ownship and then roll out of the turn. As soon as the intruder was directly ahead of ownship and not heading toward ownship, the pilot knew that the intruder was no longer a threat. During a turn away when an attempt is made to pass in front of ownship it is not clear that the situation has been resolved until ownship is directly in front of the intruder. During this maneuver both aircraft are going in the same direction and it can take a long time to reach this position. The experiment described in reference 3 showed that pilots made better judgements in predicting whether an intruder would pass in front or behind their ownship as prediction time decreased. A turn toward the intruder reduces this prediction time whereas a turn away increases it.

These considerations suggest that there may be rational reasons that the pilots turned toward the intruder aircraft even though this maneuver requires initially turning through a collision course. These results suggest that if pilots use a CDTI to assess conflict situations and the command is to turn away from the intruder that pilots may make maneuvers opposite to the command. One possiblity for avoiding this problem would be for the CAS algorithm to command vertical maneuvers in situations where a turn away command would normally be issued. A second possibility is through the CDTI design. In this study the group of pilots with the relative predictor made fewer maneuvers to go behind the intruder when the intruder was on a course that would take it behind ownship than the group of pilots that had the ground referenced predictor. A third possibility is training pilots not to initiate collision avoidance maneuvers based on CDTI situation information. Instructing pilots that the other aircraft is receiving a complementary maneuver command would probably be persuasive. The results of this experiment might have been quite different if the pilot knew that the intruder had a CDTI or CAS and might therefore maneuver to avoid ownship. However if pilots feel that the CAS generates to many false alarms, they will probably start using CDTI and external visual cues to make independent threat assessments and evasive maneuvers in spite of training to the contrary.

CONCLUSIONS

Pilots were biased toward maneuvering so as to pass behind the intruder even when the intruder was programmed to pass behind their aircraft.

Of the two predictor display types, the pilots with the relative predictor display made fewer turns to pass behind the intruder, waited longer to make their first maneuver, and achieved about the same separation at closest approach.

Pilots maneuvered approximately 10, 20 or 30 seconds after the intruder appeared on the CDTI when the intruder was initialized 30, 60 or 90 seconds from the point of minimum miss distance.

Pilots generally expressed satisfaction with minimum achieved horizontal separations of 4000 to 5000 feet.

Future experiments would investigate the interaction between situation information displayed on a CDTI and maneuver commands from a collision avoidance system. Other experiments will investigate whether pilots can use the situation information on a CDTI to make small maneuvers well before a CAS alarm would sound that will resolve potential conflicts without triggering an alarm. These experiments will also investigate how pilot behavior changes when the intruder is a piloted simulator with a CDTI and/or collision avoidance system.

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