HUMAN FACTORS, 1987, 29(4), 371–382

Perspective Traffic Display Format and Airline Pilot Traffic Avoidance

STEPHEN R. ELLIS,[1] *and* MICHAEL W. McGREEVY, *NASA–Ames Research Center, Moffett Field, California and the School of Optometry, University of California, Berkeley, and* ROBERT J. HITCHCOCK, *Department of Cybernetics, San Jose State University, San Jose, California*

Part-task experiments have examined perspective projections of cockpit displays of traffic information as a means of presenting aircraft separation information to airline pilots. Ten airline pilots served as subjects in an experiment comparing the perspective projection with plan-view projections of the same air traffic situations. The pilots' task was to monitor the traffic display in order to decide if an avoidance maneuver was needed. Pilots took more time to select avoidance maneuvers with a conventional plan-view display than with an experimental perspective display. In contrast to previous results, if the pilots selected a maneuver with the perspective display, they were more likely to choose one with a vertical component. Tabulation of the outcomes of their initial avoidance decisions with both perspective and plan-view displays showed that they were more likely to achieve required separation with maneuvers chosen with the aid of perspective displays.

INTRODUCTION

The search for a natural display format for a cockpit display of traffic information is as old as the concept itself. The idea for a cockpit traffic display probably originated at the RCA Princeton Electronics Laboratory in 1941, but it was not implemented until after World War II (Herbst, Wolff, Ewing, and Jones, 1946). The basic RCA proposal was to transmit a televised image of the air traffic controller's radar display to a receiver in the cockpit. Terrain and navigation information was provided by optical overlays on both the controller's display and the pilot's video display. Limitations in the existing technology, however, restricted the flexibility with which the display could be formatted. The map format, for example, was north-up rather than heading-up, and thus would have presented a disorienting display when the aircraft was heading south (Baty, Wempe, and Huff, 1974; Ellis, Kim, Tyler, McGreevy, and Stark, 1985; Wickens, 1984).

During the intervening years, various investigators have examined possible cockpit traffic displays for use by the airlines for traffic separation and as a collision-avoidance aid (Boeing Commercial Airplane Company, 1977; Verstynen, 1980). Display formats have generally adhered to the plan-

[1] Requests for reprints should be sent to Stephen R. Ellis, MS 239-3, NASA–Ames Research Center, Moffett Field, CA 94035.

view format originally used for the RCA project, though most now use either heading or track-up formats with a north-up option.

More recently, studies of cockpit traffic displays conducted at the Ames Research Center have focused on the display *format* as opposed to other considerations such as system integration questions and operational procedures. These studies have examined the effect of display background, display update rate (Palmer and Ellis, 1983; Palmer, Jago, Baty, and O'Connor, 1980), and aircraft symbology (Hart and Loomis, 1980) on pilots' estimates of spatial separation and on their patterns of avoidance maneuvers (Ellis and Palmer, 1981; Smith, Ellis, and Lee, 1984).

All of these previous studies concerned with traffic display format have been conducted with plan-view type displays. In such displays, the vertical separation is represented by text displays of aircraft altitude attached to the aircraft symbol. This kind of displayed text is called a *data tag*. An alternative mode of indicating relative altitude is to change the shape of the aircraft symbols. This technique is called *shape encoding*. An example of shape encoding is the use of a full hexagonal symbol to represent an aircraft at the pilot's own altitude. An upper half of the hexagon would then be used to represent aircraft above the pilot's altitude, and the lower half would represent aircraft below the pilot's altitude.

Since none of these previous formats had provided a convenient representation of the vertical dimension of separation, we developed a more natural way of presenting combined horizontal and vertical traffic separation to airline pilots. We selected a perspective format because its dimensionality matches the three-dimensional characteristics of traffic separation. We hoped that this perspective format would match pilots' visualizations of their situations in three-dimensional space, and that the format would be a significant improvement over previous uses of perspective projections to show aircraft separation (e.g., Bird, 1975). We believed that the more natural characteristics of a perspective display, compared with plan-view, would assist in the detection and resolution of traffic conflicts.

The development of this format was also experimentally useful because it allowed investigation of previously observed biases in pilots' maneuver patterns. Earlier investigations in part-mission (Palmer, 1983) and part-task simulation (Smith et al., 1984) had shown, for example, that when pilots were given sufficient time (at least 60 s) they preferred to use horizontal maneuvers to avoid intruding aircraft.

In general, the justifications given for the horizontal maneuvers were procedural. The pilots often based their selection on the extra freedom the usual FAA rules give them for horizontal as compared with vertical maneuvers. For example, justifications for the turns were often "to keep the other aircraft in sight" or "to avoid leaving the assigned altitude." The turns frequently were toward the intruding traffic.

This turning-towards bias, however, is not always observed. It has been found, for example, to be modulated by other aspects of the encounter, especially the heading difference between the aircraft involved (Smith, et al., 1984). Thus, we suspected that the preference for horizontal avoidance maneuvers might not be due to the procedural justification given and also could be modified by the characteristics of the display and the encounter.

Specifically, we thought that the preference for horizontal maneuvers was not based merely on the procedural factors cited by the pilots, but might actually arise from their own difficulties in using the supplementary text written on the plan-view displays—the data tags—to visualize three-dimensional separation. Accordingly, the following experiment was conducted, in which pilots viewed identical sets of traffic encounters presenting identical separation information. The information was presented on either a plan-view or a perspective display. If the display format were influencing the pattern of pilot avoidance maneuvers, pilots using the perspective display should have selected more maneuvers with vertical components.

Analysis of the factors influencing a pilot's decision to initiate an avoidance maneuver while monitoring traffic on a cockpit traffic display is particularly important since these displays may by installed along with automatic collision-avoidance systems. The designers of such systems will need to be familiar with the avoidance decision logic that airline pilots have developed from years of flight experience. Clearly, potential inconsistencies, both in the pilots' collision-avoidance logic, and in the logic of automatic systems, must be identified and resolved. The following experiment extends previous investigations into the kind of initial-maneuver techniques and biases airline pilots may bring to the interpretation of cockpit traffic displays (Palmer et al., 1980; Smith et al., 1984).

METHODS

Subjects

Ten current or recently retired airline pilots served as subjects in this experiment.

The Perspective Display

The perspective display presented a view of the airspace surrounding the pilot's ownship through a "synthetic camera" that was positioned above and behind it, viewing it slightly from one side. The vertical scale was expanded by a factor of five, in a manner corresponding to usual practice in the construction of three-dimensional topographical maps (Jenks and Brown, 1966). The use of a perspective projection to present the traffic situation entailed a choice of many specific parameters of the projection; for example, the effective focal length of the synthetic lens and consequent field of view, the position and direction of the viewing vector, and the amount of expansion of the vertical scale. Since we could find little theoretical or practical guidance for making these choices, we based them primarily on structured interviews with five pilots before the experiment began. During these interviews, the pilots commented on the appearance of the display when a great variety of different projections were used. This interaction with the pilots was made possible by providing an interactive design tool that quickly generated pictures with various perspective parameters for perusal and permutation. The specific projection we chose was nevertheless somewhat ad hoc; the choice of a display remains an area for considerable future investigation.

The projection we ultimately used was a correct-perspective view from an eyepoint 30 km behind ownship, looking down on ownship from an elevation angle of 30 deg with a 50-deg field-of-view angle, and rotated 8 deg so that ownship could be viewed a bit on its right side. The viewing vector was oriented directly toward ownship. Because we were dealing with a synthetic camera, we were able to select the sizes of the aircraft independently of the position of the eyepoint. The size of ownship was constant at 8.0 mm across on the display and was chosen so that it would be clearly visible. The display was 127 mm square. The sizes of all other aircraft were than rescaled relative to ownship according to their perspective projection. It is important to note that the rescaling of all aircraft with respect to ownship and the differential scaling of the vertical axis resulted in an actual projection significantly different from a strictly "correct" projection with the

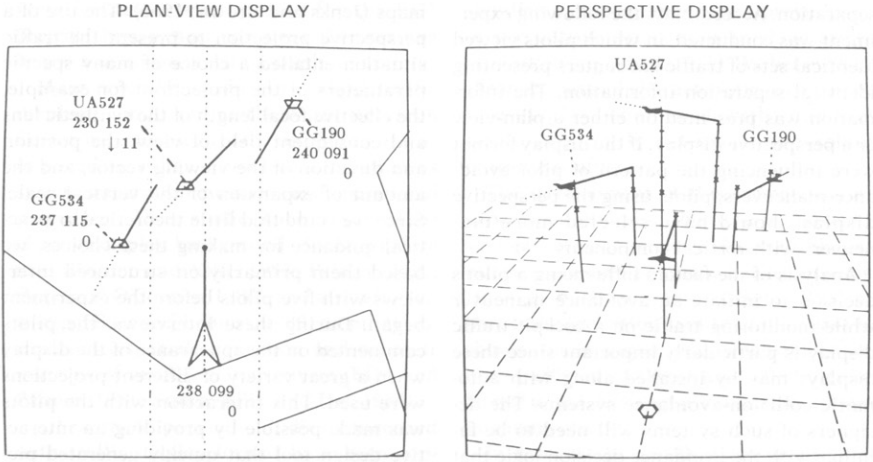

Figure 1. *Comparison of a plan-view (left) and a perspective traffic display (right) for an identical traffic situation.*

perspective parameters we used. All displays were viewed about 60 cm from the display surface under photopic conditions. Display line luminances were about 30 cd/m².

Aircraft on the display were represented by schematic airplane-like symbols and were positioned so that their correct current location was under the nose of the symbol. Ownship was always presented so that it was in the center of the display. Each aircraft was presented with a 60-s ground-referenced predictor and trailed 10 dots separated by 4-s periods, representing previous positions. Horizontal separation and aspect were unambiguously presented by placing reference lines from the present and future positions of all aircraft onto a grid ruled with 3-nautical-mile intervals that were shown 5000 feet below ownship. The grid appeared to move under ownship in proportion to its ground speed and was aligned so that its centerline always corresponded to ownship's instantaneous ground track. Thus, the grid could serve as a moving two-dimensional frame of reference for judging present and future horizontal separation.

Vertical separation was presented by calculating a level plane at ownship's altitude passing through all of the reference lines. The intersection of this plane with each reference line was shown by small *x*'s drawn on the reference lines. The intervals between the *x*'s and all present or future positions of aircraft were divided into 1000-foot intervals by tick marks.

An important aspect of all of the symbology selected for use with the perspective display was that it presented "ownship-relative" information. For example, the 1000-foot altitude tick marks indicate relative vertical separation, and the alignment of the grid to ownship's ground track provides a relative horizontal-separation metric. In this way, the display presents what Falzon (1982) calls the "variables" of an encounter as opposed to "properties," which are the specific characteristics of the aircraft involved such as speed, heading, and absolute altitude.

Plan-View Control Display

A plan-view format with ground-referenced, one-minute predictors and 40 seconds of history similar to that on the perspective display served as a control (see left side of Figure 1). The data tags on this display showed speed (knots) and altitude (hundreds of feet) on the middle line, and vertical rate information (hundreds of feet per minute) on the bottom line. Upward- and downward-pointing arrows indicated climb and descent, respectively. Dashed lines three nautical miles on each side of ownship's ground track and route lines provided a sense of motion over terrain. Thus, this display presented separation information similar to that presented on the perspective display and served as a control for testing the hypothesis regarding horizontal-maneuver bias.

Experimental Design

Display type was crossed with subjects in a repeated-measures design with counterbalanced order of presentation and independent groups analysis to control for asymmetric transfer. The encounters used on all displays were designed so that in each situation there were two aircraft displayed with ownship: an intruder, 90 s from time of minimum separation, and a pseudo-intruder, 110 s from minimum separation. The trajectory of the pseudo-intruder was selected so that it never produced a spacing violation with ownship.

The traffic environment was that of a terminal control area (TCA) under true instrument meteorological conditions. All aircraft were medium commercial transports and were to be considered under air traffic control. No other aircraft were equipped with cockpit traffic displays. Ownship was in straight-and-level flight in conformance with its current clearance to maintain 10 000 feet and 240 knots if no spacing violation occurred for the duration of the scenario, which lasted 90 s at most.

Encounter Geometry

The intruder's trajectories were selected to randomly provide 108 geometrically different encounters with a variety of horizontal and vertical speeds, horizontal and vertical miss distances, and heading differences. This was done by systematically varying the intruder's heading difference with ownship (0, ±30, ±60, ±90, ±120, ±150 deg) and randomly pairing these heading differences with horizontal miss distances (±0.5, ±1.5, ±4.0 nautical miles), vertical miss distances (±300, ±750, ±1500 feet), and intruder vertical speeds (0, ±2000 feet/min) in a repeated-measures design in which heading difference was crossed with display type. The algebraic sign of the other variables was ignored. This variation served to provide the 108 different traffic scenarios to be presented to each subject. Thus, any systematic selection of maneuvering would be collected from a wide variety of potential traffic encounters. This wide variety points to an advantage of using a part-task technique, since neither full-mission nor part-mission experiments are capable of allowing exploration of such a wide experimental space.

Subject's Task

The pilot's task was to monitor the developing conflict situation as if he were flying in ownship, and to recommend an avoidance maneuver. Maneuvers were to be selected if the pilot determined that an intruding aircraft would pose a spacing violation by coming within 3 nautical miles horizontally and 1000 feet vertically. If the pilot foresaw a violation, he was then to select an avoidance maneuver (climb, descent, turn, or combined maneuver) by moving the stick of the simulator in the direction he would use if actually flying an aircraft. He also could signal with a stick-mounted button when he had seen enough of the developing conflict to determine that no avoidance maneuver would be necessary. Either of these decisions would terminate the encounter scenario. The pilot's decision time was measured from the beginning of the encounter, when the traffic display first appeared on the CRT screen, to the time when he either selected a maneuver or decided he no longer needed to monitor the traffic display because the danger of a conflict had passed. The times and types of maneuvers selected were automatically recorded by the simulation computer.

Immediately after making an avoidance decision, the pilot answered several questions on a questionnaire concerning the specific characteristics of the avoidance maneuver he had selected. He indicated the desired bank angle, the desired degree of angular course deviation, the desired rate of climb or descent, and the desired amount of change in altitude. The pilots took from one to two minutes, immediately after termination of the encounter, to complete the questionnaire. This information allowed the experimenters to simulate the maneuver on a data analysis computer to determine some of the consequences had the pilot been allowed to execute the maneuver he selected.

Significantly, the pilot was never allowed to see the consequences of his selected avoidance decision. This condition, which was successfully used for a similar purpose in a previous experiment (Smith et al., 1984), was specifically intended to reduce the effects of practice and training on the results. The experiment was thus intended to take an inventory of pilots' maneuver predispositions based on their extensive flying experience.

To prevent this inventory from being corrupted by the experience of the experiment itself, we carefully avoided training the pilots either explicitly or implicitly in specific avoidance procedures or in the consequences of their own decisions. No pilot, however, was allowed to participate in the experiment until he had demonstrated complete understanding of the symbology used on the display and successful operation of the simulator controls. This understanding was provided by approximately one hour of briefing and practice before the beginning of any particular experimental run.

Experimental Environment

The experiment was conducted in two sessions separated by about one week. Each session, including initial instructions, lasted between four and five hours. All sessions were conducted in the NASA–Ames Multicab room, which allowed the subjects to sit in simple aircraft simulators and monitor the displays on an Evans and Sutherland PS II calligraphic display positioned on the control panel. This test facility is described in detail elsewhere (Hart, 1982). It provided a fairly realistic cockpit environment in which the pilots could monitor the developing traffic conflicts. All of the usual flight controls are present: stick, rudder, and pedals. No external visual scene could be provided. The cabs were partially closed to isolate the pilot and increase the realism of the simulation. The pilots were kept in audio contact with the experimenter by an intercom link.

Each subject received written instruction booklets that described the purpose and assumptions of the experiment and the operation of the simulator cockpits. The pilots were told to adopt one of the roles of the "pilot not flying," whose usual duties include a radio watch to keep track of potential traffic conflict. The cockpit traffic display provided the source of this information instead of the usual aircraft radio communications. The subjects were told to assume that the traffic display presented true conditions unaffected by weather, tracker lags, or radar noise, and that wind was negligible.

RESULTS

The statistical tests on the results reported in this section have been checked to eliminate the possibility of asymmetric transfer (Poulton, 1974) by using a repeated-measures analysis with 10 subjects and then confirming any significant effect with an independent-groups analysis with 5 subjects per group.

The pilots' mean decision time either to initiate a maneuver or to decide that no maneuver would be necessary was 38 s for the plan-view display and 35 s for the perspective display. This difference was not statistically significant, $F(1,9) = 0.447, p > 0.05$; $F(1,8) = 0.555, p > 0.05$. However, an analysis of variance conducted on the data showed a highly significant interaction between type of display and heading difference, $F(5,45) = 3.51, p < 0.01$; $F(5,40) = 5.71, p < 0.001$, which on inspection showed that for all but head-on traffic, the pilots' decision time with the perspective display was from 3 to 6 s faster than with the plan-view display (see Figure 2). For head-on traffic, the reverse was true, and the perspective display actually took about 5 s longer to interpret. This undoubtedly resulted from that fact that an intruder's symbology was practically impossible to interpret when it flew along the axis of the viewing vector, as was the case for head-on traffic. Under these conditions, the reference lines from both present and future positions were practically superimposed, and it was hard to tell if the intruder was coming or going. Thus, it is reasonable to conclude that, for the task used in this experiment, the perspective display provided a time advantage for the conditions in which its symbology could be seen.

The pilots selected avoidance maneuvers somewhat more frequently when using the plan-view displays than when using the perspective display. The mean number of maneuvers with plan-view was 59.3, versus 49.6 for the perspective display. This difference is, however, not statistically significant, $t(9) = 1.40, p > 0.05$; $t(8) = 0.07, p > 0.05$.

However, a breakdown of the types of maneuvers chosen shows a striking difference in the maneuver patterns for the two displays.

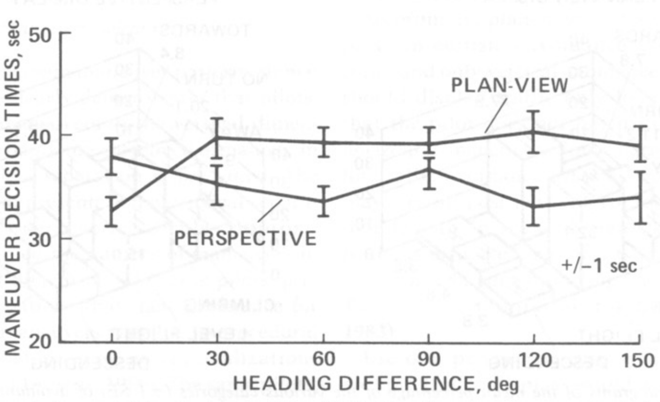

Figure 2. *Mean and standard error of the pilot decision time to make maneuver decisions.*

The left part of Figure 3 shows the maneuver pattern for the plan-view display. This pattern replicates an earlier finding from both part-mission and part-task experiments. These results showed that when intruding aircraft are seen at least 60 s before minimum separation, horizontal maneuvers seem to be preferred (Palmer, 1983; Smith et al., 1984). The right part of Figure 3 clearly shows a shift to more maneuvers with vertical components when pilots used the perspective display.

This tendency may be analyzed subject by subject by calculating the ratio of each pilot's maneuvers with vertical components to those without vertical components. Though correlated with a percentage, this score is superior for statistical analysis because it is not constrained to a fixed range of 0 to 100. Tabulation of this score for each pilot separately showed that all pilots had a greater preference for vertical maneuvers with the perspective display (sign test, $p < 0.002$). The mean of the vertical maneuver score for the plan-view display was 0.77 and the mean for the perspective display was 2.33. This difference can be analyzed by a t test for repeated measures and double-checked by an independent groups t test. Both confirm the relatively increased number of vertical maneuvers with the perspective display that is clear from Figure 3, $t(9) = 4.30, p < 0.002$; $t(8) = 2.62, p < 0.03$.

We have assessed some aspects of the quality of the initial maneuvers that the pilots selected with both types of display, such as the frequency of the pilots' failure to maneuver when necessary for safe spacing. This analysis of the patterns of the pilots' avoidance maneuvers was accomplished by tabulating each extrapolated encounter outcome into one of six possibilities. For each encounter, a pilot decided whether or not a maneuver would be required to avoid a separation violation. A decision to make no maneuver was "correct" if, in fact, no separation violation would have occurred. If, however, a no-maneuver decision resulted in a separation violation, this decision was "incorrect." A decision to make a maneuver was termed necessary if the planned separation for an encounter resulted in a separation violation.

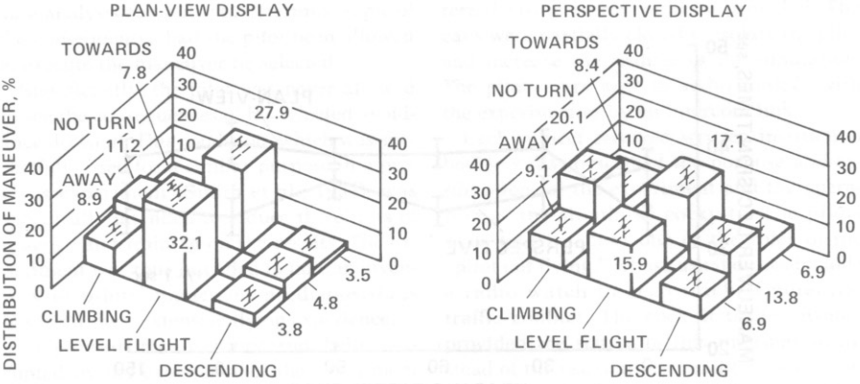

Figure 3. *Histograms of the mean percentage of the various categories (±1 SE) of avoidance maneuvers broken down by display type.*

Furthermore, a necessary maneuver was "successful" if it would have avoided the violation, or "unsuccessful" if it would not. On the other hand, a decision to maneuver was termed unnecessary if no separation violation would have occurred. Such an unnecessary maneuver was a "blunder" if it would have created a separation violation. An unnecessary maneuver that would not create a separation violation was categorized as a "wasted" maneuver.

Frequency counts of each possible outcome were analyzed for each pilot and each display. All categories except incorrect show an overall advantage for the perspective display. Two categories show statistically significant differences insensitive to the statistical method of repeated-measures analysis: unsuccessful, $t(9) = 5.71$, $p < 0.001$; sign test $p < 0.002$; and blunder, $t(9) = 3.464$, $p < 0.0085$; sign test $p < 0.04$. The smaller number of unsuccessful maneuvers with the perspective display remained statistically significant when checked with the more conservative independent groups t test, $t(8) = 3.58$, $p < 0.01$.

DISCUSSION

Patterns of Maneuver Selection

The difference in maneuver patterns shown in Figure 2 clearly demonstrates that pilots' avoidance maneuvers in the vertical dimension are strongly affected by the manner in which vertical separation is presented. The more natural presentation of vertical separation on the perspective display approximately doubled the number of maneuvers in the vertical dimension. Thus, the pilots' previous explanations that their preference for horizontal maneuvers was due to procedural reasons must be seen as rationalizations (Dreyfus and Dreyfus, 1986). The same pilots, when provided a second chance to interpret a given encounter (and unaware of the repetition because of the large number of different encounters and the intervening time between test sessions), chose more vertical maneuvers when using a perspective display.

The presence or absence of a vertical component in a pilot's initial avoidance maneuver is practically important because the planned implementation by the FAA of the Traffic-Alert and Collision Avoidance System (TCAS) will initially only command vertical maneuvers. Such maneuvers would be in conflict with pilots' overall biases if traffic information were presented on a plan-view format with sufficient preview time for pilots to consider a horizontal maneuver. Significantly, the pilots' preference for horizontal maneuvers is reduced if they are allowed to monitor a developing conflict for 60 s or less (Palmer, 1983). The horizontal bias almost disappears if a preview of only 40 or 25 s is allowed (E. A. Palmer, personal communication, October 9, 1986). This dependence on preview time probably reflects the fact that vertical maneuvers, particularly descents, are quicker than turns. Thus, when the time for maneuvering is short, vertical maneuvers are preferred.

Accordingly, plan-view cockpit traffic displays in collision-avoidance systems that command only vertical avoidance maneuvers should display traffic only long enough so that the pilot does not begin to consider a horizontal maneuver. Some current designs for traffic-avoidance systems that also display aircraft position conform to this recommendation. In these designs, conflicting traffic is displayed only if it is less than 40 s to a point of minimum separation (Radio Technical Commission for Aeronautics, 1983).

Use of a perspective display format for a cockpit traffic display would relax the restriction on preview time, since with such

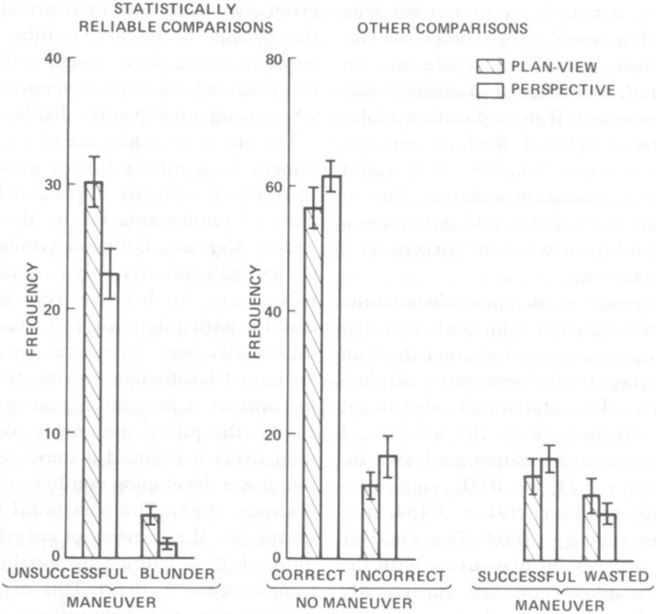

Figure 4. *Barplot showing the means and the standard errors for the frequency of possible outcomes.*

displays pilots would be less inclined to make purely horizontal maneuvers. However, because a constraint on preview time also has the advantage of reducing the amount of traffic shown on the display, the selection of a display format should not be based solely on its probable effect on pilot maneuver biases.

Timing of Maneuver Selection

The absolute response times used by the pilots to evaluate whether avoidance maneuvers would be required are undoubtedly closely related to the specific task and instructions. The approximate 10% time reduction for interpretation of the perspective display, however, probably does reflect a *relative* difference and shows that decision time can be reduced by avoiding the use of data tags that must be read to find vertical separation. The requirement that the pilot read four sets of numbers associated with each vehicle in the plan-view display—as opposed to only the aircraft identification tag on the corresponding aircraft symbol on the perspective display—probably accounts for the difference in decision times.

The particular problem of superimposition of the display symbology seen with the perspective format for head-on traffic is analogous to the problem of superimposition of data tags on the plan-view display. Since the plan-view display had the advantage of an automatic algorithm that prevented superimposition of the data tags, a similar system for adjusting the eyepoint to provide a less frontal view of head-on traffic might have helped the perspective display and further reduced pilot decision time while using it. Clearly, any implementation of a perspective display will require a solution to the problem of superimposed symbology. As an alternative to automatic decluttering, pilots might be given some control over the position of the eyepoint.

Elaborate quantitative evaluation of the quality of the pilots' avoidance maneuvers while using each display is beyond the scope of this experiment. This is primarily because the experiment was designed as a way to inventory pilots' initiation of traffic avoidance, not to assess the proficiency with which they could carry out such a maneuver. The latter analysis would require substantial training (to asymptotic behavior) in order to provide a realistic and useful comparison of display formats. The reported relative differences are worth noting, however, because they suggest that use of the perspective display resulted in improved avoidance maneuvering with fewer blunders and fewer unsuccessful attempts to achieve a specified separation. Furthermore, the relative decision times and maneuver patterns reported above are significant in themselves because they reflect the biases and opinions with which pilots would greet the introduction of a cockpit traffic display into the cockpit. In the cases of our subjects, these opinions are based on thousands of hours, in some cases more than 10 000 hours, of airline experience and thus reflect the kind of ingrained opinion and perception that might appear in time of stress.

In summary, the results of the current experiment point toward the usefulness of investigating more natural display formats for the integrated presentation of three-dimensional separation information. The improvements in decision time and avoidance performance that can be attributed to the perspective format in this experiment are probably not the maximum achievable, since the format itself was not systematically optimized for the pilot's use. Our research on the influence of the parameters of a projection on picture perception will provide a basis for further improvements in parameter selection (McGreevy and Ellis, 1986; McGreevy, Ratzlaff, and Ellis, 1985). These improvements could also be integrated into intelligent perspective display systems that automatically configure themselves to provide their users with the most interpretable perspective projection possible.

ACKNOWLEDGMENTS

A preliminary version of this report were presented at the May 1984 AGARD Conference on Human Factors Considerations in High Performance Aircraft. The research reported here was partially supported by NASA Cooperative Agreement NCC-2-86 to L. Stark at the University of California, Berkeley.

REFERENCES

Baty, D. L., Wempe, T. E., and Huff, E. M. (1974). A study of aircraft map display location and orientation. *IEEE Transactions on Systems, Man and Cybernetics, SMC-4*, 560-568.

Bird, J. M. (1975). *On the display of three dimensional air traffic control situations. Applied psychology* (Note A.P. 47). Birmingham, England: University of Aston.

Boeing Commercial Airplane Company. (1977). *Cockpit displayed traffic information study* (Report No. D6-42968). Seattle, WA: Author.

Dreyfus, H. L., and Dreyfus, S. (1986). *Mind over machine.* New York: Free Press.

Ellis, S. R., and Palmer, E. A. (1981). *Threat perception while viewing single intruder encounters on a cockpit display of traffic information* (NASA TM 81341). Moffett Field, CA: NASA–Ames Research Center.

Ellis, S. R., Kim, W. S., Tyler, M., McGreevy, M. W., and Stark, L. (1985). Visual enhancements for perspective displays: Perspective parameters. In *Proceedings of the 1985 International Conference on Systems, Man and Cybernetics* (pp. 815-818). New York: IEEE.

Falzon, P. (1982). Display structures: Compatibility with the operator's mental representations and reasoning processes. In *Proceedings of the 2nd European Annual Conference on Human Decision Making and Manual Control* (pp. 297-305). Wachtberg-Werthoven, West Germany: Forschungsinstitut für Anthropotechnik.

Hart, S. G. (1982). Effect of VFR aircraft approach traffic with and without cockpit display of traffic information. In *Proceedings of the 18th Conference on Manual Control* (AFWAL-TR-3021; pp. 522-544). Wright-Patterson AFB, OH: Air Force Flight Dynamics Laboratory.

Hart, S. G., and Loomis, L. L. (1980). Evaluation of the potential format and content of a cockpit display of traffic information. *Human Factors, 22,* 591-604.

Herbst, P. J., Wolff, D. E., Ewing, D., and Jones, L. R. (1946). The TELERAN proposal. *Electronics, 19,* 125-127.

Jenks, G. F., and Brown, D. A. (1966). Three dimensional map construction. *Science, 154,* 837-846.

McGreevy, M. W., and Ellis, S. R. (1986). The effects of perspective geometry on judged direction in spatial information instruments. *Human Factors, 28,* 421-438.

McGreevy, M. W., Ratzlaff, C., and Ellis, S. R. (1985). Virtual space and two-dimensional effects in perspective displays. In *Proceedings of the 21st Annual Conference on Manual Control.* (NASA CP 2428; pp. 29.1-29.14). Moffett Field, CA: NASA–Ames Research Center.

Palmer, E. A. (1983). Conflict resolution maneuvers during near miss encounters with cockpit traffic displays. In *Proceedings of the Human Factors Society 27th Annual Meeting* (pp. 757-761). Santa Monica, CA: Human Factors Society.

Palmer, E. A., and Ellis, S. R. (1983). Potential interactions of collision avoidance advisories and cockpit displays of traffic information. In *Proceedings of the Society of Automotive Engineers* (Paper 831544; pp. 433-443). Warrendale, PA: Society of Automative Engineers.

Palmer, E. A., Jago, S. J., Baty, D. L., and O'Conner, S. L. (1980). Perception of horizontal aircraft separation on a cockpit display of traffic information. *Human Factors, 22,* 605-620.

Poulton, E. C. (1974). *Tracking skill and manual control.* New York: Academic Press.

Radio Technical Commission for Aeronautics. (1983). *Minimum operation performance standards for the traffic-alert and collision avoidance system (TCAS) (airborne equipment)* (RTCA/DO-185, prepared by committee SC-147). Washington, DC: Author.

Smith, J. D., Ellis, S. R., and Lee, E. (1984). Perceived threat and avoidance maneuvers in response to cockpit traffic displays. *Human Factors, 26,* 33-48.

Verstynen, H. A. (1980). *Potential roles for the cockpit traffic display in the evolving ATC system* (Report No. SAE-800736). Warrendale, PA: Society of Automotive Engineers.

Wickens, C. D. (1984). *Engineering psychology and human performance.* Columbus, OH: Charles Merrill.