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AVOIDANCE MANEUVERS SELECTED WHILE VIEWING COCKPIT TRAFFIC DISPLAYS

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SUMMARY

Ten airline pilots rated the collision danger of air traffic presented on cockpit displays of traffic information (CDTI) while they monitored simulated departures from Denver. They selected avoidance maneuvers when necessary for separation. Most evasive maneuvers were turns rather than vertical maneuvers. Evasive maneuvers chosen for encounters with low or moderate collision danger were generally toward the intruding aircraft. This tendency lessened as the perceived threat level increased. In the highest threat situations pilots turned toward the intruder only at chance levels. Intruders coming from positions in front of the pilot's own ship were more frequently avoided by turns toward than when intruders approached laterally or from behind. Some of the implications of the pilots' turning-toward tendencies are discussed with respect to automatic collision avoidance systems and coordination of avoidance maneuvers of conflicting aircraft.

INTRODUCTION

Advances in aviation electronics make CDTI (cockpit displays of traffic information) a possible solution to congestion problems caused by current and projected air traffic (refs. 1 and 2). One of the possible roles of CDTI may be as a backup to the current air traffic control system. But CDTI may additionally provide a means of increasing safety, capacity, and efficiency of air traffic flow (ref. 3). The safety of this flow could be enhanced through improved pilot traffic monitoring, reduced emergency reaction times, and improved detection of blunders, such as altitude deviations. These goals might be achieved, for example, through better use of the "see and avoid" rule in visual flight rule (VFR) conditions; CDTI could help locate traffic out the window. Similarly, air traffic capacity and efficiency could be improved through the use of CDTI, since its use could allow more precise pilot-controlled spacing, merging, and tactical maneuvering to resolve potential traffic conflicts, thus helping pilots achieve optimum trajectories and reduced separation in coordination with other traffic.

Various questions have been raised, however, concerning problems posed by the introduction of CDTI systems. Pilot workload might increase (ref. 4). Pilot-controller conflicts might arise during the resolution of air traffic threats. Pilots might become unduly fascinated with CDTI and distracted from other cockpit duties. And finally, CDTI might interfere with pilot responses to collision avoidance systems also present in the cockpit (ref. 5).

Furthermore, since incorporation of pilot avoidance patterns into the collision avoidance logic could help reduce the conflict between pilots and automatic systems,

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the understanding of pilot biases while using CDTI would be of value in the design of such logic. For example, collision avoidance systems have been designed previously to maximize separation between aircraft, e.g., ATARS (ref. 6); however, pilot avoidance patterns may conflict with such a pure separation criterion (refs. 5 and 7).

Accordingly, any evaluation of CDTI for assisting the air traffic control process requires an investigation of pilot decisionmaking in conjunction with the use of CDTI in a wide variety of air traffic situations. The following experiment is a continuation of a series of experiments investigating pilot evasive maneuvers when the pilot is confronted with conflicting traffic on CDTI (refs. 5 and 8). The experiment was primarily designed to provide new data concerning the effect of the pilot's subjective perception of collision danger when monitoring an encounter with conflicting traffic. Objective parameters, such as relative speeds, heading difference, altitude, and miss distance, determine the physical characteristics of such encounters. Subjective factors such as perceived collision danger are only partly a function of the physical situation and provide a separate influence on the pilots' maneuvers.

In the following experiment, the subjective aspect of the encounter was investigated by examining the effect of presenting geometrically identical encounters on displays with different map ranges. We were particularly interested in the effect of different map ranges because for any given actual separation in the airspace the larger map range brings aircraft closer together on the face of the display. Thus, increase in map range conceivably could produce artificial increases in perceived collision danger by creating a false sense of close proximity of nearby aircraft. We chose to provide all displayed aircraft with constant time predictors since previous research (ref. 9) has suggested that pilots would require such predictors in order to interpret CDTI displays accurately.

METHODS

This investigation was designed as a part-task experiment using a three-factor central composite design (ref. 10). The factors used were intruder horizontal miss distance, intruder speed, and intruder initial starting altitude. The central composite design was repeated for two different map ranges and thus each of the factors was crossed with map range. This design allows the combination of a number of independent variables, resulting in many distinct traffic scenarios. Such an experiment would be prohibitively expensive and time consuming to use in more realistic simulations with fully crossed designs. However, the design precludes analysis of more than first order interactions. Since the higher order interactions are usually smaller and difficult to interpret, this limitation was considered acceptable by the investigators.

Subjects and General Procedure

Ten line-qualified commercial airline pilots whose flying time ranged from 5000 to 25,000 hours were tested. There were three captains, six first officers, and one second officer who had previously served as a first officer. The experiment consisted of 96 separate part-task scenarios of CDTI air traffic simulations presented with an Evans and Sutherland calligraphic picture system (Type PS 1). The experiment was controlled by a PDP 11/40 computer running a program called INTRUD which generated the display and the traffic pattern, and recorded the pilots' responses (ref. 11). Pilots responded on the Evans and Sutherland console, which was placed on a table in front of the display. The ten pilots took from 1.0 to 3.0 hours each to complete all 96 scenarios. The average time was 2.2 hours. A short debriefing after each experimental run consisted of a question and answer session. The pilots took a 10-minute break after each hour of experimentation.

Definitions of Dependent Variables

During each traffic scenario, pilots could respond by indicating an intention to call the air traffic controller (ATC) or by selecting an avoidance maneuver or both. The time of these responses was measured with respect to the time before the predetermined minimum separation between the conflicting aircraft. The time of calling ATC was intended to measure pilot sensitivity to a situation unusual enough to require more information from ATC. The time to maneuver was interpreted as the time at which the pilot could no longer tolerate conditions without maneuvering his own ship (OWNSHIP). The pilot had to identify which of the aircraft caused his "ATC call" or maneuver by a workbook entry following each encounter. Each scenario stopped at the time the pilot selected a maneuver or ended after 2 minutes if he chose not to maneuver. The pilot's maneuver options were (1) no maneuver, (2) right turn only, (3) right turn and climb, (4) right turn and descend, (5) climb only, (6) descend only, (7) left turn only, (8) left turn and climb, and (9) left turn and descend. The ten pilots rated their perceived level of collision danger to OWNSHIP for the preceding scenario when each scenario ceased and the display froze as it had last appeared. The variable, collision danger, ranged across seven levels (1 through 7). Threat levels 1, 4, and 7, respectively, were anchored for the pilot by the definitions: no danger, standard spacing violation, and imminent near miss or collision. The pilot assigned one of these numbers to each simulated encounter.

Fixed Display Conditions

In addition to the intruding aircraft described below, each scenario featured two other aircraft. One was an air transport, initially situated at about the 10 o'clock position on the display, which always circled in a holding pattern with a data tag indicating an altitude of approximately 3048 m (10,000 ft) MSL. This circling transport was displayed with minor random perturbations of its speed and turn rate. It was the only aircraft turning in any of the scenarios. A second background aircraft had headings and speed distributions similar to the aircraft designated as intruder but randomly chosen for each scenario. However, this "pseudo-intruder" was always indicated to be at 2743 m (9000 ft) MSL with a horizontal miss distance with respect to OWNSHIP of 6.4 km (3.5 n. mi.). The presence of the "pseudo-intruder" forced the subject to discriminate the true intruder from two similar and potentially threatening aircraft moving toward OWNSHIP on different headings.

The display map formed a 20.3-cm (8-in.) square at a distance of 63.5 cm (25 in.) from the subjects and subtended a visual angle of approximately 18° (see fig. 1). The characters and symbols ranged in visual angle from 0.5° to 0.75° (5.5 to 8.2 mm), except for the OWNSHIP symbol, which subtended 1.75° (1.92 cm) along its longest dimension. Since we wished to be sure that accurate encounter information was available to the pilot, the display size was somewhat larger than that which actually might be used in a cockpit. The focus of the experiment was on the pilots' decision processes rather than on problems that might be introduced by the more limited resolution and potential clutter on a smaller display.

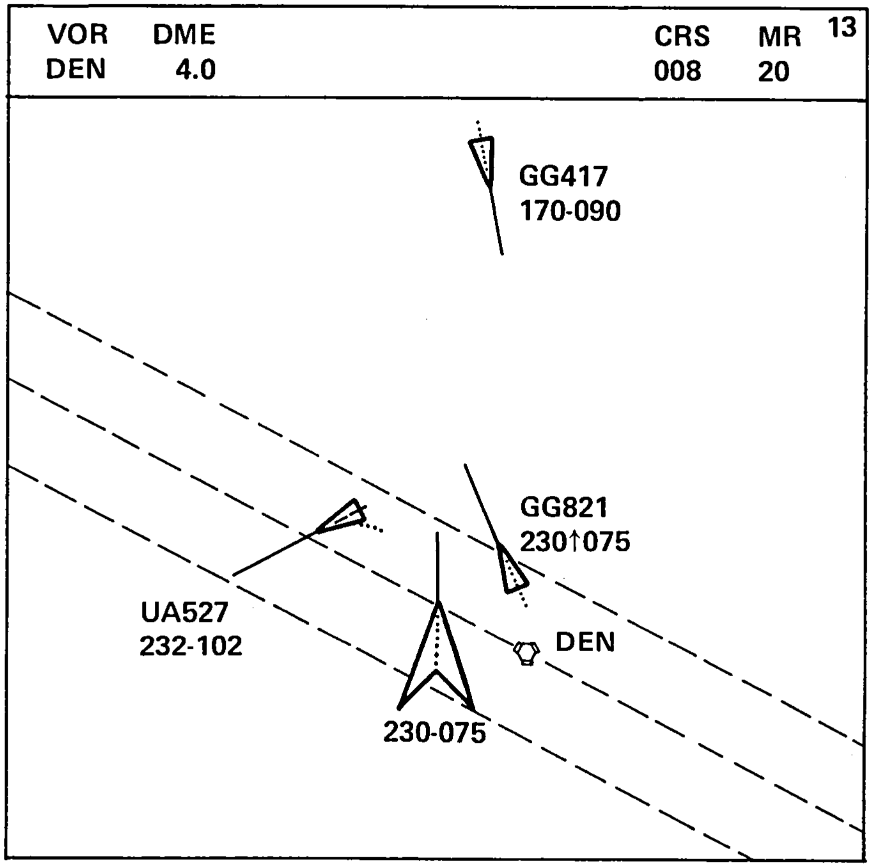

Figure 1.- Representative traffic scenario: The banner at the top indicates the currently tuned VOR, the DME distance to this station, the course from the station, and the distance in nautical miles from OWNSHIP to the top of the map, i.e., the map range. OWNSHIP is at an angle of 70° with respect to the 008 radial from the Denver VOR. The dashed lines indicate a band ±3 n. mi. along the current course. The predictors on all aircraft extrapolate current velocity for 60 sec. The history dots show 40 sec of previous positions with each dot corresponding to a 4-sec update.

As can be seen in figure 1, OWNSHIP was centered on the plan-view track-up display two thirds of the distance down from the top of the map. Intruding aircraft positions were updated every 4 sec. All aircraft traveled on the heading pointed to by their symbol. The course prior to vectoring, the runways, and the VOR were perceived to move continuously beneath OWNSHIP because of its higher update rate (five to six times per second) and small displacement at each update. The data tag for each aircraft listed: [first line] aircraft identification; and [second line] speed in knots IAS, direction of vertical movement (↑ up, - level, ↓ down) and altitude in hundreds of feet (MSL). The apex of each symbol indicated current position of the aircraft. The end of the solid line leading in the direction of flight indicated the predicted position in 60 sec. The dotted line trailing each symbol indicated a 40-sec history of previous ground-referenced position. OWNSHIP was a chevron and all other aircraft were triangles. The top of the map showed the name of the currently tuned VOR; the range from that VOR (DME in n. mi.); the course heading (CRS); and the map range (MR). The map range corresponded to the distance from the OWNSHIP position to the top of the map. Each scenario was sequentially numbered at the upper right corner of the display.

Fixed Encounter Parameters

OWNSHIP, the intruder, and the pseudo-intruder flew straight trajectories throughout all scenarios. In all scenarios OWNSHIP was flying straight and level at 230 knots IAS and at an altitude of 2286 m (7500 ft) MSL (712 m (2167 ft) AGL) above the Denver Stapleton airport.

Variable Encounter Parameters and Display Conditions

Previous studies have shown that pilots have difficulty in determining whether an intruder will pass in front of or behind their OWNSHIP (ref. 8) and, somewhat surprisingly, that miss distances ranging from 1 n. mi. in front to 1 n. mi. behind OWNSHIP did not influence perceived collision danger (ref. 5). Accordingly, only forward miss distances over a much larger range were selected for this experiment. This choice enhanced the possibility of detecting an effect of miss distance and reduced the problem of mixed response strategies based on where the intruder is perceived to cross the OWNSHIP trajectory. The planned levels of the independent variables concerning the intruding aircraft were determined by the central composite design. They were, respectively, intruder horizontal miss distance at the end of each sceanrio: 0.0, 1.0, 2.5, 4.0, and 5.0 km (0.0, 0.6, 1.5, 2.4, and 3.0 n. mi.), always forward of OWNSHIP. Intruder speeds were 130.0, 171.5, 230.0, 289.5, or 330.0 knots IAS, and intruder starting altitude relative to OWNSHIP altitude was -610 m (-2000 ft), -363 m (-1190 ft), 0 m, +363 m (1190 ft), or +610 m (2000 ft). The levels of each variable occurred in a 1:4:6:4:1 ratio such that the third or middle level was used most frequently. Intruder headings relative to OWNSHIP (-157.5°, -112.5°, -67.5°, -22.5°, +22.5°, +67.5°, +112.5°, or +157.5°; see fig. 2) were each presented an equal number of times and were randomized across the factors of the central composite design. The vertical miss distance of the intruders at the end of each scenario were similarly randomly varied across three levels; 152 m (500 ft) below OWNSHIP, at OWNSHIP's altitude, and 152 m (500 ft) above OWNSHIP.[1] The vertical speeds varied from 381 m/min (1250 ft/min) to -381 m/min (-1250 ft/min). This procedure generated 48 different encounter geometries, which were presented to the pilot with either a 18.5-km (10-n. mi.) or a 37-km (20-n. mi.) map range for a total of 96 encounters.

Experimental Procedure

Each pilot initially read a briefing booklet describing the research, the flight scenario, and the display format and symbology (see appendix A). The pilot was to consider himself commander of OWNSHIP, a medium-sized transport (727 or 737) enroute from Denver to Chicago. Having just taken off, he was to envisage being temporarily vectored off his outbound course (Denver 008 radial) because of thunderstorms. He was equipped with on-board CDTI showing true conditions unaffected by sensor noise or tracker lag. Other aircraft on the display were to be considered as having neither a CDTI nor a collision avoidance system. He was to assume that he was flying on automatic pilot and was to make ATC calls and maneuvers as he would during a normal departure from the Denver Stapleton airport. All calls to ATC and maneuvers would be assumed to be only in response to threat to OWNSHIP.

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[1]The vertical speed of each intruder was fixed by its relative starting altitude and its relative ending altitude (vertical miss distance). The time to minimum vertical separation for the scenarios varied since some intruders would start above (or below) OWNSHIP and fly to a point below (or above) OWNSHIP at 120 sec.

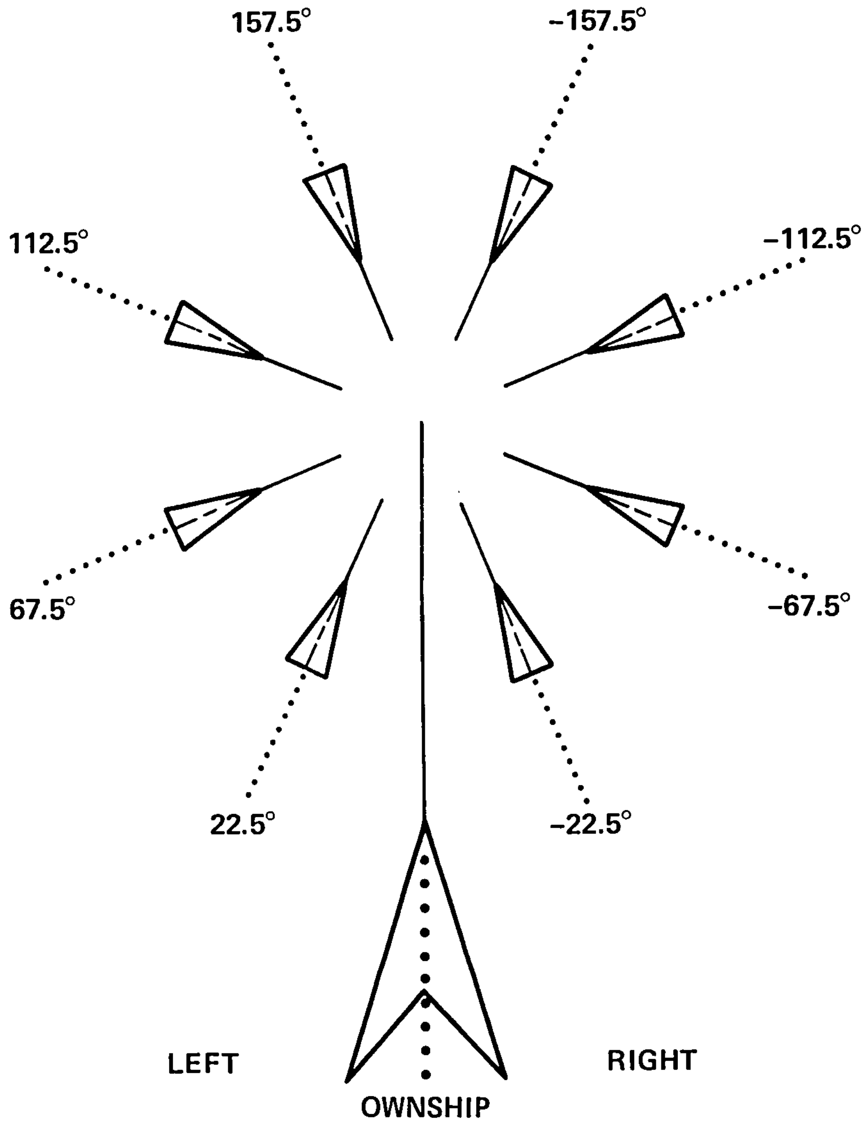

Figure 2.- Intruder headings relative to ownship: Diagram of the eight heading differences used in the experiment. Intruders would approach OWNSHIP from one of these orientations during each scenario. Pilot maneuvers to the left would be considered toward intruders with positive headings and away from intruders with negative headings.

After terminating each scenario, the pilot wrote down the tag number of the aircraft causing him to maneuver and his perception of the collision danger level of the scenario. Maneuvers were selected by pilot activation of discrete console switches. Use of a maneuver switch signaled the time the pilot would have maneuvered and the type of maneuver he chose, and terminated the trial by freezing the display in order to allow him to identify the aircraft causing his response.

Each pilot familiarized himself with the procedure and display during 16 practice scenarios which took about 20 min to complete. The experiment did not begin until all the pilot's procedural questions were answered and his performance on the practice scenarios demonstrated his understanding of the responses he was expected to make.

When uninterrupted by a pilot-selected maneuver, the scenarios required 120 sec to run to completion at which time the intruding aircraft would reach the predetermined horizontal miss distance. The sequence of scenario presentation was changed for each of the ten pilots to control for possible pilot fatigue or trends in pilot responses. Since the pilot could reduce the time spent on each scenario by maneuvering early, he had some control over the total duration of the experiment. We could thus check for evidence of boredom by examining each pilot's decision latencies as the experiment progressed. We found no evidence of pilots attempting to reduce the duration of the experiment.[2]

Definition of Maneuver Categories

For some analyses all climbing maneuvers ("climb," "climb right," and "climb left") were collapsed together. Similarly, all descending maneuvers were collapsed. All maneuvers except "climb only" and "descend only" were considered when calculating whether a response was turning toward or turning away from the intruder. A turn of OWNSHIP in the current direction of the intruder constituted "turning toward" and likewise turning OWNSHIP away from the intruder constituted "turning away" (see fig. 2). This coding assumed that the intruder's position was on the same side of OWNSHIP throughout the scenario and was determined by its heading difference as indicated in figure 2.

RESULTS

The ten pilots made 782 maneuvers in a total of 958 scenarios. In 930 of the 958 scenarios, pilots identified a threatening aircraft. In the 28 scenarios in which a threatening aircraft was not identified, there was only one scenario in which a maneuver was selected; no collision danger was reported for this encounter. The average collision danger for each of the remaining 27 scenarios, in which no maneuver was selected, was very low (1.04).

The following experimental results fall into two distinct categories. The first section describes the rather idiosyncratic effects of the independent variables on the major dependent variables. The following sections describe the highly reliable patterns of avoidance maneuvers selected by the pilots.

Multiple Regression

Multiple regressions of ATC call time, maneuver time, and subjective threat rating on five independent variables (horizontal miss distance, relative starting

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[2]For each pilot the regression of maneuver time on the sequence number of scenarios was computed. If there was a trend indicating boredom, for example, there could have been longer maneuver times for early scenarios and shorter maneuver times for later scenarios as the pilots attempted to shorten the experiment. No such trends were found.

altitude, speed, map range, and vertical miss distance) were computed separately for each pilot (ref. 10) (see table 1). The regression equations included terms for all possible linear, quadratic, and cubic main effects, and all possible first order interactions.[3] The multiple R_s ranging from 0.55 to 0.87, though statistically significant at the $p < 0.01$ level for almost all regressions, were not particularly large (see appendix B for table of regression coefficients).

TABLE 1.- REGRESSION EQUATIONS

$$[1]\ \text{Maneuver time} = A + \sum_{i=1,5} a_i x_i + \sum_{i=1,4} b_i x_i^2 + \sum_{i=1,3} c_i x_i^3 + \sum_{\substack{i=1,5 \\ j=1,5^{a}}} d_i x_i x_j + \text{error}$$

[2] ATC call time =	"	"	"	"	"	"
[3] Collision danger =	"	"	"	"	"	"

a(i),b(i),c(i),d(i)	= regression coefficients
x(i),y(i)	= independent variables
A	= intercept
error	= error with mean equal to zero

Subscript identities

i	Independent variable
1	Intruder speed
2	Intruder horizontal miss distance
3	Intruder relative starting altitude
4	Intruder vertical miss distance
5	Map range

[a]The interaction between intruder starting altitude and vertical miss distance was not included because they were correlated in the scenarios.

There was little commonality among the pilots' statistically reliable regression coefficients. The full regression equations provided as tables in the appendix present the multiple R_s, standard errors, and regression coefficients for all the regressions calculated for each subject. Not more than five pilots ever had statistically reliable, $p < 0.05$, coefficients for any of the same terms in any of the regressions. The main effect with the most intersubject agreement was that of horizontal miss distance on collision danger. For four pilots it did show a tendency for closer encounters to be associated with increased collision danger. The interaction with the most intersubject agreement was the joint effect of intruder speed and the display map range on the time five subjects chose to make ATC calls. This interaction reflects that fact that for any given time to minimum separation slower aircraft are closer to OWNSHIP. Thus, a difference in map range can determine when aircraft of different speeds appear on the display (see appendix B).

In general, the regressions on the independent variables used to create the various scenarios illustrate a pattern of statistically reliable effects that differs

[3]Regressions were also run without the quadratic and cubic terms, but no substantially different results were found.

substantially from pilot to pilot. This individual variation underscores the potential for misinterpretation if all the pilots were averaged together. In view of these clear individual differences, we have adopted the analytic philosophy that the data should be analyzed on a subject-by-subject basis. We present results from analyses on the pooled data only if we can also verify them on a subject-by-subject basis.

Since perceived collision danger was a focus of this experiment, an alternative regression analysis was attempted using step-wise regression in order to focus on the effect of the systematically varied independent variables on it, particularly the effect of minimum horizontal separation and map range. In addition to the partial correlation coefficients, this technique provided information about the relative importance of the regression terms by the order in which they were entered into the equation. The regression results from both conventional regression and the step-wise regression could provide a basis for segregating pilots into groups with different strategies for evaluating collision threat. In general, however, consistent subgrouping based on the systematic independent variables did not emerge (see the appendix).

Histograms

Since another focus of the experiment was the potential effect of different map ranges; frequency distributions of maneuver time and ATC call time were created separately for each of the two map ranges (see figs. 3(a) and 3(b)). Figure 3(a) shows a characteristic difference in the distribution of ATC call times between the two map ranges which was observed for all the pilots — that is that ATC calls were made earlier with the 37-km (20-n. mi.) map range than with the 18.5-km (10-n. mi.) map range.

Unlike the effect of map range on ATC call time, the differences between the histograms of maneuver times, which appear as an early peak in the 37-km (20-n. mi.) map histogram of figure 3(b), were attributable to only three pilots. These pilots apparently maneuvered as soon as they could identify the intruder. For these three pilots, maneuvers were made earlier with the 37-km map range than with the 18.5-km map range. If the data from these three are removed, as in figure 3(b), the difference between the distributions of maneuver times for the two map ranges is greatly reduced. The time of other pilots' maneuver selections varied substantially. One pilot almost always maneuvered during the last minute before the end of the encounter. Others maneuvered at intermediate times, but no pilot showed a pattern that could be interpreted as attempting to maneuver whenever an intruder got within a fixed distance on the face of the display.

We further examined the possibility of the pilots' use of a separation criterion in terms of inches on the display rather than miles on the map by calculating the percent of maneuvers made by each subject with times to minimum separation ranges of 30 sec or less. Thirty seconds to minimum separation was chosen because that is the time after which one might reasonably expect automatic collision avoidance alarms to trigger. Across both map ranges, about 14% of all maneuvers fell into this category. Over all pilots, there was a suggestion that more maneuvers were made with time to minimum separation of less than 30 sec when the pilots used the 18.5-km map range: 17% of all maneuvers made with the 18.5-km map were in this range compared to 10% made with the 37-km map. However, only five subjects showed a higher percentage of maneuvers 30 sec or less before minimum separation for the 18.5-km as compared to the 37-km map. Thus the tendency to allow intruders to come temporally closer before maneuvering when using the 18.5-km map range was not general. Similarly, only 6.5%

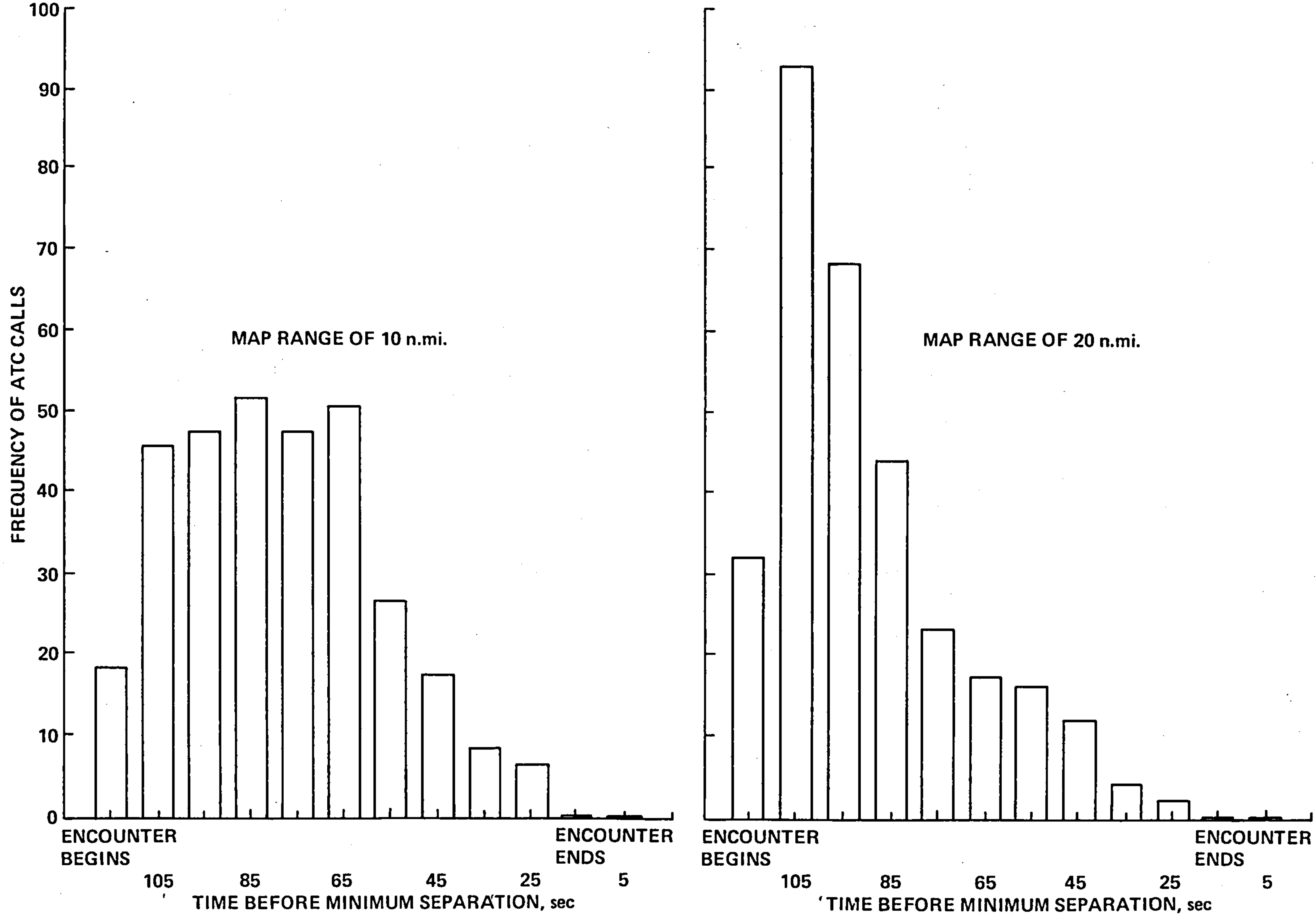

Figure 3(a).- Histograms of ATC call time by map range: The total frequency of all pilots' calls to ATC concerning potential traffic problems is plotted as a decreasing function of time before minimum separation.

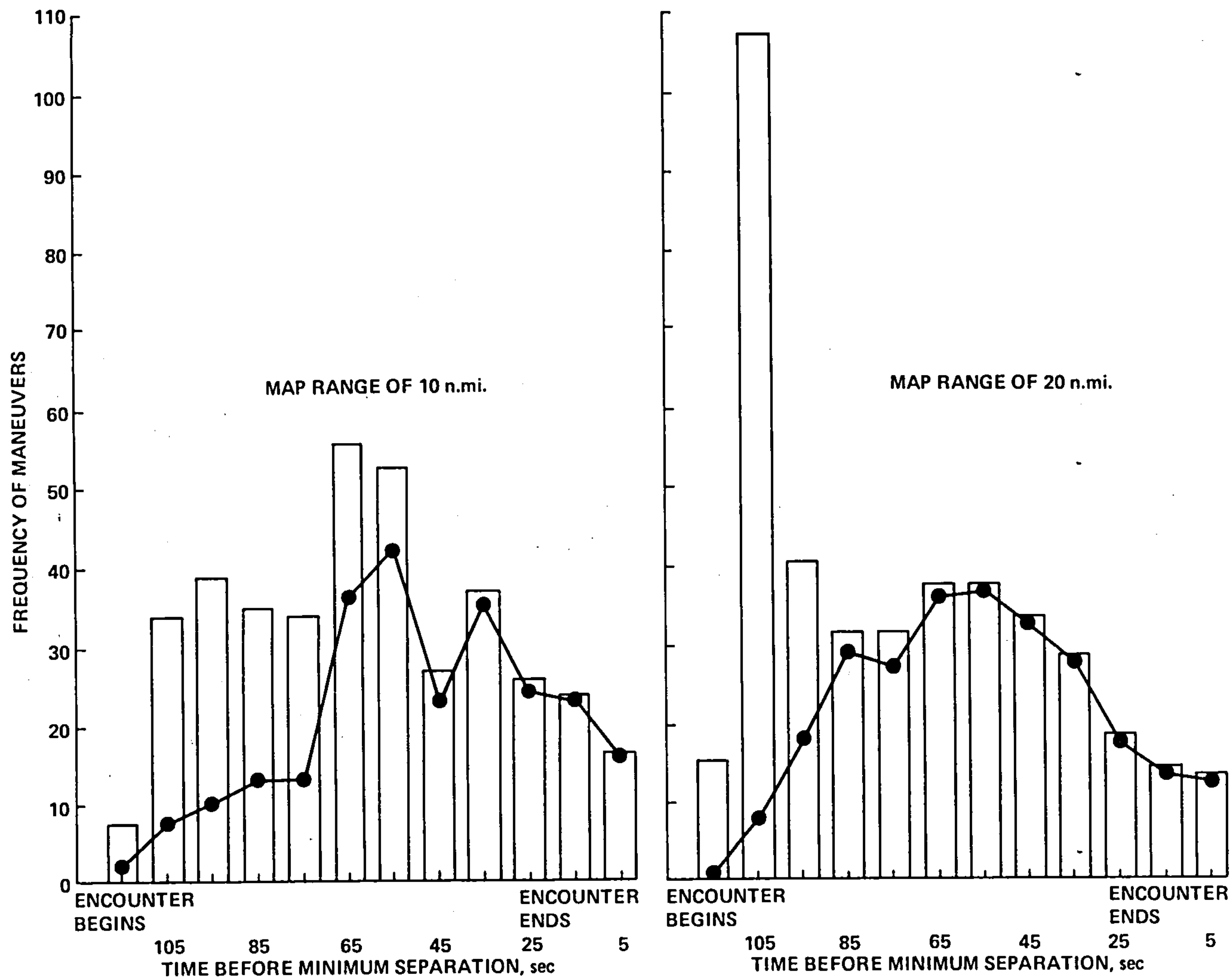

Figure 3(b).- Histograms of maneuver time by map range: The total frequency of all pilots' selection of traffic avoidance maneuvers is plotted as a decreasing function of time before minimum separation. The solid line shows the effect upon the distribution if the three "early decision" pilots are removed from the analysis.

of all the maneuvers made less than 30 sec before the end of the encounter involved encounters with minimum separations less than 1.5 n. mi. Thus, the effect of map range on time of maneuver decision appears to be limited to encounters with the larger miss distances. Accordingly, subject-by-subject distributions of maneuver times confirmed the regression results showing no general or consistent variation over the group of ten pilots attributable to map range.

PILOT MANEUVER TENDENCIES

Figure 4 shows the distribution of all eight pilot maneuvers and includes the category of level flight and no turn, i.e., no response.

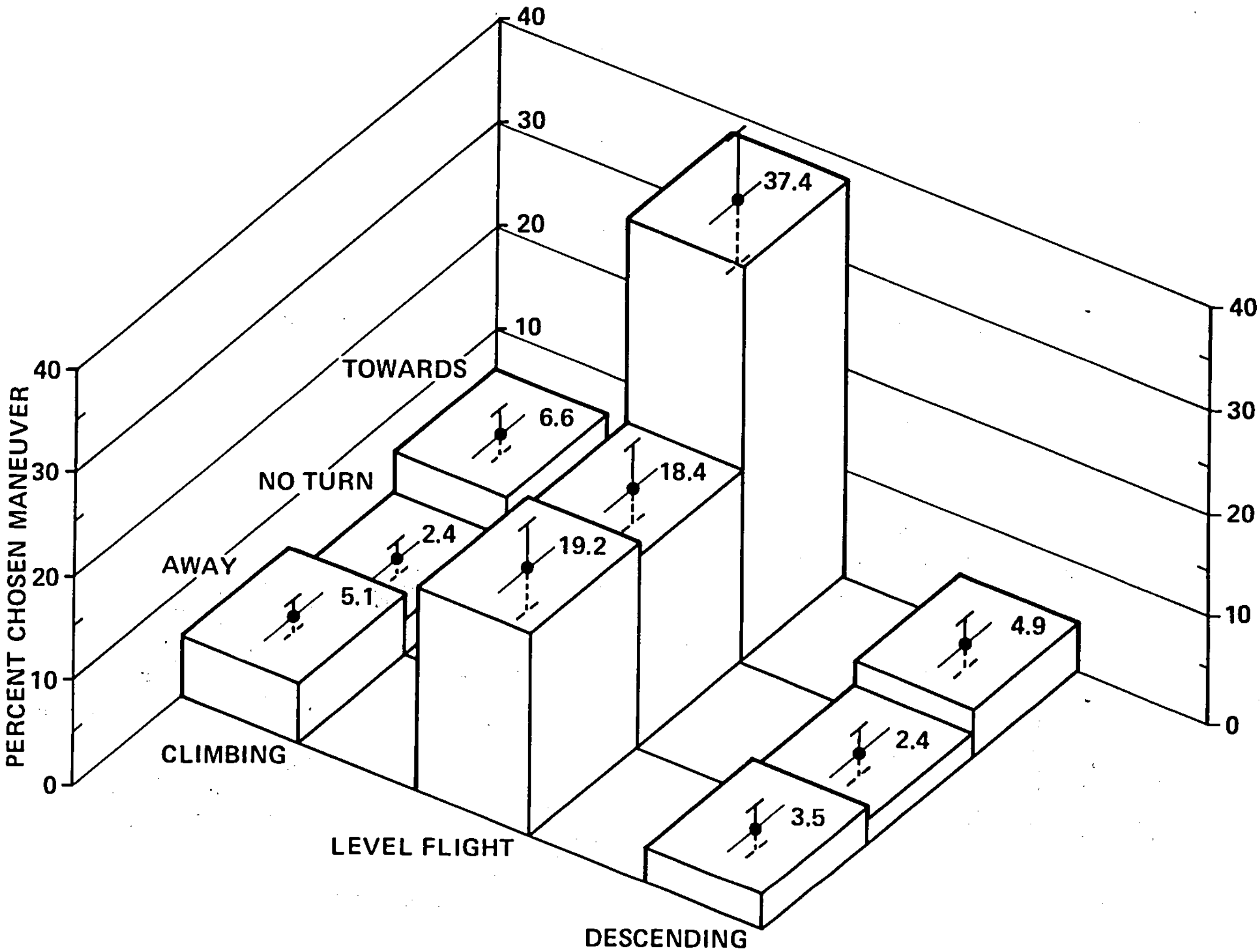

Figure 4.- Distribution of chosen maneuvers: Nine cell figure with mean percentage and standard error of all nine maneuver options. The distribution of the mean percentages shows a predominance of the horizontal maneuvers, a slight tendency to turn toward the intruding aircraft, and a slight preference for climbing over descending vertical maneuvers.

The decisions to turn or climb appeared independent of each other as shown by a statistically powerful χ-square test on a table of total numbers of maneuvers in each category used in figure 4 (χ-square = 8.74, df = 4, $p > 0.05$). Inspection of this figure shows that the middle row of purely horizontal maneuvers or no maneuvers is substantially larger than the top or bottom rows. This tendency was examined pilot by pilot by collapsing maneuver selections into three categories, purely vertical, purely horizontal, and mixed, in order to create table 2 (the no-maneuver option was not included).

TABLE 2.- DISTRIBUTION OF HORIZONTAL, VERTICAL, AND MIXED MANEUVERS

Pilot	1	2	3	4	5	6	7	8	9	10	Totals	Mean(SE)
Horizontal only	80	24	58	15	27	65	38	79	91	76	544	54.0(8.38)
Vertical only	0	0	0	22	6	0	9	5	2	2	46	4.6(2.16)
Mixed	1	63	23	23	27	5	17	12	3	18	192	19.2(5.63)
Chi-square	93.1 *a*	25.4 *a*	43.1 *a*	2.2	7.4 *b*	67.3 *a*	15.5 *a*	53.7 *a*	97.3 *a*	59.3 *a*		

df = 2

[a] $p < 0.005$

[b] $p < 0.01$

If pilots ignored the display and made purely random selections of the eight maneuvers, one would expect a relative proportion of 1:1:2 across the three response categories: horizontal, vertical, and mixed. Nine of the ten pilots diverged from the null hypothesis and showed a strong preference for pure horizontal as opposed to vertical maneuvers (two-tailed sign test, $p < 0.015$). In contrast, none of the pilots showed a reliable left/right bias in his choice of horizontal maneuver.

In order to further examine the pilots' choice of horizontal maneuvers, the distribution of eight maneuvers shown in figure 4 was collapsed into two cells for each pilot: all turns toward and all turns away from the intruder (see table 3). Six of the ten pilots had an overall tendency to turn toward the intruder more frequently than away. However, chi-square tests of the hypothesis that turns toward and away occur with equal frequency show this bias to be reliable for only four subjects. An analysis of maneuvers in the last 30 sec before an encounter shows a stronger bias but

TABLE 3.- TURNS TOWARD AND AWAY FROM INTRUDERS (OVERALL)

Pilot	1	2	3	4	5	6	7	8	9	10	Total
Overall											
Toward	52	48	66	16	49	64	33	54	46	38	466
Away	29	39	15	22	5	4	22	28	48	56	268
Chi-square	3.83	0.47	17.8 *a*	0.48	21.5 *a*	32.9 *a*	1.11	4.23 *b*	0.0	1.74	
Less than 30 sec to encounter											
Toward	19	15	11	0	28	3	13	0	0	1	90
Away	5	6	2	0	2	0	1	0	0	1	16
Chi-square	4.46 *b*	2.02	4.14 *b*	--	13.9 *a*	--	4.37 *b*	--	--	--	

df = 1

[a] $p < 0.005$

[b] $p < 0.05$

still is not reliable across pilots (see totals in table 3). However, if the distribution of maneuvers was collapsed across all encounters and all pilots, turns toward the intruder occurred twice as often as turns away.

Horizontal Maneuvers and Subjective Threat

Another perspective on the difference between the pilots' decision to turn toward or away from an intruder is provided by the perceived collision danger associated with the pilots' maneuver decisions. For each pilot the average judged collision danger was computed for all turns toward and all turns away from the intruder (table 4). For nine out of ten pilots the average collision danger was judged greater for scenarios in which they turned away than for those in which they turned toward (two-tailed sign test, $p < 0.015$).

TABLE 4.- AVERAGE COLLISION DANGER FOR TOWARD AND AWAY MANEUVERS BY PILOT

Pilot	1	2	3	4	5	6	7	8	9	10
Maneuver:										
Toward	3.15	4.75	5.35	4.81	3.90	5.33	4.79	2.46	5.33	5.50
Away	4.83	5.41	6.07	5.18	4.00	7.00	5.09	3.14	5.58	5.29

Further analysis of the relationship between collision danger and the tendency to turn toward the intruder shows that the level of judged collision danger modulated the percent of turning-toward maneuvers. For each pilot the percent of turning-toward maneuvers was determined for the subsets of encounters with differing levels of judged collision danger. Linear regressions were then determined for each subject with percent turning-toward maneuvers as the dependent variable. The slopes of all regressions were negative, indicating that increases in the danger of the scenario resulted in a decreased likelihood that the evasive maneuver would involve turning toward the intruder (see table 5). This result is summarized in figure 5, which shows that increases in the perceived collision danger of traffic encounters generally decreases the pilot bias to turn toward the intruding aircraft. For low collision dangers (from 1 to 3) pilots preferred to turn toward the intruder 4.3 times as frequently as to turn away.

TABLE 5.- REGRESSIONS OF PERCENT TOWARDS MANEUVERS ON COLLISION DANGER

Pilot	1	2	3	4	5	6	7	8	9	10
Slope	-9.28	-19.4	-9.46	-13.8	-0.41	-5.00	-4.10	-14.6	-15.5	-8.10
Constant	103.3	154.8	133.6	124.8	94.7	120.0	84.6	107.9	121.2	86.2
Correlation	-.72	-.97	-.91	-.77	-.08	-.71	-.54	-.96	-.81	-.64

(Two-tailed sign text, $p < 0.0032$)

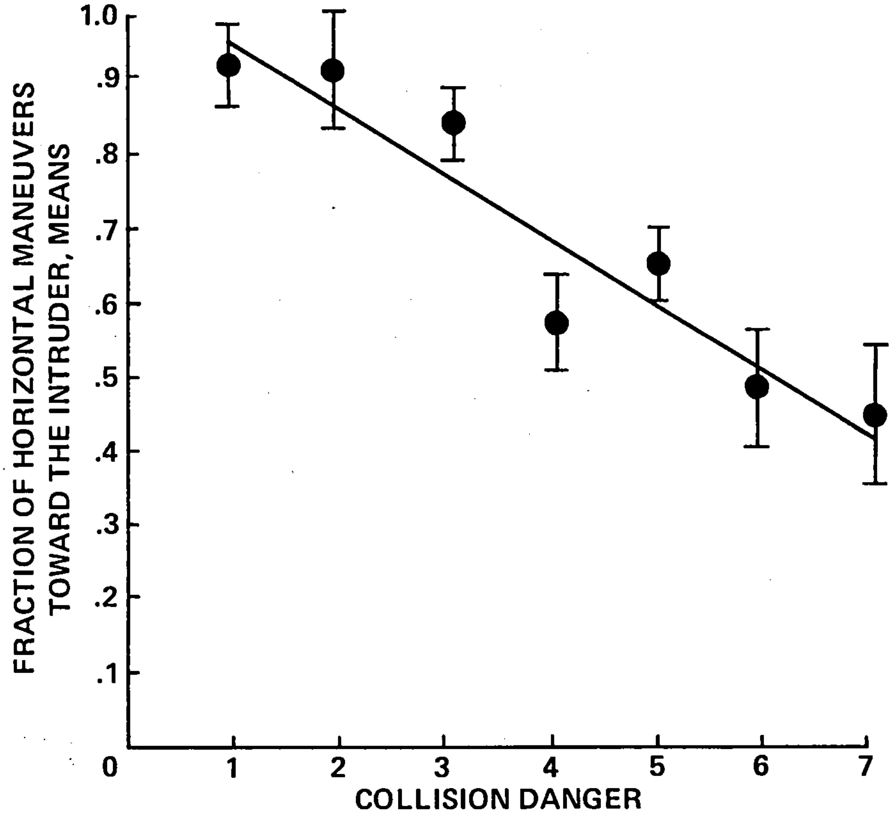

Figure 5.- Turning toward intruder vs collision danger: Turning-toward maneuvers of ten pilots at each of seven levels of relative danger. Percent values (±1 standard error) averaged across each pilot. A simple linear regression on the averaged fraction of horizontal maneuvers that were toward the intruder resulted in: $Y = -9.393X + 109.286$ and is plotted on the figure.

Evasive Maneuvers and Encounter Geometry

Heading difference of intruding aircraft- The heading difference of the intruding aircraft relative to OWNSHIP[4] also modulated the pilots' threat perception and their decisions to turn toward or away from the intruder. The mean perceived level of threat for each intruder heading was determined across subjects. Subject-by-subject regressions were then determined to illustrate the effect of the absolute value of heading difference on mean collision danger (see table 6). All of these regressions have negative slopes, indicating that for intruders approaching more and more frontally, i.e., larger absolute values of heading difference, pilots perceived scenarios as presenting less danger of collision.

Probably reflecting the difference in perceived threat, intruders coming from positions in front of the pilot's OWNSHIP were more frequently avoided by turns

[4]This heading difference would be zero if both OWNSHIP and the intruder were flying the same heading and would be 180° if they flew exactly opposite headings.

TABLE 6.- REGRESSIONS OF MEAN COLLISION DANGER ON ABSOLUTE VALUE OF HEADING DIFFERENCE

Pilot	1	2	3	4	5	6	7	8	9	10
Slope	-0.012	-0.001	-0.007	-0.016	-0.006	-0.007	-0.010	-0.006	-0.004	-0.009
Constant	4.433	5.003	5.784	5.205	3.378	5.450	4.803	3.134	5.771	6.496
Correlation	-.910	-.159	-.798	-.922	-.604	-.876	-.843	-.643	-.862	-.977

(Two-tailed sign test on regression slopes, $p < 0.0032$)

toward than when they approached laterally or from behind (see fig. 2). Accordingly, regressions of percent maneuvers toward the intruder on the absolute value of heading difference were computed for each pilot (see table 7). All ten pilots had positive regressions, indicating that increases in the absolute value of heading difference resulted in more maneuvers toward the intruder. The table confirms the across-subject results in figure 6 in which the average responses for the ten pilots show a regular increase in the percent of turns toward the intruder as the absolute value of heading difference increases.

TABLE 7.- REGRESSIONS OF PERCENT TOWARD MANEUVERS ON ABSOLUTE VALUE OF HEADING DIFFERENCE

Pilot	1	2	3	4	5	6	7	8	9	10
Slope	0.005	0.006	0.003	0.005	0.001	0.001	0.004	0.004	0.005	0.007
Constant	.227	.019	.561	.066	.806	.822	.291	.326	.039	.183
Correlation	.97	.89	.89	.96	.81	.77	.94	.91	.89	.91

(Two-tailed sign test of the sign of these regression slopes, $p < 0.0032$)

Starting Altitude of Intruding Aircraft

An attempt was made to analyze bias in the choice of vertical maneuvers as was done for horizontal maneuvers. The intruder's starting altitude took five values: -2000, -1190, 0, 1190, and 2000 ft relative to OWNSHIP. For each of these altitudes, the intruder flew to a vertical miss distance of -500, 0, or 500 ft relative to OWNSHIP. Table 8 lists climbing and descending maneuvers for all ten pilots as a function of whether the intruder started below, above, or at OWNSHIP's altitude.

These data pooled across all pilots suggest that pilots tend to maneuver away from intruders at different initial altitudes; intruders starting below OWNSHIP cause climbs and intruders starting above OWNSHIP cause descents. This tendency was further examined by computing the percent climbs of all vertical maneuvers for each of the intruder starting altitudes. In table 9 the regressions of percent of climbing evasive maneuvers on intruder starting altitude are presented. The predominance of negative slopes of the regressions shows that increases in the relative starting altitude of the intruder causes a decreased likelihood of climbing.

In figure 7 the results averaged across pilots confirm that pilots tended to climb to evade intruders starting below them. However, this averaged response does not support a conclusion that intruders starting above cause descending evasive

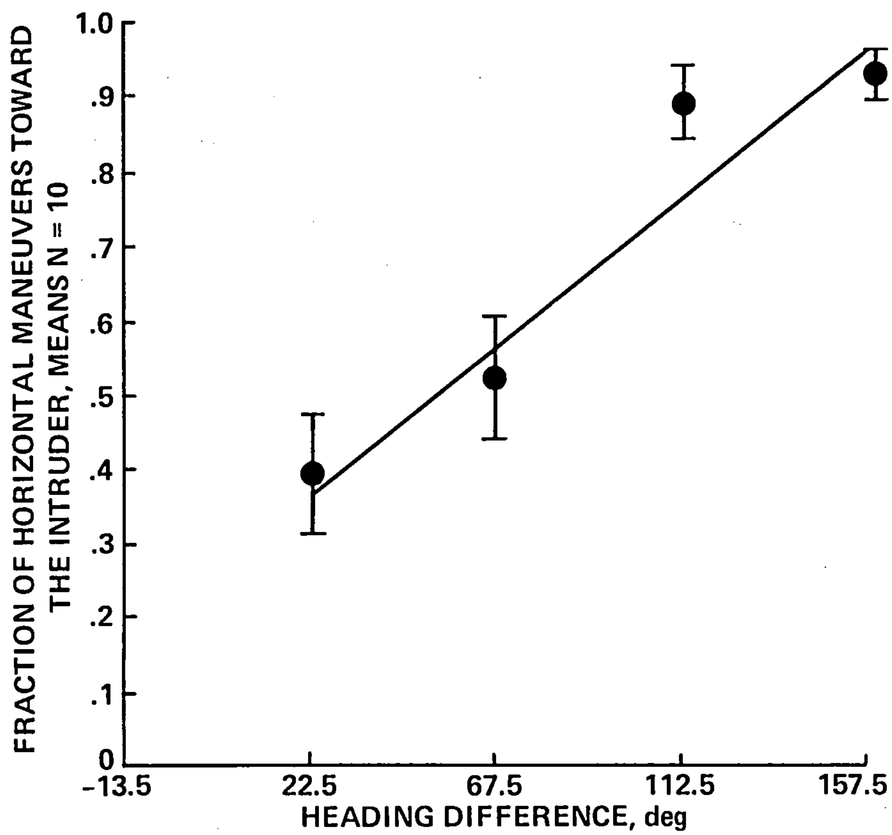

Figure 6.- Turning toward intruder vs intruder heading difference: The fraction of horizontal maneuvers toward the intruder were averaged across each pilot for each heading difference to calculate mean fractions and standard errors. Since no difference was found between positive and negative intruder headings, the absolute value of the heading difference was used. The simple linear regression through the average values is: $Y = 0.408X + 29.34$ and is plotted.

TABLE 8.- CLIMBING AND DESCENDING MANEUVERS OF ALL PILOTS ACCORDING TO STARTING ALTITUDE OF INTRUDER

	Below -2000/-1190	Same altitude 0	Above 1190/2000	Total
Climb	67	53	15	135
Descend	5	50	48	103
Total	72	103	63	238

(Chi-square = 67.683, degrees of freedom = 2; $p < 0.001$)

TABLE 9.- REGRESSIONS OF PERCENT OF CLIMBING MANEUVERS ON INTRUDER STARTING ALTITUDE

Pilot	1[a]	2	3	4	5	6	7	8	9[a]	10
Slope	--	-0.037	-0.032	-0.017	-0.012	-0.042	0.000	-0.010	--	-0.030
Constant	--	37.56	27.29	41.44	69.00	50.00	95.4	66.03	--	58.17
Correlation	--	-.92	-.61	-.70	-.96	-1.00	0.00	-.66	--	-.85

(Two-tailed sign test of the sign of the regression slopes, $p < 0.0156$)

[a]Two pilots [1 and 9] performed climb/descent maneuvers with the intruder at only one relative starting altitude and thus had to be excluded from this analysis.

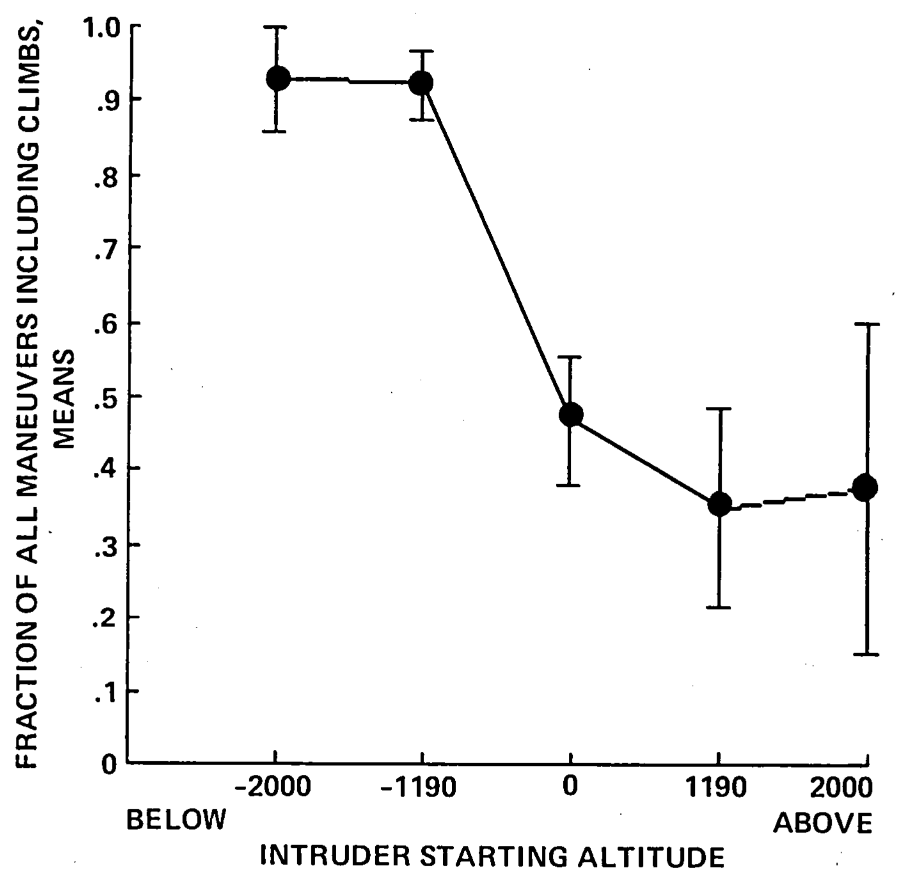

Figure 7.- Pilot vertical maneuvers vs intruder starting altitude: The fraction of all maneuvers that included a climbing component was averaged across all pilots and plotted for each of the five relative starting altitudes of the intruding aircraft. Each average is bounded by ±1 standard error. Since some pilots selected no vertical maneuvers when confronted with intruders from a particular starting altitude, the number of values used from each standard error varied. The number of pilots that contributed a value to each of the averages displayed are 7, 8, 10, 7, and 4 for -2000, -1190, 0, 1190, and 2000 ft starting altitude, respectively.

maneuvers. The mean percent climbing response is essentially the same at starting altitudes of 0, 1190, and 2000 ft.[5]

Since there were relatively few maneuvers selected with a vertical component, there were insufficient data to examine the possibility that either perceived threat or heading difference influenced choice of vertical maneuver.

DISCUSSION

The results of this experiment at first seem paradoxical. The major independent variables did not influence the timing of simulated ATC calls, pilot maneuver selections, or pilot perceived collision threat in uniform ways across all pilots. The pattern of the pilots' actual maneuver selections, however, exhibited substantial regularities across all subjects. Our general inference from this contrast is that the pilots in this experiment adopted decision strategies sensitive to subjective aspects of the encounters (perceived threat or perceived miss distance), which varied from pilot to pilot.

Multiple Regressions and Histograms

Since the three central composite design factors, horizontal miss distance, intruder speed, and initial intruder altitude, did not affect the timing of the pilots' avoidance behavior or their perception of collision danger in consistent ways, these factors principally served as a means of systematically generating a variety of encounters with which to examine the effect of the map ranges, 18.5 km and 37 km. Similarly, the random variation of the heading difference and vertical miss distance aided this comparison by introducing added elements of uncertainty, thus maintaining pilot interest by ensuring that the different scenarios appeared distinct, novel, and unrelated to each other.

Importantly, the failure to identify reliable effects of the independent variables on timing or perceived collision danger should not be a basis for deciding that they do not generally influence pilot behavior. The range of the variables used may simply have been too small to have been perceived by the pilots under the specific experimental conditions. Minimum miss distance, for example, provided a hint of an effect and might show a stronger effect if it were varied over a larger range.[6] Thus, the differing patterns of pilots' response timing and threat perception may reflect genuine variation in the pilots' sensitivities to the parameters defining the traffic conflicts.

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[5]Pilots selected vertical maneuvers to avoid intruders originating from various starting altitudes. Thus, the number of pilots used in computing each mean in figure 7 varies because some pilots selected no vertical maneuvers for intruders originating at a particular starting altitude. In figure 7 the large standard errors of the response to intruders starting above may in part be due to the small number of pilots selecting vertical maneuvers for intruders starting from +1190 and +2000 ft.

[6]Palmer (ref. 9) has argued, however, that pilots have difficulty detecting whether an intruder will pass in front or behind OWNSHIP: The miss distance might have to be considerably increased before a reliable effect on the timing of ATC cells or maneuvers is detected.

Despite statistically powerful tests, we have no systematic evidence that the pilot responses were affected by the map scale of the displayed information. Rather, the pilots seem to have genuinely interpreted the symbolic information shown in terms of the actual traffic encounter. The most direct evidence for this conclusion comes from the failure of map range to show consistently statistically reliable effects on the three major dependent variables, ATC call time, maneuver time, or judged collision danger. The analyses of the overall distributions of ATC and maneuver times generally support this conclusion. The pilots' appropriate rescaling of their interpretation of the display is probably due to "yardsticks" that were provided by the 60-sec predictors which previous experiments show to be the part of the intruder symbol most often viewed (refs. 12 and 13).

The difference that was noticed between the 18.5-km and 37-km ATC call time histograms undoubtedly results from the fact that on any particular encounter it is necessary to wait longer to see the intruder on the display with the smaller map range. Interestingly, this reliable effect of map range on ATC call time is not evident in the regression analysis. The large within-subject variation in ATC call time itself obscures this difference.

The contrast between the distributions of maneuver time is a better test of the symbolic interpretation of the display since the intruding aircraft was visible on both the 18.5-km and 37-km map range during the period when maneuvers were made. Aside from the three "early-decision" pilots, the individual distributions of maneuver time were not affected by changes in map scale.

The maneuver time histograms provide data of potential importance for the interaction of CDTI and collision avoidance systems. Most of the maneuvers, about 86%, occurred before 30 sec to minimum miss distance, a time well before most collision avoidance systems would issue a positive avoidance command. Only the approximately 14% of all maneuvers which were made within 30 sec of an encounter are in potential conflict with collision avoidance alarms. Interestingly, about 86% of the maneuvers within 30 sec of an encounter were turns toward the intruder. This percentage is higher than the overall percentage, which was about 60% turning toward. This increase in the tendency to turn toward for the late maneuvers may be explained by the tendency of the pilots to maneuver earlier for the encounters judged more threatening. Thus, the late maneuvers are primarily executed for lower threat encounters and, as in the case with lower threat encounters in general, show a stronger turning-toward tendency.

Indeed, almost all (93.5%) of the late maneuvers occurred with predetermined miss distances of 1.5 n. mi. or more. The close encounters, collisions, and near misses almost always prompted maneuvers earlier than 30 sec to minimum separation.

Another aspect of the maneuvering before reaching minimum separation is that the extensive maneuvering within 60 sec of minimum separation could introduce uncertainty and complicate the task of the automatic collision avoidance algorithms. Alternatively, the pilot maneuvering might bypass the collision avoidance alarms by preventing sufficiently close encounters from occurring. The development of a model summarizing pilot maneuver bias while using CDTI might help determine how often the pilot maneuvers early and bypasses the CAS alarms.

Maneuver Distributions

Horizontal and vertical maneuvers- In view of the substantial variation in pilot decision timing and threat evaluation, the amount of intersubject agreement in maneuver selection is striking. The pilots demonstrated significantly more purely horizontal maneuvers than purely vertical maneuvers, as shown in table 2. This predominance of horizontal maneuvers may be due to procedural influences such as the relatively greater horizontal latitude allowed pilots under FAA regulations compared to the greater restriction in vertical spacing,[7] concerns for passenger comfort and safety, or fuel conservation. Alternatively, the better display of the horizontal traffic situation may have biased the pilots to choose horizontal maneuvers.

Turning Toward Intruder and Collision Danger

The observation that the pilots' impression of collision threat was a strongly modulating influence on their turning-toward tendency underscores the importance of such subjective factors. These factors are particularly important since pilots often have difficulty accurately perceiving whether an intruder will pass in front of or behind their aircraft (ref. 9). Since maneuver decisions are apt to be based on perceived separation, perceived time to minimum miss distance, and perceived heading difference, we plan to quantitatively examine these subjective variables in future experiments.

Since the turns toward the intruders temporarily decrease separation but more quickly resolve the conflicts, pilots appeared willing to accept this momentary decrease in separation in order to protect themselves from the future problems of an unresolved encounter. Since pilots have mentioned that the turning-toward maneuver potentially keeps the intruder in sight, their choices of maneuvers may also have been motivated by previous VFR flight experience (ref. 5). Of course, using CDTI the intruder would always be in sight on the display, regardless of the geometrical relationship of OWNSHIP and the intruder.

Heading Difference

Pilots tended to turn toward the intruder when the intruder was approaching frontally (large heading difference), but this bias lessened when the approach was more lateral or from behind (small heading difference). When turning toward an intruder that is in front of OWNSHIP, a smaller, shorter-duration turn is required to maneuver OWNSHIP so as to get behind the intruder. Also, when the absolute value of heading difference is large, the horizontal separation between the intruder and OWNSHIP is greater, allowing more space for the turning-toward maneuver. Conversely, smaller absolute values of heading difference place the intruder closer to a course parallel to that of OWNSHIP with less space for maneuver and the requirement for a longer duration turn in order to get behind the intruder. Thus, when the heading difference was small, a turn toward would require a long-duration maneuver. During such a maneuver slight changes in the intruder's heading could put OWNSHIP at greater risk. Accordingly, as they occasionally mentioned in their debriefing, pilots were concerned that the intruder might maneuver and choose maneuvers to reduce future possible conflicts by turning away.

Another influence on the maneuvers made to avoid aircraft may arise from the fact that turns toward an aircraft which is going to pass in front of OWNSHIP with a heading difference greater than 45° will increase ultimate minimum separation. However,

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[7]5.6-9.3 km (3-5 n. mi.) horizontal separation versus 305-m (1000-ft) separations between IFR aircraft and 152-m (500-ft) separation between IFR and VFR aircraft.

if the intruder's heading difference is less than 45°, then turns toward it may reduce minimum separation. This difference does not generalize to all turns and critically depends upon the amount of heading change a turn produces. However, the pilots' greater preference for turns toward intruders with large heading differences may result from their perception that turns toward such intruders can increase minimum separation.

Starting Altitude

The subjects demonstrated a significant tendency to climb away from intruders starting below OWNSHIP (fig. 7). There is no corresponding evidence of a tendency of pilots to descend below intruders starting above OWNSHIP. The explanation for a lack of the descent tendency may be due to the fact that OWNSHIP is only 762 m (2167 ft) above the ground, having just taken off from the Denver Stapleton airport. During debriefing, five of the ten pilots mentioned that they were concerned about the proximity of the ground during their maneuver decisions. The lack of a descent tendency may also have been due to a preference for positive g maneuvers or due to the pilots being on departure and therefore planning to gain altitude for their flight to Chicago. The effect of the pseudo-intruder (always 457 m (1500 ft) above OWNSHIP) should, if anything, bias pilot maneuvers toward descents.

In general we might expect the flight segment to affect vertical maneuver selection. If OWNSHIP were cruising at a higher altitude, we might expect to find a more symmetrical response. Similarly, on arrival pilots might climb less and on departure they might climb more (ref. 5).

The fact that pilots mainly used horizontal maneuvers may have been due to the poor presentation of the vertical situation. The altitude of the intruder and direction of vertical movement were available only as data tags. Thus, the pilot was presented with a relatively poor representation of vertical separation. Given this lack of precise intruder vertical position information, pilots understandably avoided a possible increase in risk associated with a vertical "turning-toward" maneuver. Future experiments with analog displays of intruders' vertical position might demonstrate different vertical maneuvering strategies.

Specific Findings

The following specific observations represent initial pilot behavior when using CDTI without specific training or avoidance procedures. They summarize the statistically reliable results of the experiment. However, since the current experiment is part of an ongoing series of related experiments, these results should not be regarded as final conclusions regarding pilot avoidance behavior when using CDTI.

1. Pilots tended to select avoidance maneuvers at least 30 sec before the point of minimum separation from an intruding aircraft.

2. Timing of maneuver selection was affected by time of appearance of the intruding aircraft, but inches on the display were not confused with true separation in nautical miles.

3. Pilots most often selected horizontal maneuvers to resolve conflicts.

4. Pilots often avoided potential conflicts by turning toward intruding aircraft, but when they reported greater collision danger this tendency lessened.

5. The greater the heading differences were between OWNSHIP and the intruder, i.e., the more frontal the intruder's approach, the greater was the pilots' tendency to turn toward them.

6. Pilots tended to climb away from intruders which appear initially below OWNSHIP, but corresponding descents from intruders above OWNSHIP were less frequent.

GENERAL CONCLUSION

A general implication of the pilots' tendency to turn toward an intruder is that two pilots, each equipped with CDTI displays, might both attempt to maneuver so as to get behind each other, thus decreasing separation (ref. 8). A similar phenomenon has been described in maritime navigation and is termed "radar assisted collision" (ref. 7). As in the case of ship captains, pilots may require training with appropriate right of way rules and/or use of automatic systems to guarantee safe aircraft separation.

ACKNOWLEDGMENTS

The authors wish to thank Ms. Amy Wu of Informatics, Inc. for her untiring assistance in preparing the CDTI displays for this experiment.

APPENDIX A

COCKPIT DISPLAY OF TRAFFIC INFORMATION

J. D. Smith and Steve Ellis
April 16, 1981

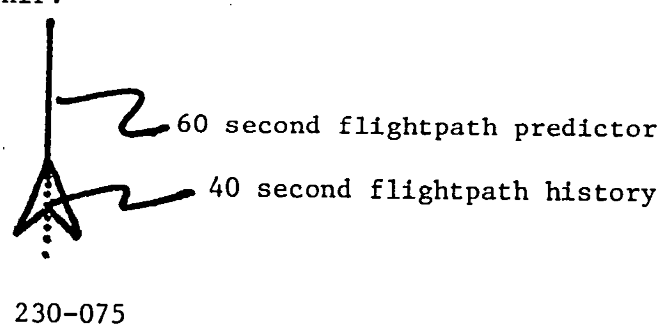
INTRODUCTION

This series of displays of air traffic conditions presents scenarios of various levels of threat. The purpose of the experiment is to measure pilot response to any perceived threat during these traffic conditions and the relative danger to his ship. One goal of this experiment and related studies is to develop automatic logic systems consistent with pilot threat perception.

Other aircraft displayed will vary in a number of objective dimensions such as miss distance, turn rate, horizontal and vertical velocity and bearing relative to OWNSHIP. OWNSHIP parameters, however, will remain the same throughout the experiment. You will be flying six sets of sixteen traffic conditions. The experimental sequence is divided into a familiarization/practice session; the experimental traffic conditions and a debriefing.

SYMBOLOGIES

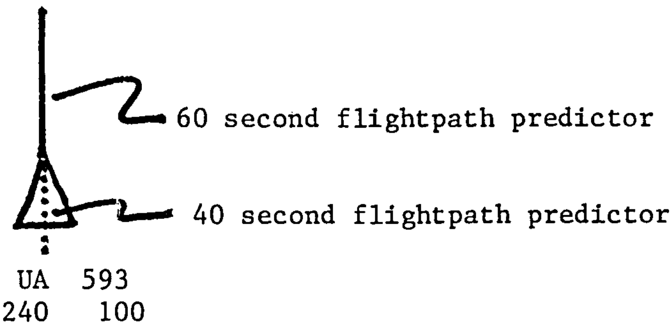
OWNSHIP:



OWNSHIP TAG:
XXX-YY-ZZZ

- XXX- Groundspeed, measured in knots
- YY - Indication of vertical speed: up arrow, climbing; -, level flight; down arrow, descending
- ZZZ- Barometric Altitude, measured in hundreds of feet (i.e., 075 corresponds to 7500 ft)

INTRUDER:

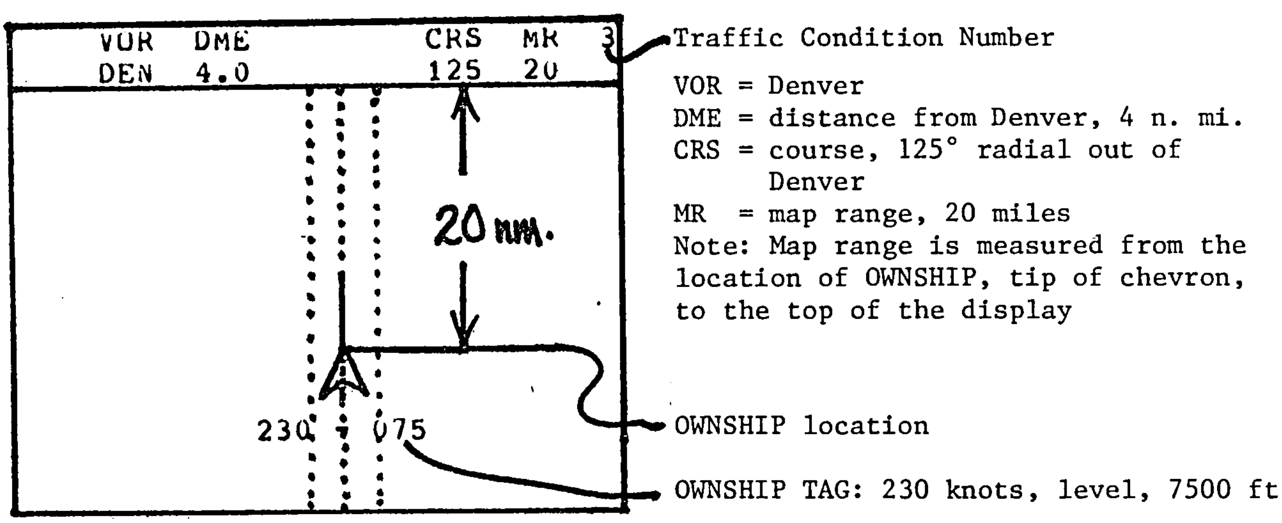


INTRUDER TAG:
UA NNN
XXX-YY-ZZZ

- UA - Designates airline, i.e., United Airlines
- NNN- Designates flight number
- XXX- Groundspeed, measured in knots
- YY - Indication of vertical speed: up arrow, climbing; -, level flight; and down arrow, descending
- ZZZ- Barometric altitude, measured in hundreds of feet (i.e., 100 corresponds to 10,000 ft)

Note: Actual position of each aircraft is at the forward tip of the symbols that represent them.

DISPLAY CONSOLE:



Navigation points:
- Way point
- VOR/DME

Note: This is a map up display where you are vectored off course. The course reference (CRS 008) refers to the center dotted line.

NOTE: Assume that your onboard CDTI (computer display of traffic information) will at all times display to you true conditions unaffected by weather or radar tracker noise.

BASIC SCENARIO:

You are the commander of OWNSHIP, a medium transport such as a 727 or 737, outbound from Denver to Chicago on the eight degree radial to GILL. You have been temporarily vectored off your course. Your onboard CDTI (computer display of traffic information) will at all times portray to you true conditions unaffected by weather or radar tracker noise. Other aircraft on your display have transponders but have neither displays of traffic nor automatic collision avoidance systems.

SOME ADDITIONAL ASSUMPTIONS:

Assume IFR conditions (i.e., you can't visually see other aircraft).
Assume that you are flying with the autopilot.

TASK:

In all traffic conditions you are requested to monitor the display for one or both of two contingencies. First, should you decide that a condition is comparable to one where you would call the ATC regarding your situation, pull of the 'ATC call' switch at the left of your console. Two, if the situation develops such that you decide to maneuver in order to decrease the threat of collision, pull the switch corresponding to your desired maneuver: (Note: only switches marked "X" are active.)

CONSOLE

X	X	0	X	0	X	0	X	0	X	0	X	0	X	0	X
ATC CALL	left		climb left		descent left		climb		descend		climb right		descend right		right

----------------Pilot Maneuver (select one only)----------------

Note: When you pull the "ATC Call" or a maneuver switch, it assumed that these decisions refer to a threat of collision by an intruder (which you designate by data tag) with OWNSHIP. Should you decide to call ATC or maneuver for any other reason please write down the reason in your workbook.

The CDTI display will freeze at the time you pull a maneuver switch. Should you not choose to maneuver the display will automatically be stopped after 2 minutes.
For every traffic condition:

1. Write the number of aircraft of principal concern, and
2. Circle the relative danger to OWNSHIP as one of the seven danger levels below

1	2	3	4	5	6	7
no danger			standard spacing violation relative to OWNSHIP			collision or near miss with OWNSHIP imminent

Circle one of these levels for each traffic condition in your booklet.

PRACTICE RUN:

In order to familiarize you with this CDTI and the experimental task you will fly a practice series of traffic conditions. Enter your danger level rating and any comments you have regarding each traffic condition.

DEBRIEFING:

A short discussion of the experimental traffic conditions will follow each set of 16 scenarios. Discussion and rerunning of selected traffic conditions will follow completion of all six sets of conditions.

APPENDIX B

The following tables list all the statistically significant regression coefficients found in regressions which were calculated to analyze the independent variables of this experiment.

TABLE B1.- REGRESSION WITH ATC CALL TIME AS DEPENDENT VARIABLE

Subject	Multiple R	Standard errors of regression	Regression coefficients								
			Linear effects					Quadratic effects			
			Speed	Horizontal miss distance	Intruder starting altitude	Vertical miss distance	Map range	Speed	Horizontal miss distance	Intruder starting altitude	Vertical miss distance
1	0.631[a]	18.7	---	---	-0.03[b]	---	---	---	---	---	---
2	.756[a]	13.7	---	---	---	---	---	---	---	0.001[a]	---
3	.772[a]	13.7	---	---	---	-0.04[c]	---	0.001[a]	---	.001[a]	---
4	.789[a]	11.5	---	---	---	---	3.79[a]	---	---	---	---
5	.597[a]	13.8	---	---	---	---	3.54[a]	---	---	---	---
6	.664[a]	14.4	---	---	---	---	---	---	---	---	---
7	.566	25.4	---	---	---	---	---	---	---	---	---
8	---Insufficient variance in data for analysis---										
9	.761[a]	11.3	---	---	---	---	---	---	---	---	---
10	.878[a]	11.4	---	---	---	---	7.96[b]	---	---	---	---

Subject	Cubic effects			Interactions									Constant of regression
	Speed	Horizontal miss distance	Intruder starting altitude	Speed × horizontal miss distance	Speed × intruder starting altitude	Speed × vertical miss distance	Speed × map range	Horizontal miss distance × intruder starting altitude	Horizontal miss distance × vertical miss distance	Horizontal miss distance × map range	Map range × intruder starting altitude	Map range × vertical miss distance	
1	---	---	---	---	---	---	---	---	---	---	---	---	-70.8
2	---	---	---	---	---	---	---	---	---	---	0.001[c]	---	-119.1
3	---	---	-0.001[c]	---	---	0.001[b]	-0.015[a]	---	---	---	---	---	-107.2
4	0.001[b]	---	-.001[a]	---	---	---	-.018[a]	---	---	---	---	---	-138.7
5	---	---	---	---	---	---	-.017[a]	---	---	---	---	---	-116.6
6	---	---	---	---	---	.001[c]	---	---	---	---	---	---	-108.1
7	---	---	---	---	---	---	---	---	---	---	---	---	---
8	---Insufficient variance for analysis---												
9	---	---	---	---	---	---	-.012[a]	---	0.008[c]	---	---	---	-113.3
10	.001[c]	---	---	---	---	---	-.038[a]	---	---	---	---	---	-144.4

[a] $p < 0.05$ [b] $p < 0.025$ [c] $p < 0.01$

TABLE B2.- REGRESSION WITH MANEUVER TIME AS DEPENDENT VARIABLE

Subject	Multiple R	Standard errors of regression	Regression coefficients								
			Linear effects					Quadratic effects			
			Speed	Horizontal miss distance	Intruder starting altitude	Vertical miss distance	Map range	Speed	Horizontal miss distance	Intruder starting altitude	Vertical miss distance
1	0.577[a]	19.9	---	---	---	---	---	---	23.02[c]	---	---
2	.668[a]	16.3	---	---	---	---	---	---	---	0.001[a]	---
3	.745[a]	17.6	---	---	---	---	---	---	---	.001[a]	---
4	.798[a]	14.3	---	---	---	---	3.54[c]	---	-13.3[b]	.001[a]	---
5	.658[a]	18.8	---	---	---	---	---	---	---	---	---
6	.573	18.0	---	---	0.001[c]	---	---	---	---	---	---
7	.550	27.6	---	---	---	---	---	---	---	---	---
8	.814[a]	10.4	---	---	---	---	---	---	---	---	---
9	.765[a]	11.2	---	---	---	---	---	---	---	---	---
10	.699[a]	14.8	---	---	---	---	---	---	---	---	---

Subject	Cubic effects			Interactions									Constant of regression
	Speed	Horizontal miss distance	Intruder starting altitude	Speed × horizontal miss distance	Speed × intruder starting altitude	Speed × vertical miss distance	Speed × map range	Horizontal miss distance × intruder starting altitude	Horizontal miss distance × vertical miss distance	Horizontal miss distance × map range	Map range × intruder starting altitude	Map range × vertical miss distance	
1	---	-6.69[c]	---	---	---	---	---	---	---	---	---	---	-59.3
2	---	.001[b]	---	---	---	---	---	---	---	---	0.001[a]	---	-36.4
3	---	---	---	---	---	---	-0.02[a]	---	---	---	---	---	-98.0
4	0.001[a]	5.41[a]	---	---	---	---	-.01[b]	---	---	---	---	---	-111.3
5	---	---	---	---	---	---	---	---	---	---	---	---	---
6	---	---	---	---	---	---	---	---	---	---	---	---	-68.8
7	---	---	---	---	---	---	---	---	---	---	---	---	---
8	---	---	---	---	---	---	-.01[a]	0.003[c]	---	---	---	---	-109.8
9	---	---	---	---	---	---	-.01[a]	---	0.007[c]	---	---	---	-105.1
10	---	---	---	---	---	---	-.01[b]	---	.01[c]	---	---	---	-115.0

[a] $p < 0.05$ [b] $p < 0.025$ [c] $p < 0.01$

TABLE B3.- REGRESSION WITH COLLISION DANGER AS DEPENDENT VARIABLE

Subject	Multiple R	Standard errors of regression	Regression coefficients								
			Linear effects					Quadratic effects			
			Speed	Horizontal miss distance	Intruder starting altitude	Vertical miss distance	Map range	Speed	Horizontal miss distance	Intruder starting altitude	Vertical miss distance
1	0.803[a]	1.25	---	-3.3[a]	---	---	---	---	---	---	---
2	.805[a]	.67	---	-2.1[a]	---	---	---	---	0.06[b]	---	---
3	.654[a]	1.26	---	---	---	---	---	---	---	---	---
4	.719[a]	1.64	---	---	---	---	---	---	---	---	---
5	.702[a]	1.28	---	---	---	---	---	---	---	---	---
6	.786[a]	1.18	---	-1.8[c]	---	---	---	---	---	---	---
7	.588[a]	1.06	---	-1.6[c]	---	-0.003[c]	0.22[c]	---	---	---	0.001[b]
8	.613[a]	1.61	---	---	---	---	---	---	---	---	---
9	.536	---	---	---	---	---	---	---	---	---	---
10	.360	---	---	---	---	---	---	---	---	---	---

Subject	Cubic effects			Interactions									
	Speed	Horizontal miss distance	Intruder starting altitude	Speed × horizontal miss distance	Speed × intruder starting altitude	Speed × vertical miss distance	Speed × map range	Horizontal miss distance × intruder starting altitude	Horizontal miss distance × vertical miss distance	Horizontal miss distance × map range	Map range × intruder starting altitude	Map range × vertical miss distance	Constant of regression
1	---	---	---	---	---	---	0.001[c]	---	---	---	---	---	10.8
2	---	---	---	---	---	---	---	---	---	---	---	---	9.0
3	---	---	---	---	---	0.001[c]	---	---	---	---	---	---	8.7
4	---	---	---	---	---	---	---	---	0.001[b]	---	---	---	6.6
5	---	---	0.001[a]	---	---	---	---	---	---	---	---	---	5.9
6	---	---	---	---	---	---	---	---	---	---	---	---	3.4
7	---	---	---	---	---	---	---	---	---	---	---	---	.9
8	---	---	---	---	---	---	---	---	---	---	---	---	6.6
9	---	---	---	---	---	---	---	---	---	---	---	---	---
10	---	---	---	---	---	---	---	---	---	---	---	---	---

[a]$p < 0.05$ [b]$p < 0.025$ [c]$p < 0.01$

Step-wise regressions were calculated using, in addition to the systematically varied independent variables, some of the randomly changed variables such as heading difference, the initial slant range between OWNSHIP and the intruder, initial horizontal and vertical separation between OWNSHIP and the intruder, the length of the intruder's predictor, and an encoding of whether the intruder intercepted OWNSHIP's altitude during the encounter. These regressions confirm the importance of the heading difference for determining perceived collision danger and suggest that horizontal miss distance may also be a factor influencing perceived collision danger. Horizontal miss distance probably should be varied over a greater range for it to show up as a reliable predictor of collision danger under the display conditions we were using.

TABLE B4.- STEP-WISE REGRESSION WITH COLLISION DANGER AS DEPENDENT VARIABLE COEFFICIENTS OF TERMS KEPT IN THE ANALYSIS

			Linear effects							
Subject	Multiple R	Standard errors of regression	Speed	Horizontal miss distance	Intruder starting altitude	Vertical miss distance	Map range	Intruder heading difference	Absolute intruder heading difference	Intruder intercepts OWNSHIP altitude
1	0.813^{a}	1.12	0.005^{5*}	-3.3^{1}	---	---	---	---	-0.008^{2}	---
2	.815^{a}	.59	---	-2.1^{1}	-0.001^{2}	---	---	---	---	---
3	.791^{a}	.83	---	-1.2^{1}	---	---	---	---	-.004^{4}	0.244^{3}
4	.745^{a}	1.40	---	-1.4^{1}	---	---	---	---	-0.14^{2}	-.338^{5}
5	.663^{a}	1.22	---	---	---	---	---	---	---	---
6	.855^{a}	.84	---	-2.0^{1}	---	---	---	---	---	---
7	.625^{a}	1.45	---	-2.0^{1}	---	---	---	---	-.007^{3}	---
8	.606^{a}	.95	---	---	---	---	---	---	-.005^{4}	-.293^{2}
9	.473^{a}	1.06	---	---	---	---	---	---	-.008^{1}	---
10	.500^{a}	.73	---	---	---	---	---	---	-.003^{3}	---

	Quadratic effects									Interactions		
Subject	Closing rate	Slant range	Intruder starting altitude	Horizontal separation distance	Vertical separation distance	Horizontal miss distance	Intruder starting altitude	Vertical miss distance	Predictor length	Speed × map range	Horizontal miss distance × map range	Constant of regression
1	---	---	---	---	---	0.562^{4}	0.001^{3}	---	---	---	---	5.39
2	-0.57^{4}	---	---	---	---	.36^{5}	---	---	0.027^{6}	---	0.036^{3}	6.84
3	---	---	---	---	---	---	---	---	---	0.001^{2}	---	5.73
4	---	---	---	---	---	---	-.001^{3}	---	.069^{4}	---	---	7.11
5	-1.46^{1}	---	---	---	---	---	---	---	---	.0001^{2}	---	4.74
6	---	---	---	---	---	---	---	---	---	.0001^{2}	.003^{3}	6.01
7	---	---	---	---	---	---	---	---	---	---	.059^{2}	6.28
8	-1.32^{1}	---	---	---	---	---	---	---	---	---	.031^{3}	5.55
9	-.33^{3}	---	0.0001^{2}	---	---	---	---	---	---	---	---	6.83
10	-.28^{2}	---	---	---	---	---	---	---	-.043^{1}	---	---	6.24

*Superscripts show order of inclusion of terms in the regression.

$^{a}p < 0.05$.

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16. Abstract Ten airline pilots rated the collision danger of air traffic presented on cockpit displays of traffic information (CDTI) while they monitored simulated departures from Denver. They selected avoidance maneuvers when necessary for separation. Most evasive maneuvers were turns rather than vertical maneuvers. Evasive maneuvers chosen for encounters with low or moderate collision danger were generally toward the intruding aircraft. This tendency lessened as the perceived threat level increased. In the highest threat situations pilots turned toward the intruder only at chance levels. Intruders coming from positions in fornt of the pilot's own ship were more frequently avoided by turns toward than when intruders approached laterally or from behind. Some of the implications of the pilots' turning-toward tendencies are discussed with respect to automatic collision avoidance systems and coordination of avoidance maneuvers of conflicting aircraft.

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