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Evaluation of Perspective and Coplanar Cockpit Displays of Traffic Information to Support Hazard Awareness in Free Flight

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ABSTRACT

We examined the cockpit display representation of traffic, to support the pilot in tactical planning and conflict avoidance. Such displays may support the "free flight" concept, but can also support greater situation awareness in a non-free flight environment. Two perspective views and a coplanar display were contrasted in scenarios in which pilots needed to navigate around conflicting traffic, either in the absence (low workload) or presence (high workload) of a second intruder aircraft. All three formats were configured with predictive aiding vectors that explicitly represented the predicted point of closest pass, and predicted penetration of an alert zone around ownship. Ten pilots were assigned to each of the display conditions, and each flew a series of 60 conflict maneuvers that varied in their workload and the complexity of the conflict geometry.

Results indicated a tendency to choose vertical over lateral maneuvers, a tendency which was amplified with the coplanar display. Vertical maneuvers by the intruder produced an added source of workload. Importantly, the coplanar display supported performance in all measures that was equal to or greater than either of the perspective displays (i.e., fewer predicted and actual conflicts, less extreme maneuvers). Previous studies that have indicated perspective superiority have only contrasted these with UNIplanar displays rather than the coplanar display used here.

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1 INTRODUCTION

A dramatic increase in the volume of air traffic over the past 15 years has placed substantial pressure on the National Airspace System. Air traffic control technology currently in use to support traffic separation and management is limited, and has required the use of excessive restrictions in order to maintain safety in a system which has experienced increased delays, escalating operating costs and decreased overall efficiency (RTCA, 1995). These problems may be overcome, however, by the introduction of enabling technologies which have the potential of radically changing the way the current National Airspace System is structured, leading to dramatically improved efficiency while maintaining a high level of safety. This technology combines airborne and ground based systems to support precise estimates of aircraft position, heading and velocity. A concept known as free flight has been introduced to describe how the National Airspace System can evolve to take advantage of this new technology. The RTCA Select Committee on Free Flight defines the concept as:

> A safe and efficient flight operating capability under instrument flight rules (IFR) in which the operators have the freedom to select their path and speed in real time. Air traffic restrictions are only imposed to ensure separation, to preclude exceeding airport capacity, to prevent unauthorized flight through special use airspace, and to ensure safety of flight. Restrictions are limited in extent and duration to correct the identified problem. Any activity which removes restrictions represents a move toward free flight. (RTCA, 1995, p. 3)

As stated in the preceding definition, the proposed changes under free flight will reduce or eliminate many of the restrictions placed on air transport operators by air traffic control (ATC). The current system of highly restricted, ATC-selected flight paths will give way to a flexible scenario in which pilots will be able to fly more direct and fuel efficient routes to their destinations, provided that safe separation from other aircraft can be maintained. Because of the increased flexibility of flight path selection supported by free flight, the burden of responsibility for ensuring safe separation may shift, to some degree, from ATC to the cockpit. In fact, even under the current system pilots at times use the traffic display contained in the Traffic alert and Collision Avoidance System (TCAS) now installed in commercial aircraft to monitor their separation from other traffic. This has occasionally led to situations in which ATC clearances were ignored by pilots who initiated maneuvers in response to information on the TCAS traffic display, causing potentially serious erosions of ATC authority (Ripley and Klemm, 1995; Mellone and Frank, 1993). While the precise nature of the distribution of responsibility between ground and air for assuring separation has yet to be determined, and will certainly involve some level of automation, it will nevertheless require that the pilot maintain a robust awareness of surrounding air traffic. To maintain an adequate state of situation awareness, pilots must monitor the relative position, bearing and speed of nearby aircraft to determine if loss of separation is a possibility, and to select appropriate maneuvers to avoid or resolve potential conflicts should they occur. Information displays will have to support pilots' awareness of those critical variables which define the evolving traffic environment around them.

The information necessary to determine whether other aircraft represent a threat is four-dimensional, requiring the integration of three spatial dimensions with time to produce estimates of future proximity between one's own aircraft and other air traffic. Traditionally, this type of information has been displayed to the air traffic controller or pilot using a top-down planar format which graphically represents latitude and longitude with position on the X and Y axes of the viewing plane, while depicting altitude and airspeed with alphanumeric codes and symbolic icons (i.e., current TCAS traffic display; air traffic control displays). The advantage of the top-down planar format is the precision and ease with which horizontal judgments can be made because of the compatible mapping between the spatial analog code of the display and the analog nature of the information it represents. The disadvantage is the relative difficulty in integrating or comparing the analogically coded horizontal information with the digitally coded altitude data, as well as the difficulty in extracting vertical trends (rate of climb or decent) from the digital format. In some proposed prototypes two planar displays (referred to as coplanar) are used to present information from the X-Y and X-Z planes of the data space (Wickens and Prevett, 1995). This provides a more compatible representation of the information from each plane, eliminating the need to compare analog and digital display codes. The disadvantage of coplanar displays, however, is evident when the operator is trying to compare or integrate values on all three axes, across both planar displays. Potential costs include increased visual scanning between the two 2D panels, greater working memory requirements (retaining values from one panel to integrate or compare with the other panel), matching corresponding data points presented in each of the two 2D panels, and the demands of cognitive integration or reconstruction of the three-dimensional data space from the two 2D displays (Wickens, Merwin, and Lin, 1994).

Given that the information necessary to make estimates of future aircraft position requires the integration of the three spatial axes, a three-dimensional display format might offer distinct advantages over planar formats. Indeed, earlier work on the proposed cockpit display of traffic information or CDTI (a predecessor of the TCAS system; Abbot et al., 1980) has shown performance benefits for integrating the three spatial axes in a perspective display (Ellis, McGreevy, and Hitchcock, 1987). However, other research has clearly shown that performance can be impaired by perspective displays (McGreevy and Ellis, 1986). The reasons for this impairment are related to both the difficulty in making estimates of position along the three axes, resulting from the integration of the dimensions as they are projected onto the frontoparallel plane, and to the perceptual biases induced by the geometric parameters used to generate the projection (McGreevy and Ellis, 1986; Rosenberg and Barfield, 1995).

The choice of whether to use a perspective or planar format to present information is determined by the relative magnitude of the advantages and costs which can be expected when the three spatial axes are integrated. Several recent experiments which have attempted to measure the relative costs and benefits of presenting three-dimensional position information in planar and perspective formats have found inconsistent results. In the current work, we review these earlier studies and propose an experiment in which we attempt to reconcile some of the previous findings in the context of a cockpit air traffic display to support awareness of future aircraft conflicts. After a brief overview of the CDTI literature, we discuss the relevant work on the perception of three-dimensional perspective displays. We follow this with a review of research which has compared perspective and planar formats for information display. Finally, we describe the rationale for the current study, in which we compare perspective and coplanar CDTI formats using a part-task flight simulation paradigm.

1.1 Cockpit Display of Traffic Information (CDTI)

A considerable body of work examining the display formatting of air traffic information in the cockpit has accumulated primarily from research supported by and conducted at the NASA research centers starting in the 1970's (Abbott et al., 1980; Smith, Ellis and Lee, 1984; Chappell and Palmer, 1983; Williams, 1983; Palmer, 1983; Kreifeldt, 1980; Hart and Loomis, 1980; Palmer, Jago, Baty and O'Conner, 1980; Ellis, McGreevy and Hitchcock, 1987). Much of this work has dealt with issues beyond the scope of the current study but is nevertheless relevant to the current research, and therefore will be briefly presented here. The work described in this section involved information presented in a top-down planar format, with altitude data, when available, presented digitally or symbolically using shape coded icons. Experiments comparing planar and perspective display formats will be described in section 3.

Palmer and his colleagues (1980) report a series of experiments in which subjects judged whether intruder aircraft would pass in front of or in back of their own ship (altitude was not relevant to the judgment), using a display which provided combinations of several types of information (see Figure 1).

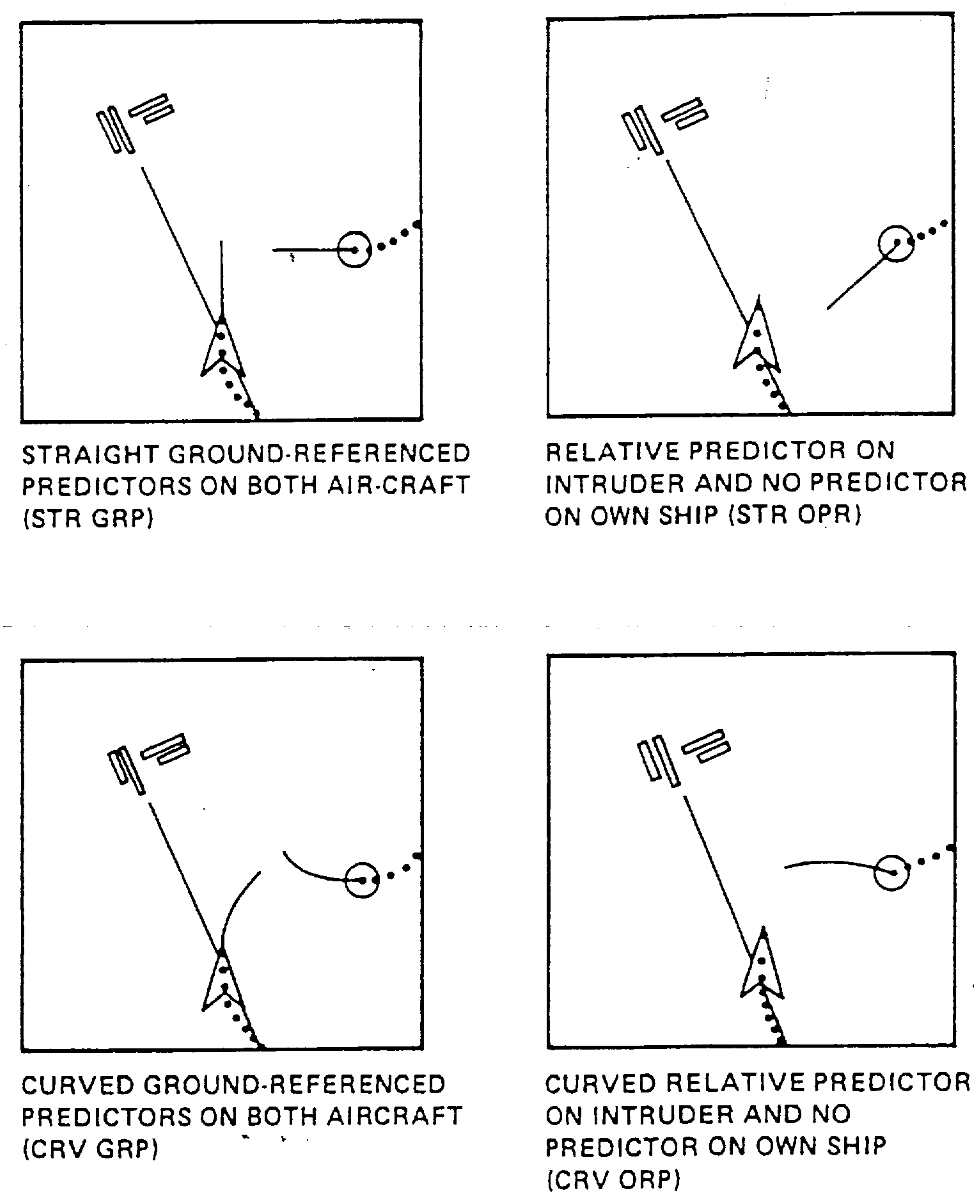


Figure 1. A reproduction of four display formats used by Palmer et al. (1980), showing different types of predictive information for CDTI.

The authors found that displayed history of position information (dots trailing behind aircraft icons) did not improve performance, but was desired by pilots if no other explicit turn rate information was provided. Better performance was observed when lines indicating predicted position at some future time were provided, especially when turn rate information was incorporated by curving the predictor lines proportional to rate of turn. Varying update rate of the display elements between .1 and 4 seconds had no effect on performance. No differences in performance were observed when viewing time of the display was varied from 1 to 16 seconds. The authors conclude that pilots can only make accurate judgments consistently when predictor symbology is provided, and that turn rate information must be available for encounters involving aircraft that are changing their heading. In part because of the results of this research, predictive symbology has been used in several subsequent studies, and indeed plays an important role in the current experiment.

Hart and Loomis (1980) solicited opinions from general aviation and airline pilots about the appropriate display format, information content and graphic symbology of more than 100 display options for CDTI. Using the subjective data collected, the authors then employed a similar methodology to that used by Palmer and his colleagues (1980) to assess the effectiveness of the different forms of display symbology in supporting judgments of whether intruder aircraft would pass in front of or in back of (experiment 2), or above or below (experiment 3) ownship at the point of closest distance. The authors replicated several of the findings of Palmer and his coworkers (1980) in experiment 2, which dealt with horizontal judgments. Results from the first two experiments also indicated that pilots preferred coded information about the vertical situation of the intruder aircraft (full hexagon icons for aircraft within 500ft of ownship, upper half or lower half of hexagon for positions above and below 500ft, respectively; small arrow pointing up or down indicating climb or descend, respectively). However, the data from experiment 3 indicate that in spite of the pilots' preference for the analog coding of altitude, their performance with these display augmentations was not significantly different from conditions in which digital altitude tags were displayed only. The authors conclude, among other things, that judgments of vertical relationships are more difficult (take longer and are less accurate) than horizontal judgments. This finding is not surprising given that the display codes used to present vertical information were either alphanumeric or symbolic/iconic, which do not support comparative judgments as effectively as analog scales (Carswell and Wickens, 1988).

Kreifeldt (1980) summarized the results from several studies in which three pilots simultaneously flew individual CRT based instrument simulators with an air traffic controller monitoring and/or directing their approaches. The simulators had CDTI displays which showed air traffic (their own ship, the other pilots' aircraft and two additional computer controlled aircraft) as well as relevant terminal area route markings. The experiments focused on the feasibility of *distributed management*, whereby pilots assume some of the responsibility of coordinating their approaches with other aircraft using the CDTI. In one condition, ATC issued vectors and speed clearances to the pilots in a manner similar to contemporary instrument flight rules (IFR). A second condition required pilots to coordinate the insertion of their aircraft into a final approach sequence without any direction from ATC, using only their traffic displays and a voice communication channel. ATC issued sequencing commands in a third condition, but required pilots to maintain their own separation.

The author concluded that a considerable reduction in controller verbal work load without any significant increase in pilot verbal work load resulted from using the CDTI in one of the two distributed management conditions, although some pilots reported tolerable increases in visual work load. Pilots maintained tighter spacing using the CDTI in the distributed management mode than when they were issued vectors and speed commands from ATC. Pilots preferred the distributed mode to the more rigid rules, while controllers expressed contrary opinions. Overall efficiency, as expressed by the number of aircraft passing a navigational fix during the simulation runs, was greatest in the CDTI conditions. Importantly, this study demonstrates that within the limitations of the simulation paradigm used, pilots can effectively use air traffic displays for some types of maneuvers. This finding offers important support to the feasibility of the idea that pilots can bear increased responsibility for monitoring and maintaining their own separation, a key component to some of the proposals of the free flight initiative.

Using a somewhat different methodology than Kreifeldt (1984), and similar CDTI symbology to that tested by Hart and Loomis (predictive vectors and hexagonal icons for traffic; 1980), Palmer (1983) carried out an experiment in which pilots flew simulated flights during which intruder aircraft appeared. Pilots were instructed to execute small maneuvers to avert conflicts if they deemed it necessary, but to remain within 1.5 nautical miles and 500ft of their command flight path. The amount and quality of predictive information on their CDTIs was manipulated, along with the amount of intruder preview time.

The results indicated that pilots were able to avoid triggering a collision avoidance system (CAS) advisory most often when they had predictive information that was free from noise (avoided CAS advisory 90% of the time), and less often when sensor noise was present or when no predictive information was provided (CAS advisories avoided 76% and 78% of the time, respectively). As the amount of time available to assess intruder threat decreased, pilots executed maneuvers sooner and initiated more vertical maneuvers. The finding that pilots prefer vertical maneuvers as they experience more time pressure is interesting, suggesting that they are more comfortable with a strategy of trying to gain altitude separation than trying to maneuver horizontally around a perceived threat. Such a preference is consistent with the knowledge that adjustment of vertical spacing is of a lower control order (second) than is adjustment of lateral spacing (third), and hence can be accomplished with reduced lag (Wickens, 1986). If this speculation is correct, then it follows that planar display formats are not optimal for supporting this particular strategy given the greater difficulty in assessing the vertical situation from the digital or symbolic codes used to represent it. The next reported study, however, offers a contradictory view of pilots' avoidance strategies.

Smith and his associates (1984) examined the selection of avoidance maneuvers using a planar CDTI display similar to that developed in the previous studies. In addition to the horizontal position information which included predictor lines, altitude data were displayed digitally with arrows indicating vertical trend information (see Figure 2). The primary interest here was to explore the types of maneuvers made in response to a wide variety of encounter geometries, as well as the effects of a display manipulation which altered the map range of the CDTI. The results showed that pilots tended to turn toward intruding aircraft (attempting to pass behind the intruder) rather than away from them, and nearly always selected horizontal maneuvers. The strong bias to select horizontal maneuvers is in contrast to Palmer's (1983) findings, but can be explained as a strategy that is facilitated by the horizontal display format of the CDTI. The ease with which horizontal information can be extracted from the display may have encouraged pilots to evaluate threats in terms of their horizontal parameters, leading to avoidance maneuvers which also were defined in terms of the horizontal parameters. It is also true that the symbol indicating vertical trend information, the small arrow embedded in the data tag of Figure 2, is neither salient nor well integrated with the horizontal depiction and hence may have been difficult to use. A third explanation for the horizontal bias is, of course, the great emphasis placed on maintaining altitude clearance by the FAA. While Palmer's (1983) study indicated a contradictory bias in favor of vertical maneuvers, this might have been a result of the shorter time which pilots were given to evaluate the situation.

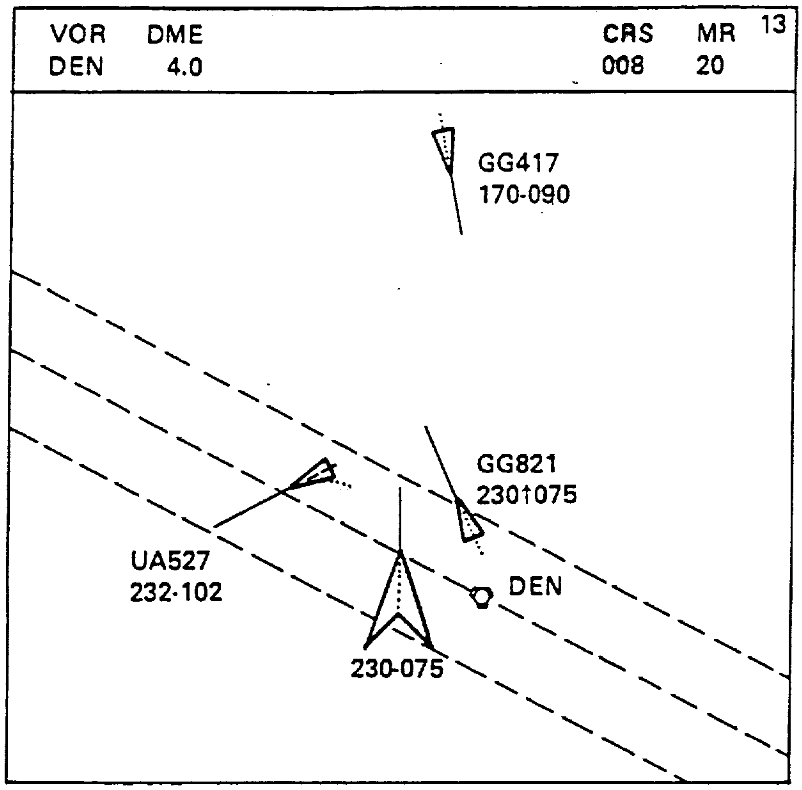


Figure 2. A reproduction of the display format used by Smith and his colleagues (1984) showing a typical traffic scenario.

The findings of the two studies can be reconciled by assuming that pilots use the strategy that is best supported by the display format, but that they may tend toward making vertical maneuvers when they do not have sufficient time to plan a horizontal maneuver. This explanation is speculative, but is in agreement with the fact that rates of closure between aircraft can be several orders of magnitude greater in the horizontal plane than in the vertical dimension, providing a greater benefit for vertical separation. In other words, the combined influence of the analog presentation of horizontal information with the FAA's strict guidelines for maintaining a prescribed altitude may occasionally be overridden (as in Palmer's experiment) by pilots' natural biases to maneuver in ways that are thought to be most effective. If this speculation is correct, a display format which presents vertical information in a spatial analog code may encourage (support) greater use of vertical components for avoidance maneuvers than would be expected from planar displays using alphanumeric digital codes to represent the altitude axis. Evidence in support of this idea will be presented later in section 3. Next, we review some background work on the perception of information presented in perspective three-dimensional displays.

2 THREE DIMENSIONAL PERSPECTIVE DISPLAYS

Before reviewing empirical research comparing planar and perspective displays, we briefly mention some important perceptual cues to depth and follow this with a description of how perspective displays are implemented in computer graphics systems. We then discuss work which has examined the nature of distortions and biases in the perception of perspective displays. Finally, we review a number of studies which have explicitly compared perspective and planar formats using a variety of tasks and domains.

Perceptual cues to depth can be grouped into two classes: monocular and binocular. Monocular cues do not rely on the combination of inputs from both eyes, and are for the most part a result of the geometry of projecting light from a three-dimensional scene onto the two-dimensional surface of the retina. This geometry, sometimes coupled with certain knowledge-based assumptions of how the world typically is structured (e.g., rigidity), allows perceptual inferences of depth and distance to be made. These cues include, but are not limited to: motion perspective; motion parallax; the kinetic depth effect; occlusion; height in the visual field; spatial gradient cues (e.g., texture gradients, density gradients, linear perspective); luminance gradients (i.e., proximity luminance covariance); saturation gradients (i.e., atmospheric or aerial perspective); shading and lighting; and object size (e.g., familiar size, size-distance invariance). Binocular cues include disparity (relative depth scaling computed from the disparate images of the two eyes) and vergence (proprioceptive feedback from the muscles controlling inward and outward movements of the eyes). For a review of visual depth cues and their implementation in displays, see Wickens, Todd and Seidler (1989).

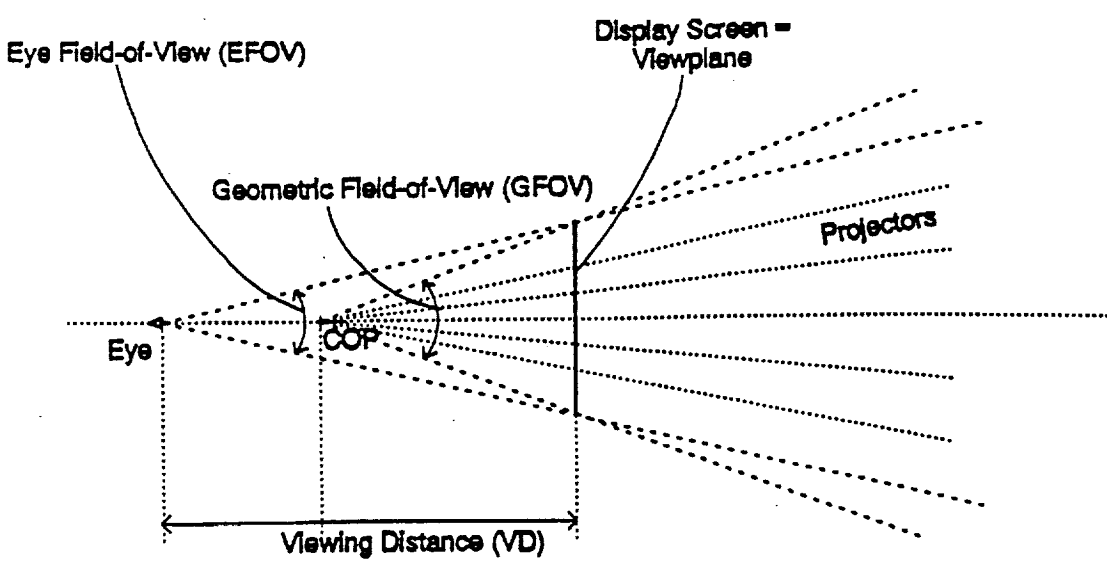
A growing body of research has examined the relative effectiveness of both monocular and binocular depth cues in a variety of settings. Most of this work has focused on the effects of stereoscopic and motion cues on the perception of depth or of three-dimensional structure in computer-generated displays. A typical approach of this research is to combine the two cues so that they offer either contradictory or congruent evidence of depth relations (i.e., cue-dominance studies), while estimates of depth are measured for the single-cue and dual-cue conditions. This work has generally found that both stereo and motion cues contribute to the perception of depth in displays, although their relative salience and interactivity varies substantially across experimental paradigms (Cornilleau-Peres and Droulez, 1993; Sollenberger and Milgrim, 1993; Tittle and Braunstein, 1993; Braunstein et al., 1986; Prazdny, 1986).

Relatively fewer of the cue dominance studies have focused on perspective cues. Most of these studies have compared perspective displays which include stereopsis with ones that do not. In one experiment comparing stereopsis with perspective (in this case, texture gradient), Van der Meer (1979) found the two cues to be roughly additive in their effect on perceived distance, although stereopsis was used by more subjects to judge distance when the two cues were combined incongruently. In a different paradigm in which subjects performed a manual tracking task, linear perspective was found to be just as effective as stereopsis in a condition which included graphical reference lines and floor grid lines in the display (Kim, et al. 1987). Comparing perspective cues with proximity luminance covariance (PLC), Schwartz and Sperling (1983) found that PLC affected depth perception of a wire-frame cube much more so than did perspective when the two cues conflicted with each other. Finally, Yeh and Silverstein (1992) studied the effects of stereopsis on the perception of depth relations between two geometric objects in a display which also contained perspective cues. The authors found that the addition of binocular disparity significantly improved the perception of depth relations in most of the conditions studied (Yeh and Silverstein, 1992).

For the purposes of the current research we now expand our discussion of perspective cues, focusing on their implementation in computer graphic applications, and the perceptual biases which have been identified in their use. In the next section we describe the basic fundamentals of perspective projection geometry, and follow this with a review of the literature on the perception of perspective renderings in computer generated displays.

2.1 Perspective projection parameters

The projection of positional information from a three-dimensional scene onto a two-dimensional plane is known as central, or point-projection (Foley and Van Dam, 1982; Mulder, 1994; Wickens, Todd and Siedler, 1989; Kim et al., 1987). In this technique every line converges on a single point, called the center of projection (COP) from each point in the visual scene (refer to Figure 3 for a diagram of the relevant parameters). A projected image of the scene is formed at the intersection of the projected lines (projectors) and a plane positioned between the visual scene and the COP, termed the *projection plane* or *viewplane* (the viewplane typically lies at the same position and has the same dimensions as the display screen). When the COP is infinitely far from the viewplane, the projected lines are parallel and the image formed is known as a *parallel* or *planar projection*. When the COP is some finite distance from the viewplane a *perspective projection* is formed. With parallel projection, there is a one to one ratio between the distance separating objects on the display (e.g., number of pixels) and the distance between the portrayed (virtual) objects, independent of the depth of the portrayed objects from the viewer. Perspective projection results in a decrease in displayed distance (pixels) between objects as the virtual distance from the viewer increases. The geometric parameters used to generate a perspective projection determine how the projected image appears on the viewplane. The *geometric field of view* (GFOV) describes the angle formed at the center of projection (COP) which intersects the edges of the viewplane. The *eye field of view* (EFOV) corresponds to the traditional definition of visual angle, the angle formed at the view point (or eye point) which subtends the display. The viewing distance then, is simply the distance between the eyes and the display screen.



Figures 3. A diagram of perspective display parameters, reproduced from Mulder (1994).

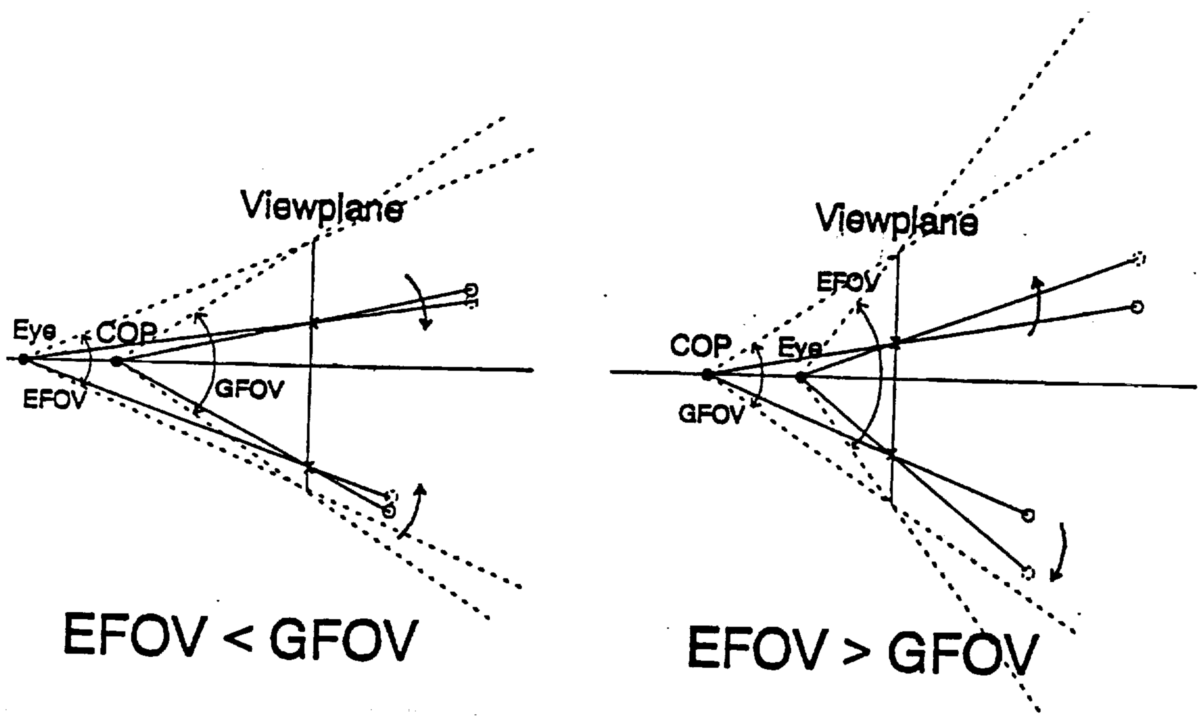


Figure 4. An example of display magnification and minification, reproduced from Mulder (1994).

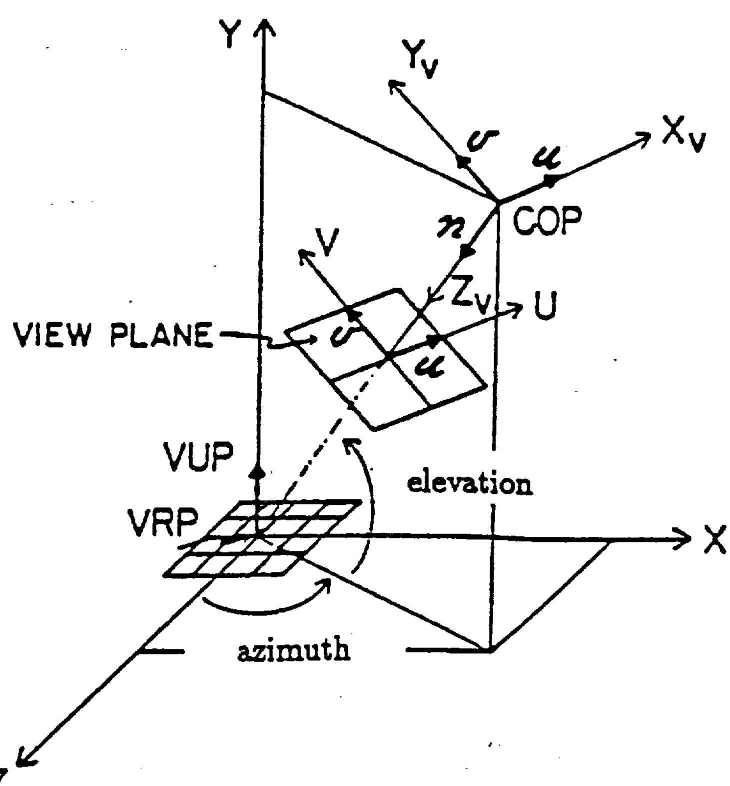


Figure 5. Example of viewing vector rotations in azimuth and elevation, reproduced from Kim (1987).

It is important to note that the center of projection and the view point are not necessarily at the same distance from the display, as they are when an observer is looking out a window at a natural scene. Differences between the positions of these two points result in the misalignment of points in the visual scene and their projections on the viewing plane. If the view point is closer to the display than the center of projection the resulting projection can appear magnified, while minification can result from the opposite arrangement of the COP and view point (refer to Figure 4). Whenever there is such a misalignment, the direction of gaze to an object on the screen does not correspond to the vector toward the depicted object in the real world. This misalignment can result in biased estimates of relative position in the projected space, which are discussed below.

Two additional parameters are important for the current discussion: *azimuth* and *elevation* viewing angles. Figure 5 shows the result of rotating the *viewing vector* (the vector projecting from the COP to the center of the visual scene) parallel to the X-Z axis, creating a non-zero *azimuth angle*, and perpendicular to the X-Z axis, creating a non-zero *elevation angle*. The manipulation of these viewing angles heavily mediates the interpretation of displayed elements and therefore represents a critical issue for researchers and display designers.

2.2 Distortion and perceptual biases associated with perspective displays

According to Mulder (1994), two general types of misinterpretation are possible in viewing perspective displays: one which is due to inherent characteristics of the geometry of the projection, and another which involves biases humans have exhibited in interpreting perspective displays. Theunissen (1993) describes a distortion (*perspective distortion*) induced solely be the geometry of the projection which results in an apparent magnification of the size of an object when the viewpoint is rotated so that the object moves from the center of the display to the edge, while viewing distance is kept constant. The author defines the distortion as the ratio of the apparent size of the object at the edge of the display to the apparent size of the same object centered in the display, where distortion D is: $D = 1/\cos(GFOV/2)$. Following this equation, increases in geometric field of view lead to larger values of perspective distortion in a non-linear manner, such that multiplying the GFOV by a factor of four, from 30 ° to 120°, results in a doubling of the perspective distortion from a factor of one to two.

Other work has identified perceptual biases which are attributed to characteristics of the human observer. For example, Roscoe, Corl and Jensen (1981) found that perspective displays depicting a forward field of view resulted in a perceptual *minification* of the displayed elements in an aircraft landing task. Objects appeared closer together and/or smaller than they actually were in the simulated space. This was the case even though the center of projection and the observers' viewpoint were located at the same position. The authors contend that this bias lead to the assumption, due to the size-distance invariance hypothesis, that objects were further from the observer than they actually were. Roscoe and his colleagues recommend a display magnification factor of approximately 1.3 to compensate for the minification bias.

In an important series of experiments begun in the mid-eighties, researchers at NASA-Ames examined and modeled the behavior of observers making judgments of relative direction of objects presented in a perspective display which represented a simplified version of a prototype air traffic display (Ellis, McGreevy and Hitchcock, 1987). This work showed that systematic errors are made that vary with both the direction of the relative bearing of the target object and with the perspective parameters used to render the display (McGreevy and Ellis, 1986; Grunwald and Ellis, 1986; Kim, Ellis, Tyler, Hannaford and Stark, 1986; Ellis, Tyler, Kim, McGreevy and Stark, 1985). For example, McGreevy and Ellis (1986) examined the types of errors made in judging the relative azimuth and elevation angles of a target cube to a reference cube in a world referenced perspective display (Figure 6). The authors manipulated the geometric field of view (GFOV) from 30 ° to 120°, creating varying amounts of perspective distortion in the display (see Figure 7). Subjects made judgments of 640 different target directions by adjusting the angular indicators on the two radial dials shown on the right side of Figure 6.

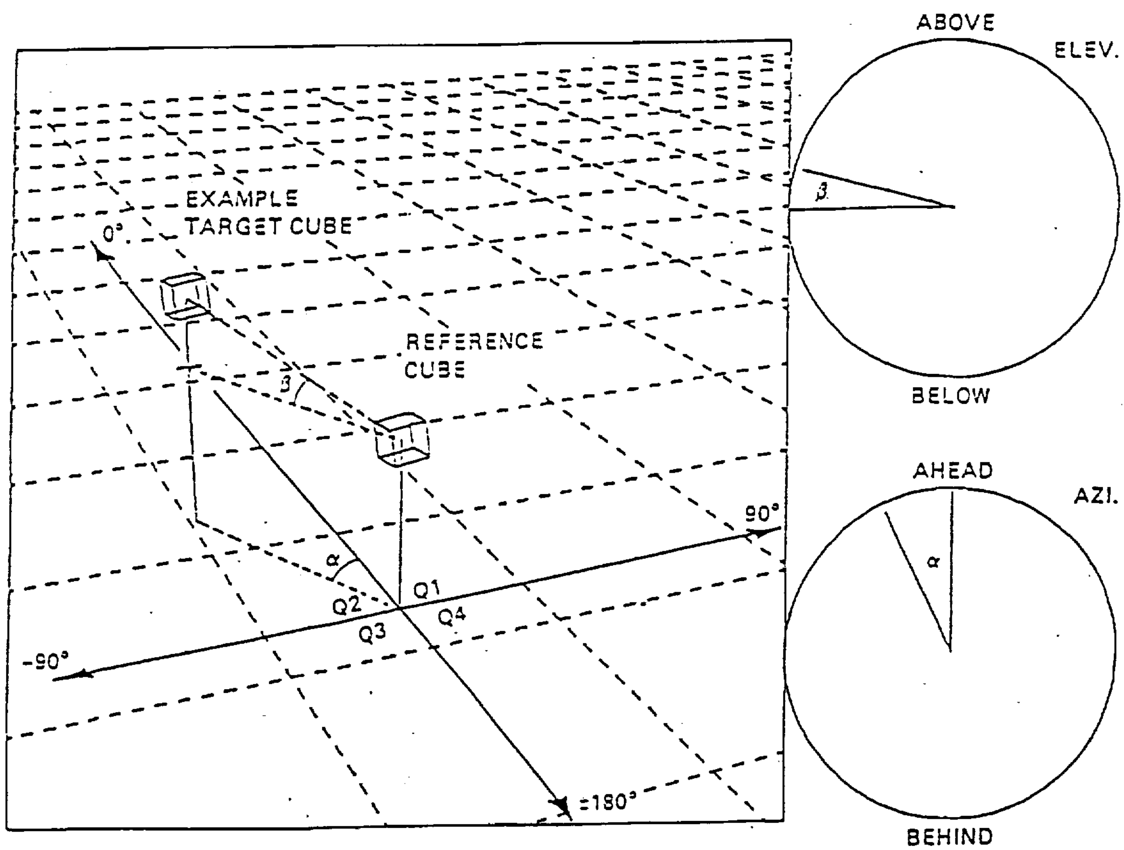


Figure 6. Perspective display and response dials used by McGreevey and Ellis (1986). Subjects made judgments of relative azimuth and elevation angle of the target from the reference cube (reproduced from McGreevey and Ellis, 1986).

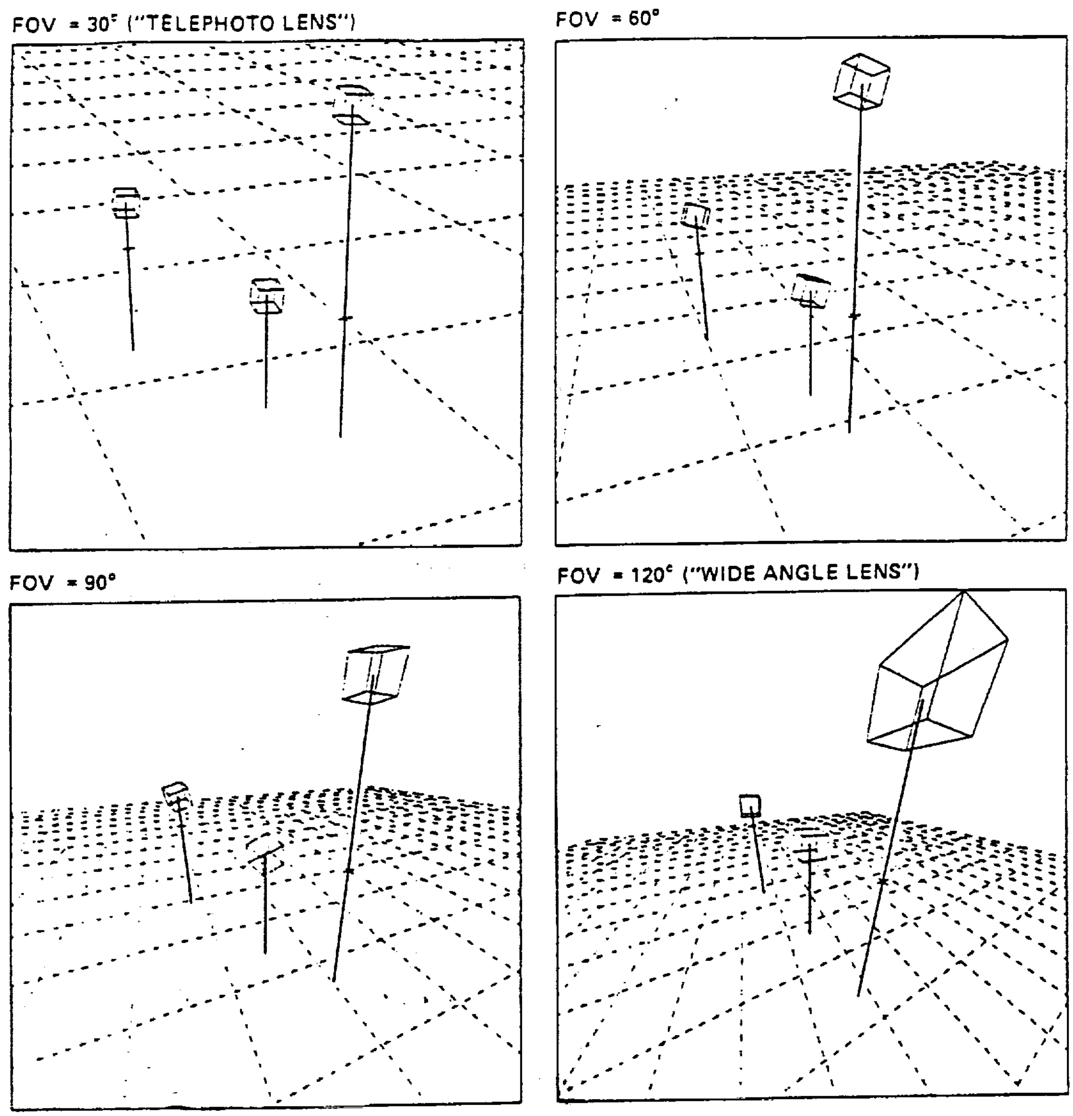


Figure 7. Representative stimuli used by McGreevy and Ellis (1986), showing perspective images of similar object arrangements which differ in geometric field of view (reproduced from McGreevy and Ellis, 1986).

The results showed two general findings: 1) target elevation angle was consistently overestimated, particularly for narrow (30°) geometric fields of view, indicating a perceived expansion of the vertical axis; and 2) azimuth errors varied in a sinusoidal pattern from one direction quadrant to the next, with the direction of the errors gradually reversing between narrow (30°) and wide (120°) fields of view.

The authors proposed two sources to model the pattern of azimuth errors: 1) the *virtual space effect*; and 2) the *3D-to-2D projection effect* (2D effect). The virtual space effect results from the mismatch between the geometric field of view presented in the display and the visual angle subtended by the display. If the observer assumes that the image is projected according to the visual angle of the display (that the display represents a window to a virtual space), then a greater mismatch between the assumed perspective and the actual geometric perspective leads to more heavily biased judgments. If the observer's visual angle is less than the geometric field of view, their estimates of object position will be biased toward the center of the display, the converse being true when the VA is greater than the GFOV. (The findings of Roscoe and his associates, however, suggest that the actual cross-over point between magnification and minification is not located exactly at the COP, but is somewhere behind it.)

The 3D-to-2D projection effect is postulated to bias estimates of three-dimensional angular judgments toward their corresponding two-dimensional projected angles on the display. The authors contend that observers average to some degree the two angles, making this bias dependent on the azimuth of the target from the reference point. This effect also decreases as geometric field of view increases. Tharp and Ellis (1990; see also, Ellis, Smith, Grunwald and McGreevy, 1993) later showed that the systematic errors observed in this paradigm could be modeled by a mismatch between the observer's assumed viewing orientation (azimuth and elevation angle of the viewing vector to the center of the display) and the actual viewing orientation. This model assumes observers use an internal lookup table to transform the observed two-dimensional angles to three-dimensional relationships, adjusting for the observer's viewing orientation. The classic tendency to overestimate the elevation and azimuth angles of the viewing direction, as discussed by Ellis and his colleagues (1993), created the errors in estimation of the viewing vector orientation which led to the sinusoidal error patterns observed in the previous studies. Interestingly, this phenomenon is closely related to the well-known bias to underestimate the in-depth slant of planar surfaces under reduced viewing conditions, or when surfaces are projected onto two-dimensional display screens (Perrone and Wenderoth, 1993).

Barfield and his colleagues have used a similar paradigm to that of McGreevy and Ellis (1986) to examine the effects of geometric parameter manipulation on directional judgments in perspective displays (Barfield and Rosenberg, 1995; Rosenberg and Barfield, 1995; Barfield, Hendrix and Bjorneseth, 1995). Barfield and Rosenberg (1995) report a similar overestimation bias of relative elevation between a target and reference object, although this bias was reduced, but not eliminated, by the addition of binocular disparity. Azimuth errors, however, were not affected by the disparity manipulation. The authors did not offer a specific model for their results, but concluded that the compression of the vertical axis along the line of sight (the viewing vector elevation angle was 45°) caused the inflated estimates of relative altitude, a finding which replicates results from previous studies (McGreevy and Ellis, 1986; Ellis, et al., 1993). Barfield, Hendrix and Bjorneseth (1995) also found an overestimation bias for judgments of vertical separation, but only for positive viewing elevation angles (15° and 45°). A negative eyepoint angle (-15°) resulted in a response bias in which vertical separation was underestimated.

Taken together, the preceding experiments have shown the strong effect geometric parameters have on perceptual judgments made using perspective displays. While these perceptual biases are important in their own right and influence judgments of direction in perspective displays, their detailed examination is beyond the scope of the current study. The potential influence which these biases exert on strategies used in the current experimental task, however, will be discussed in sections 3.5 and 3.6. In the following section we focus on research which specifically compared performance on a variety of tasks between perspective and planar display formats, and therefore bears directly on the current topic.

3 COMPARATIVE EVALUATIONS OF PLANAR AND PERSPECTIVE DISPLAYS

A number of studies have examined the representation of three-dimensional spatial information in the domain of aviation, and in the more general field of scientific data visualization. The present discussion will focus on those papers which relate most directly to the current work, and which have reported empirical data.

3.1 Data visualization

Wickens, Merwin, and Lin (1994) investigated a number of graphical rendering techniques for displaying multivariate data. In the first of three experiments, the authors compared a perspective graph display with a coplanar format which consisted of two 2D graphs (see Figure 8). The perspective display contained reference lines which extended from each data point to the two back walls of the display. This enabled accurate check reading of data values which would otherwise have been difficult to perform because of the inherent ambiguity along the line of sight in the perspective rendering. Because of the separated graph panels in the 2D format, two color-coded points (one in each panel) indicated the values associated with one data point. The task involved answering a series of questions which required the comparison or integration of information across one, two or three of the data dimensions presented. The results showed that observers were equally efficient at reporting the value of one data dimension using either display format, but were progressively faster using the perspective display as more dimensions of the data set were required to answer the questions (both display conditions fostered equally accurate performance on all question types).

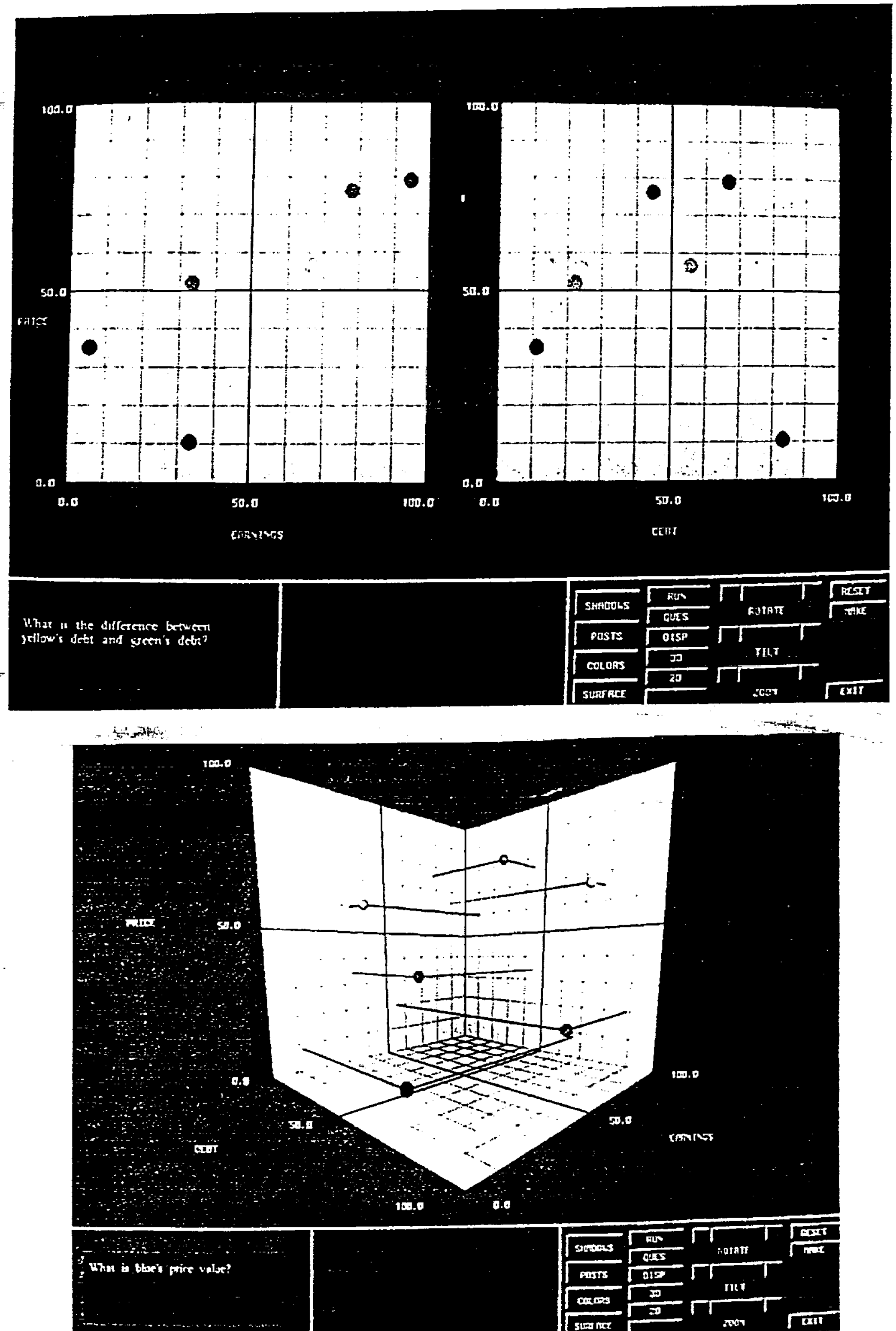


Figure 8. A reproduction of the 2D coplanar (top) and 3D perspective (bottom) display formats used by Wickens, Merwin and Lin (1994).

The authors attribute the perspective display advantage in part to the emergence of a perceptual feature which was created by the spatial integration of the data dimensions in the perspective display. The spatial integration created a surface of data points in the 3-D graph, where each data point was defined by the combination of the three-dimensional values associated with it. The integration of the three dimensions offered a more compatible representation as well for those questions which required dimensional comparison or integration (Wickens and Carswell, 1995; Boles and Wickens, 1987). The possibility that increased visual scanning between the two 2D panels (relative to the perspective format) contributed to the results was ruled out after a comparison of responses to questions requiring within- and between-panel scans on the 2D format revealed no differences in performance. The graphically integrated perspective display supported better performance than the 2D format, which required the observer to cognitively integrate the three axes for questions involving all of the data dimensions. Furthermore, the finding that the perspective display did not hinder performance for questions focusing on only one or two of the three dimensions suggests the potential cost of perceptual ambiguity introduced by integration can be overcome by using perceptual enhancements (i.e., the reference lines, or posts connecting the data points to the walls seen in Figure 8a).

3.2 Data space navigation and manual tracking

Similar findings, although with a more pronounced advantage for 3D over 2D displays, were observed by McCormick and Wickens (1995) in a paradigm involving active geographic exploration and navigation through a computer generated three-dimensional data base. Like the paradigm used by Wickens, Merwin, and Lin (1994), this paradigm differed from that simulating conventional aviation because it greatly enhanced the requirements for joint lateral and vertical maneuvering and relational judgments.

Further support for the influence of reference lines as perceptual enhancements was found by Kim and his colleagues (1987). Using a paradigm which involved a three-axis manual pursuit tracking task, the authors report that the addition of reference lines to a monoscopic perspective display improved performance to that observed in a stereo condition which did not contain reference lines. Interestingly, the combination of reference lines and stereo disparity did not yield better performance than either cue alone. Elevation angle and geometric field of view were also manipulated in this experiment, with better performance associated with elevation angles between 30 and 60 degrees, and with narrow geometric fields of view (8 to 24 degrees). Other research has compared planar and perspective displays for aircraft control, generally finding advantages for perspective formats (for a review, see Mulder, 1994; also, Haskell and Wickens, 1993). This work will not be considered further here, however, because the displays used were ego-centered, with inside out frames of reference designed to support the pilot's guidance accuracy, but not his or her global hazard (traffic) awareness (Wickens, 1995). The current paradigm focuses instead on outside-in, world-referenced displays because of their comparative advantage in presenting information fully surrounding the point of interest defined by ownship (Wickens and Prevett, 1995).

3.3 Perceptual judgments of depth relations

Focusing on basic perceptual judgments, Yeh and Silverstein (1992) examined estimates of relative depth and height of simple geometric objects positioned above a ground reference plane viewed from several elevation angles, in both mono- and stereoscopic viewing conditions. In addition to linear perspective, size, brightness and occlusion were also present in both conditions. Three viewing elevation angles were tested (15, 45 and 90 degrees), while the relative positions of a square and triangle were manipulated. The authors found that observers' judgments of which symbol was closer (or higher) were affected by the elevation viewing angle and the relative positions of the symbols themselves, and that these two variables interacted to influence performance. Increased separation of the symbols on the irrelevant axis impaired performance on the judged axis. Interestingly, altitude judgments were found to be more difficult in the 15 and 45 degree viewing conditions than when the scene was viewed from above (90 degrees). The authors contend that this is a result of the integration of the X and Y axes in the 15 and 45 degree formats, which must be decomposed in order to make a judgment on one of the two axes. For the 90 degree viewing condition, altitude was unambiguously and linearly represented by symbol size, which varied independently of symbol location in the X-Z plane. Additionally, altitude judgments were slower and less accurate than depth judgments in the two oblique viewing conditions for the same reason. It is important to note, however, that reference lines were not used in this study, forcing observers to rely solely on the other cues present to make their judgments (i.e., relative brightness, size, etc.).

3.4 Air traffic control and conflict detection

Using a more applied paradigm in air traffic control simulation, Wickens and his colleagues examined planar and perspective display formats in a series of studies which involved ATC, navigation and route planning (Tham and Wickens, 1993; Tham, Wickens, Liang, and Long, 1993; Wickens, Miller, and Tham, 1996; Wickens and May, 1994; Wickens, Campbell, Liang and Merwin, 1995; Boyer, Campbell, May, Merwin and Wickens, 1995; see Wickens, 1994 for a summary). While the individual tasks and specific display implementations varied between the studies, the methodologies used were fairly similar. The general method required observers (either accredited air traffic controllers, or certified pilots trained in rudimentary ATC skills) to make judgments about whether aircraft would conflict with other air traffic, with terrain or with prohibited air space (due to weather phenomena). In some of the experiments subjects were required to issue vectors around the three-dimensional obstacles mentioned above. Conventional planar displays with digitally presented altitude information were compared to integrated three-dimensional displays, some of which were rendered using parallel projection, others employing perspective projection. The three-dimensional displays also contained reference lines from the aircraft to the ground to disambiguate horizontal position.

Reviewed collectively, the results indicate few performance differences between the planar and three-dimensional displays tested. Where differences did occur, they typically favored the planar format, and did so primarily in time rather than accuracy, with differences generally showing up only for air traffic controllers, not pilots. Similar findings were observed in a comparison of the two ATC display formats carried out by Brown (1995). The differences observed between the two subject populations can be explained by the familiarity of the experienced controllers with the conventional planar format, a familiarity which the pilots did not posses. Additionally, in experiments which required issuing vectors around hazards, the 3D displays tended to foster fewer and wider vectors around the obstacles than did the planar displays, a difference which cannot easily be categorized as good or bad performance, but likely represents a more conservative strategy which may be result from the ambiguity of depth judgments along the line of sight fostered by the 3D displays (Wickens, 1995).

While this program of research did not find consistent performance differences between the two display formats, it is important to note that the planar displays presented vertical information digitally, rather than analogically, as has been the convention in most of the research on planar formats. This may have hindered the integration of horizontal and vertical spatial information, particularly for the pilots, who were equally inexperienced with the planar and three-dimensional formats. However, similar results were observed in a comparison of 2D and 3D weather displays to support pilot route planning (Boyer and Wickens, 1994). In this case the coplanar display suite included an analog representation of altitude. Another important point is that the parallel projection used in Wickens' (1995) three-dimensional displays may have induced biases in judging relative position of objects. Parallel projection was used to provide equal lateral resolution in the fore- and backgrounds of the displayed space. However, as was discussed earlier, previous work has indicated that this can lead to perceived magnification of the space resulting in errors in estimating spatial relations (McGreevy and Ellis, 1986).

An experiment carried out by Bemis, Leads, and Winer (1988) contrasted perspective and planar displays in support of an air intercept control task (see Figure 9). In this paradigm, controllers had to identify airborne threats and determine which patrol aircraft out of several was located closest to the threat. A planar format indicated the horizontal position of each aircraft overlaid on concentric circles (range rings) indicating distance from the center of the display in nautical miles. Vertical data could be retrieved by selecting, or "hooking" an individual aircraft. In the perspective display format, approximate altitude information could be perceived directly from the display which was viewed from an elevation angle of 41° (aircraft icons were connected to the horizontal plane using reference lines to support perception of horizontal position information). The results of the experiment showed that subjects were significantly more accurate in identifying threats and selecting the appropriate interceptor when using the perspective display. Subjects were also faster in determining the closest interceptor in the perspective condition. The advantage of the perspective display cannot exclusively be attributed to the integration of the horizontal plane and vertical axis, however, because altitude information was presented only for icons that were selected by the operator in the planar display, while approximate altitude data were always available in the perspective format, confounding the source of the performance differences.

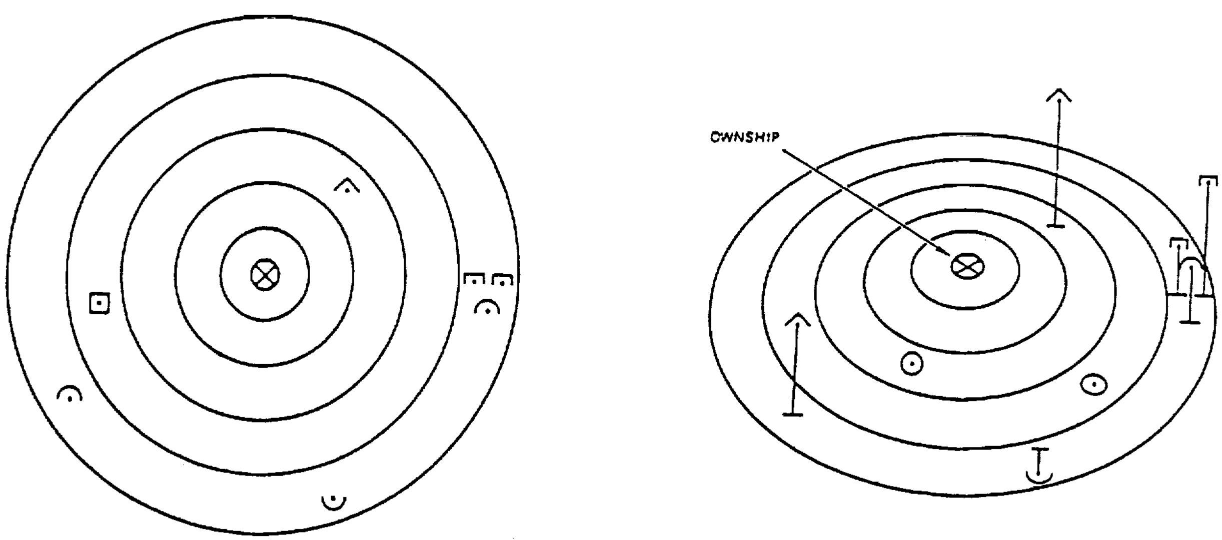


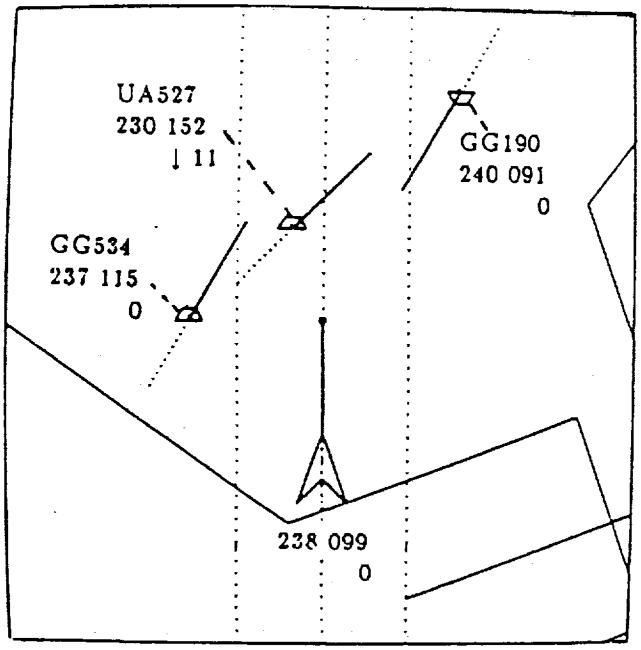
Figure 9. Example of the planar (left) and perspective (right) display formats used by Bemis, Leads and Winer (1988).

A more recent study by Jasek, Pioch and Zelter (1995) compared a number of two- and three-dimensional displays for predicting collisions in a simplified air traffic control task. The authors found that a coplanar format which displayed the X-Y and X-Z planes supported superior performance to several three-dimensional formats which employed binocular disparity and allowed the observer to actively rotate the viewpoint. The coplanar condition was also somewhat better than a planar format which displayed altitude data numerically. In a follow-up experiment which used more complex scenarios, the coplanar display was again found to support better collision prediction than the three-dimensional formats. The 3D displays did not, however, provide a lined grid on the ground plane below the aircraft (unlike the displays of McGreevy and Ellis, 1986), which would have provided linear perspective. While some of the 3D displays did contain reference lines, the absence of grid lines to disambiguate horizontal position on the ground plane may have reduced the effectiveness of the references lines.

3.5 <u>Cockpit displays to support collision avoidance</u>

In an influential study by Ellis, McGreevy, and Hitchcock (1987) the issue of vertical axis representation on the CDTI was examined by comparing perspective and planar display formats. Drawing on the cumulative results of previous research at NASA-Ames, the authors noted that the bias to make horizontal avoidance maneuvers, observed in some of the studies, might not be due to procedural flight issues as some pilots have suggested (i.e., tighter FAA restrictions on altitude clearances than on heading clearances), but rather result from the horizontal display format itself, as has been discussed in section 2. To test this hypothesis, Ellis and his colleagues used a perspective projection format to display traffic information and compared avoidance strategies selected using the perspective display to those made using a planar format. The perspective display provided a view of the three-dimensional scene from above (30°), behind (30 km) and slightly to the side (8 °) of ownship (see Figure 10). The aircraft icons as well as their predicted position one minute in the future, were connected via reference lines to a grid ruled with equi-spaced lines displayed 5000ft below ownship. This display augmentation was used to provide relative altitude information, as well as to disambiguate the horizontal position data. The planar display coded altitude data numerically, while displaying vertical trend data using an arrow to show direction and digits to indicate rate of climb or descent. As shown in Figure 10a, the relative vertical location of an intruder above or below ownship was also coded by the hexagon iconic symbology used by Hart and Loomis (1980).

The methodology presented pilots with a series of traffic encounters in which they were required to judge whether an avoidance maneuver would be necessary and if so whether a climb, descent, right turn, left turn or some combination of vertical and horizontal maneuver would be appropriate. Once a response was selected, or when the pilot determined that a conflict would not develop, the trial was terminated. Pilots did not see the results of their response selection, nor did they receive feedback on the appropriateness of their judgment. This technique was used specifically to reduce the influence of training effects, and to assess the a priori styles pilots had developed through their previous flight experience. Traffic encounters included a variety of approach geometries, from 0° (head on) to 150° (intruder approaching from close to the same heading).



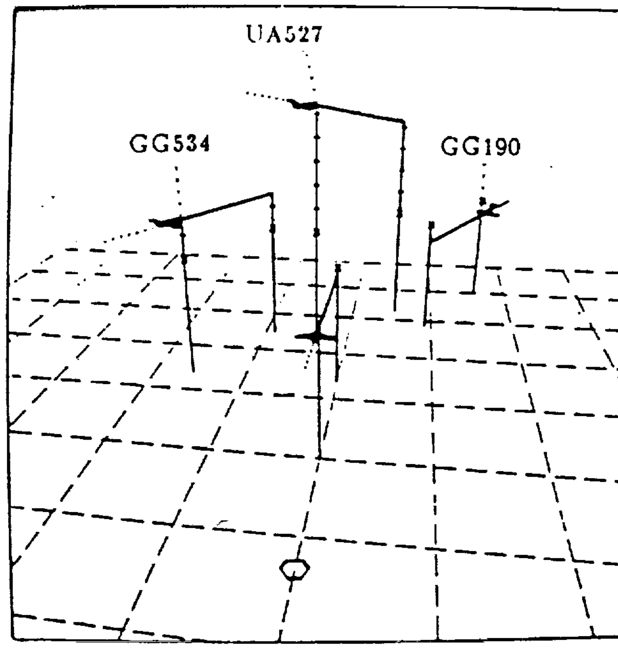


Figure 10. A reproduction of the planar (left) and perspective (right) CDTI displays used by Ellis, McGreevy, and Hitchcock (1987).

The primary response variables were the time to decide what, if any, maneuver was necessary, and the success of that decision. For all but the head on encounters, the perspective format led to faster (10-15%) decision times. Head on encounters showed a 15% advantage for the planar display which can be attributed to the fact that the intruder's heading was almost superimposed on the line of sight viewing vector in the perspective display. This made it difficult to determine if the intruder was moving toward or away from ownship. The quality of judgments was evaluated by classifying initial assessments and avoidance maneuver selection using several categories based on the appropriateness of the response. In 5 of 6 categories, advantages were found for the perspective display. A more intriguing finding is that the perspective display led to more vertical maneuvers (and just as many horizontal maneuvers) than did the planar display, supporting the authors' hypothesis about the origin of the horizontal response bias. This evidence, though, may not be specifically related to the two- and three-dimensional nature of the displays per se, but rather it may result from the fact that the specific altitude position information was presented alphanumerically in the 2D display and in an analog spatial format in the three-dimensional display. This limitation is addressed in the current study, in which we compare spatial analog representations for both separate and integrated display formats.

Support for the findings of Ellis, McGreevy ,and Hitchcock (1987) were found in a study reported by Wise, Garland, and Guide (1993), in which pilots used either a perspective or 2D electronic map, or a 2D paper map to navigate in a simulation. The task required pilots to maintain a prescribed heading and altitude until they were shown a specific map (in one of the three formats), at which time they had to determine their position with respect to restricted airspace (a terminal control area, or TCA). The results indicated that pilots using the perspective display initiated fewer unnecessary maneuvers, and fewer potentially 'negative' maneuvers, than did those using either of the 2D display formats. The perspective display also supported more maneuvers with vertical components than did the 2D maps, a result which is consistent with the findings of Ellis, McGreevy, and Hitchcock (1987).

3.6 Summary and integration: a task model

The previous discussion raises a number of important issues regarding the presentation of traffic information in the cockpit. In integrating these issues, we present a framework for describing the task of piloting while using a cockpit traffic display for monitoring separation. Figure 11 shows a hierarchical description of this task which is composed of nested functions (boxes), their interconnections, and several factors (ovals) which influence the characteristics and performance of the functions. The hierarchical organization of the diagram places the high-level function of completing a flight segment at the top of the figure. Below this are two main loops which describe the functions of navigating and controlling the aircraft (upper left) and monitoring for and avoiding other air traffic (center). These loops are considered to be operating in a somewhat serial fashion, with frequent switching occurring between them. The control loop is presented in a rather course level of detail, containing functions for selecting flight parameters, visual scanning, error minimization and control inputs. At a high level, the control loop receives input from the bottom of the monitoring and traffic avoidance loop, which consists of functions for scanning the traffic display, detecting other air traffic, evaluating future separation from this traffic, and planning and selecting avoidance maneuvers if necessary.

The right side of the figure shows a number of influences of display dimensionality which affect the monitoring, evaluation and maneuver selection functions. The positive and negative effects which the influences are considered to have on the performance of the functions into which they feed, are indicated by the plus and minus signs leading into the functions respectively, which are coded by letters for reference in the text. The display factors listed are not exhaustive, but do reflect the findings of much of the research reviewed thus far. For example, the integration of the three dimensions in the perspective display is hypothesized to facilitate the performance of maneuvers which combine vertical and horizontal elements (h), while the perceptual ambiguity associated with perspective displays will be likely to inhibit the evaluation of predicted separation (d). The unambiguous mapping of data dimensions to display axes in the coplanar format should support the accurate evaluation of future separation from traffic (c), but the separated display planes will require more visual scanning between panels (b). The coplanar display will impose the additional cost of requiring the cognitive reconstruction of the three-dimensional display space from the two 2D panels, particularly for situations in which combined vertical and horizontal maneuvers are appropriate (g). For each of the display influences listed in Figure 11, the sign of the input to the affected functions indicates the polarity of the influence relative to the other display format. Other influencing factors, some of which have been discussed in earlier sections, have a strong strategic component and feed into the planning and selection function; these include procedures, biases, doctrine, other air traffic, terrain, weather and restricted airspace, and are shown in the lower left corner of Figure 11.

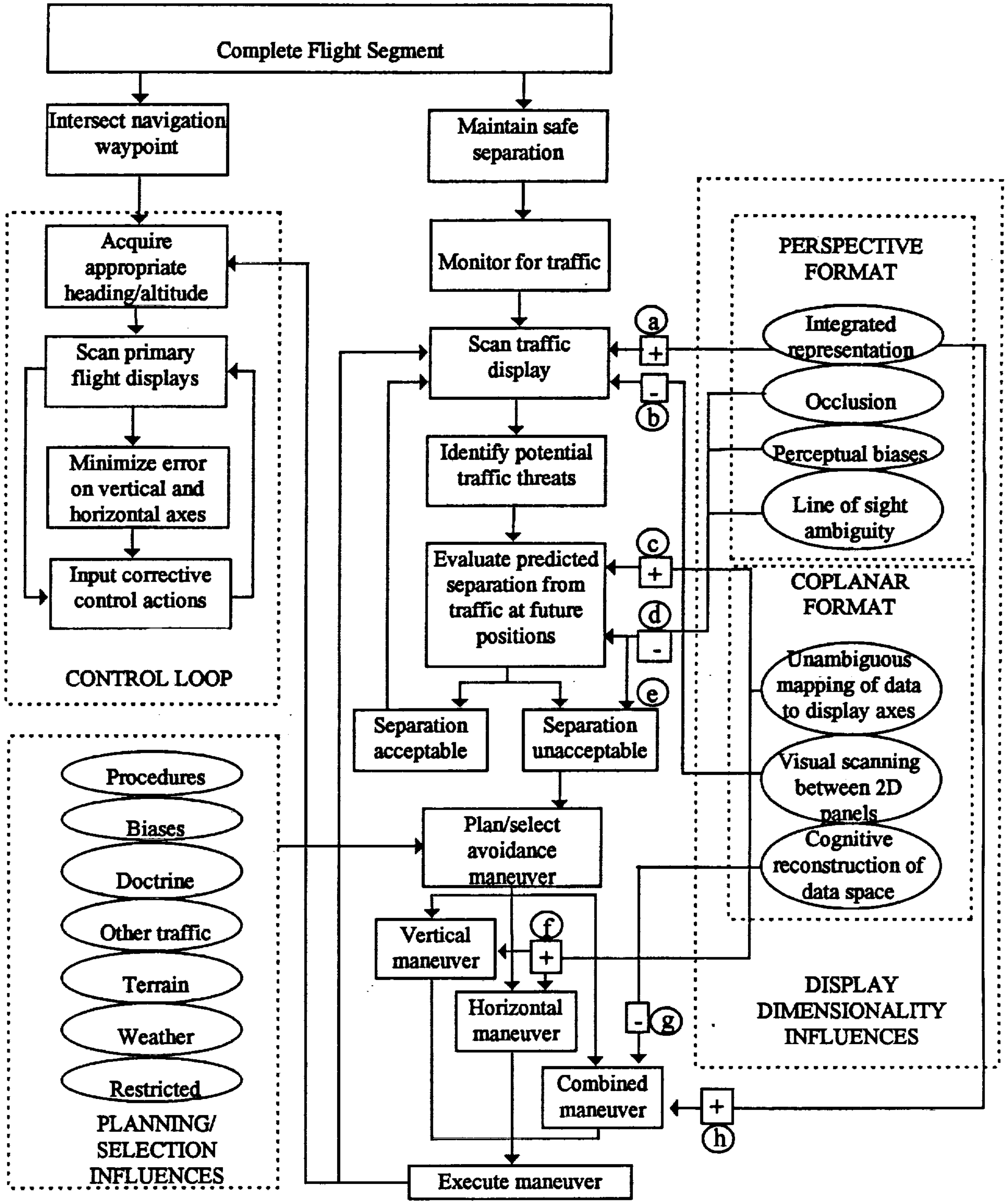


Figure 11. A Hierarchical task description indicating functional nodes, their interconnections and factors which influence the functions. Functions are outlined with boxes while influencing factors are indicated by ovals.

The structure of the task diagram is useful in providing a framework for the issues raised by research reviewed in the earlier sections. The implications of this research are briefly summarized here. First, it has been shown that predictive judgments of relative position are substantially improved by the presence of iconic symbology indicating future flight path information (Palmer et al., 1980). Moreover, Hart and Loomis (1980) concluded that assessments of relative vertical position are more difficult than horizontal position when the vertical scale is coded using alphanumeric or iconic symbology in a planar format. The results obtained by Palmer (1983) and Smith and his colleagues (1984) indicate that pilots generally make horizontal avoidance maneuvers when using planar traffic displays which do not use a spatial analog scale to represent altitude, although this finding is influenced by the amount of preview time available to select a maneuver.

As we noted above, those experiments which have compared planar and perspective renderings have offered conflicting results. The studies by Ellis, McGreevy, and Hitchcock (1987), Bemis, Leeds, and Winer (1988), and Wise, Garland, and Guide (1993) show advantages for perspective formats in air traffic related tasks; the work of Wickens and his coworkers (1995) and Brown (1995) show no such benefits for ATC tasks, while the study by Jasek, Pioch, and Zeltzer (1995) indicates worse performance for a perspective display relative to a 2D coplanar format. Such contrary findings can be accounted for in part by the tradeoff of factors influencing one or more of the functions in Figure 11. The current experiment attempts to reconcile some of these findings by manipulating the dimensionality of a CDTI which codes all three spatial axes with an analog scale, and recording various measures of conflict detection and resolution. Two perspective formats which use different viewing vector elevation angles are contrasted with a coplanar (two-panel) format. We are specifically interested in how the display dimensionality and viewing vector elevation angle influence the perception of air traffic encounters and the implication of strategies to deal with these encounters.

On the basis of the work of Ellis and his colleagues, we recognize that a perspective format might encourage the choice of more vertical maneuvers than a planar format which codes altitude data numerically. This work does not, however, offer insight into how a coplanar display, which codes each axis in a spatial analog format, would support vertical versus horizontal maneuver selection. The fact that the X-Y and X-Z planes are represented separately in such a display might affect pilots' abilities to plan a maneuver that combines vertical and horizontal components, as shown in Figure 11 (g). The integrated format of the perspective display, while fostering the simultaneous perception of position on all three axes, might impair the ability to accurately assess the spatial relations between objects due to the ambiguity inherent in the projected rendering. Such ambiguity should be reflected either in decreased accuracy in detecting conflicts (d) or in a more conservative strategy (e.g., a greater likelihood of undertaking maneuvers that were not in fact required), (f). However, the addition of reference lines may reduce this ambiguity sufficiently to allow the benefits of spatial integration to overcome the well-known limitations of perspective projection.

The comparison of coplanar and perspective displays which both code altitude information in a spatial analog format should reveal those relative advantages of the formats which are uniquely due to their integral (3D) or separate (2D) characteristic. By creating a variety of traffic encounters in which vertical, horizontal, or combined vertical and horizontal maneuvers would be most appropriate, we expect to see different strategies expressed in the performance of the required avoidance maneuvers. For example, if the depth cues and reference lines used in the perspective display do not substantially reduce the ambiguity inherent in the integration of the X-Y and X-Z planes, then we expect some combination of better conflict detection and avoidance performance in the coplanar display condition, and more cautious maneuvering (i.e., greater deviations around traffic) in the perspective conditions (f). The added difficulty of both visually scanning and cognitively integrating the two display planes in the coplanar format, however, may induce maneuver strategies which rely on only two of the three dimensions (g). That is, the top-down view in the coplanar display (X-Z plane) could be used for exclusively horizontal maneuvers, while the forward looking view (X-Y plane) would be more suitable for vertical maneuvers (i.e., because the traffic crosses from one side of the display to the other, the lack of longitudinal axis representation in the X-Y view makes it difficult to know when to maneuver left or right to avoid the traffic, but would provide the necessary altitude information to support vertical separation while the traffic is passing from one side to the other). The integration of the three axes in the perspective displays, on the other hand, may support greater use of combined vertical and horizontal maneuvering (h).

Another important question is the effect of elevation angle of the perspective display on performance. By testing two elevation angles, we compare the relative effects of compressing the vertical versus the longitudinal axes. Greater resolution on one axis results in reduced resolution on the other. The effects of differential axis compression on judgments of relative depth and altitude have been shown to be quite strong (Yeh and Silverstein, 1992; Barfield, Hendrix, and Bjorneseth, 1995). Because of the findings of this previous work, we expect greater use of vertical maneuvers for an elevation angle of 30° than for an elevation angle of 60°. The relatively more compressed vertical dimension in the 60 ° display may encourage greater use of lateral maneuvers relative to the 30° format simply because vertical maneuvering might be more difficult, due to the difficulty in resolving relative vertical positions. However, we recognize that any a priori biases which pilots bring to the simulation may affect their performance to a greater or lessor degree in one of the two perspective conditions. For example, a bias towards making predominantly horizontal maneuvers would presumably be facilitated more by the 60° elevation angle condition than by the 30° viewing angle, while preferences for vertical maneuvering may be better supported by the 30° elevation angle.

4 EXPERIMENTAL METHOD

We first provide an overview of the task and displays before presenting detailed explanations of the experimental method in the sections that follow. As was discussed earlier, the primary issue we address here is how the integration of the three spatial dimensions depicted on the CDTI influences the prediction of traffic conflicts, and how it effects the nature of the avoidance maneuvers generated in response to predicted conflicts. To examine this issue, certified flight instructors flew an instrument flight rules (IFR) part-task simulator composed of three displays. An integrated primary flight display containing attitude, altitude, vertical speed and airspeed indicators, and a directional gyro indicating heading information were located on the right side of the display screen (Figure 12 shows the instrumentation layout with the coplanar traffic display). The left side of the display contained a track-up (moving map) air traffic display rendered in either a coplanar format or in one of two perspective formats (refer to Figures 14-16). The traffic displays provided views of ownship, air traffic within a specified range and predictive symbology to support pilots' avoidance planning strategies. The pilots' task was to complete a series of trials in which they were instructed to fly to a navigational waypoint while maintaining separation from potentially conflicting air traffic. Some trials required no flight path deviations, while others necessitated avoidance maneuvers to resolve predicted conflicts.

4.1 Traffic symbology on the horizontal situation indicator

An abstract schematic diagram displaying the traffic symbology common to both the coplanar and perspective formats is shown in Figure 13. The symbology incorporated into the horizontal situation indicator consisted of icons indicating the current position of ownship and surrounding aircraft with vectors extending from each aircraft icon in the direction of their predicted trajectories (ownship's aircraft icon and vector were colored magenta; other traffic icons and vectors were colored light gray).

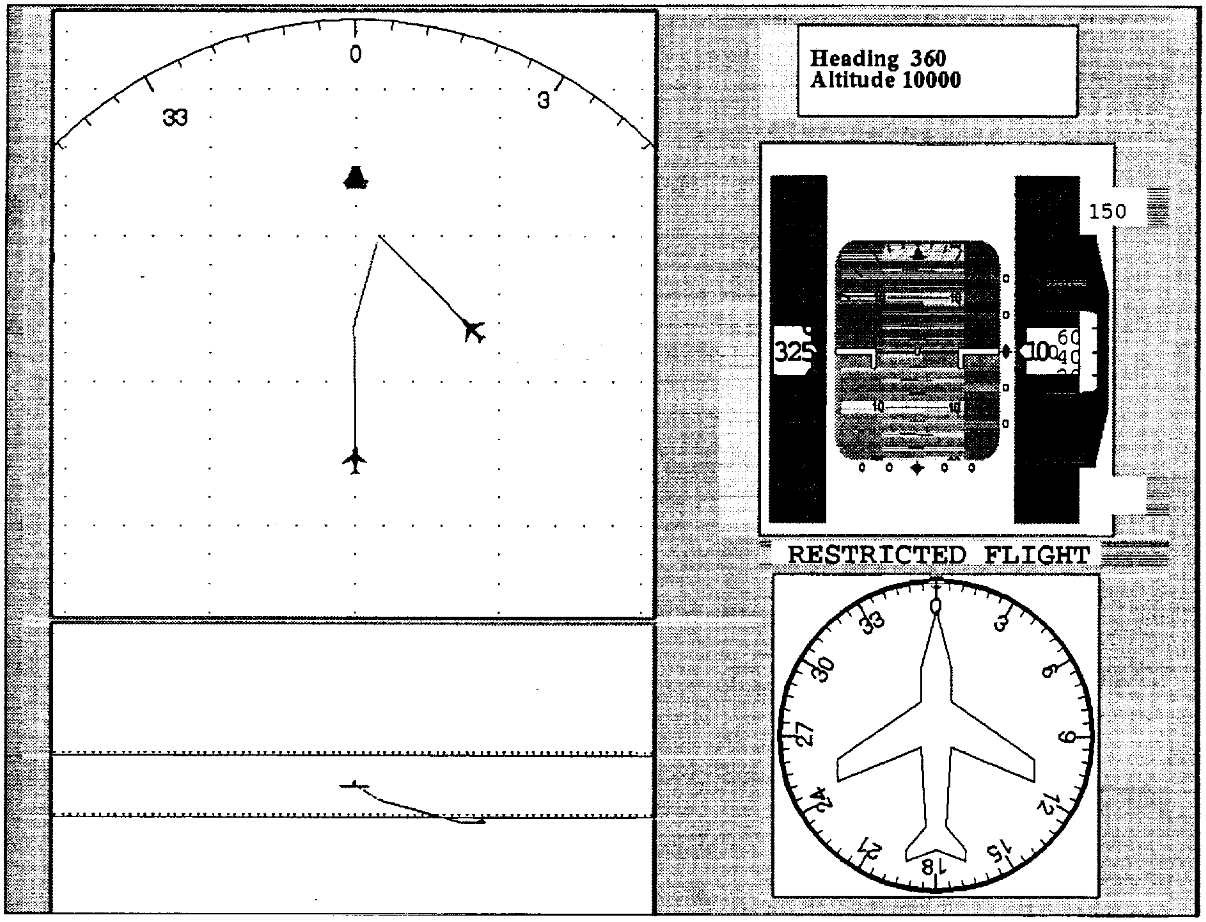


Figure 12. Depiction of the full instrument layout (presented here with the coplanar traffic display). The primary flight display is located on the upper right, the directional gyro is on the lower right. The traffic display is on the left side of the figure. The image was converted from color to gray scale, and the intensity levels were reversed for presentation purposes.

The ends of the vectors represent the predicted positions of the aircraft at a constant (but parameter adjustable) future time (45 sec in the current study). Ownship's predictive vector is calculated based upon the current position, velocity and rate of turn of the aircraft. Therefore, the predictive line extending from ownship curves in the direction of the bank angle, with a radius based on the degree of aircraft bank (refer to Figure 13). The predictive vectors of other air traffic indicate the programmed flight path that these aircraft are flying. That is, the simulation can display the intent of the other aircraft that might be changing heading or altitude. In the current study, however, traffic only changed altitude.

Extending from some point along ownship's predictive vector are one or more orange colored vectors (*traffic vectors*) indicating the future bearing to predicted threats, with the length of the vector indicating the extent of ownship's protected zone (there is one traffic vector extending toward each aircraft within a specified range). This augmentation allows the pilot to directly perceive, rather than having to estimate, the future predicted position and relative proximity of other aircraft with respect to ownship's protected zone (assuming that other aircraft will continue on their current trajectories). The traffic vectors extend from that position on ownship's predictive vector which indicates the predicted position of ownship at the point of closest pass with the traffic. As the threat moves closer to ownship, the traffic vector moves along the predictive vector toward ownship, thus explicitly representing the minimum time to loss of separation (MTSL), which is the critical time parameter pilots must be aware of to ensure separation (i.e., the amount of time they have to maneuver away from a protected zone compromise. For the purposes of this simulation, the dimensions of the protected zone are one thousand feet vertiacally and three miles horizontally). By maintaining adequate separation between the end of ownship's traffic vectors and the other aircraft's predictive icons, the planes will pass without conflict. If a traffic vector reaches another aircraft's predictive vector (a separation violation is predicted), the predictive vectors of the two aircraft will be highlighted from the current aircraft position to the predicted point of penetration, emphasizing the geometry of the encounter. Other traffic will remain low-lighted unless additional conflict predictions arise. The traffic displays themselves will rotate in a track-up fashion to facilitate integration of the presented information into the pilots' ego-centric frame of reference.

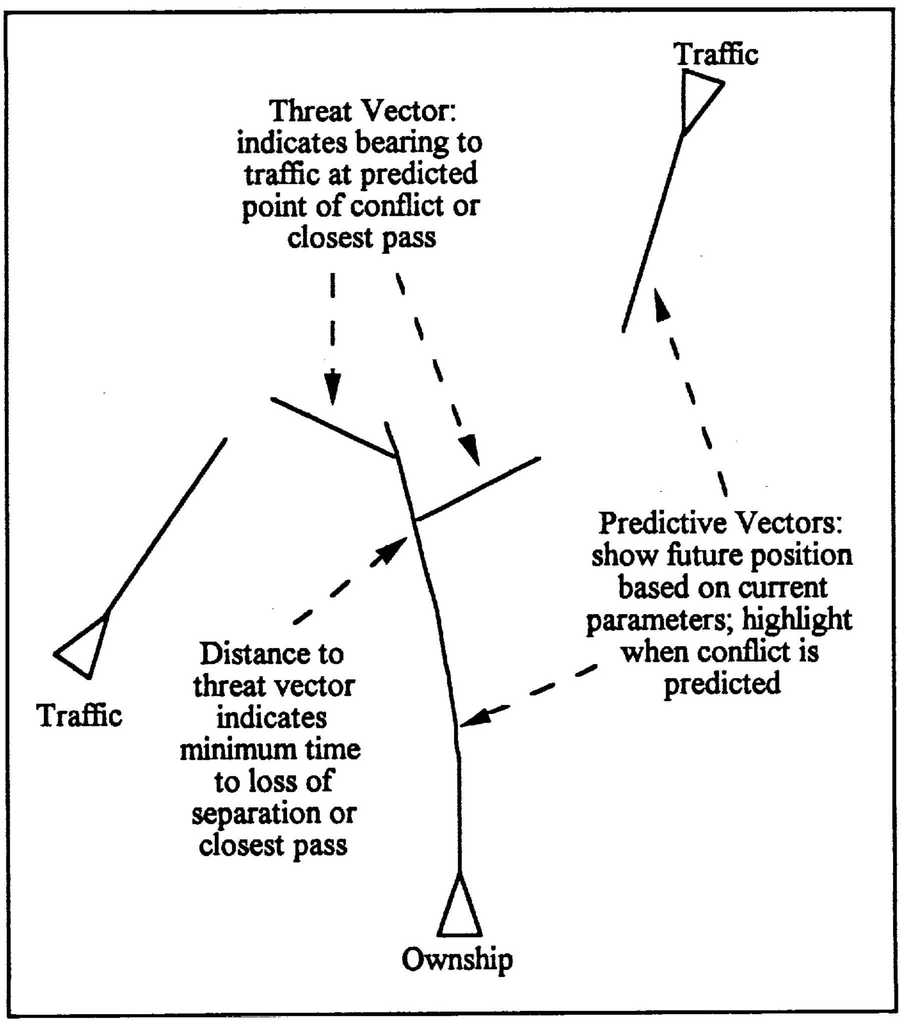


Figure 13. Schematic diagram of the symbology common to both the coplanar and perspective traffic displays.

The symbology employed here is intended to provide the information that is necessary and sufficient to effectively perceive the relative threat of nearby aircraft, and to support the planning of avoidance maneuvers should they be necessary. The predictive vectors supply critical, time-based data on the future positions of ownship and surrounding traffic. By incorporating the traffic vectors extending from ownship's predictive vector, the bearing and distance of traffic at the predicted time of closest pass is displayed directly, relieving the pilots of having to estimate these parameters from position and trend information, which has been shown to be extremely difficult (Palmer et al., 1980). Furthermore, the critical parameter of minimum time to loss of separation is coded by the distance between ownship and the traffic vectors extending from its predicted trajectory vector. This symbolic element also supports the direct perception of a critical task-related variable which would otherwise have to be estimated from the closure rates of the aircraft and their distance from each other.

4.2 <u>2D Coplanar format</u>

The coplanar display (Figure 14) consists of two adjacent windows offering top-down (X-Z) and forward-looking (X-Y) views which are projected orthogonally, providing no perspective information. The top-down display, compatible with the current EHSI, shows the symbology described above overlaid on a grid of equi-spaced lines representing 5 nautical mile increments. The lines are made up of dots positioned at intervals of 1 nautical mile. The grid rotates with ownship to provide consistent spacing information of traffic symbology. No vertical information is available from the top-down display. The forward-looking display consists of a parallel projection of the vertical (Y) and lateral (X) axes. All of the display symbology described above is presented as it would look from the rear, with some important additional symbology. Two sets of horizontal lines indicate the altitude boundaries of the alert zone surrounding ownship. The current two thousand ft. altitude region around ownship is displayed with two solid yellow lines running horizontally across the display (indicated by A on Figure 14), while the predicted vertical boundaries of ownship's alert zone are depicted by two dashed yellow lines (B on Figure 14).

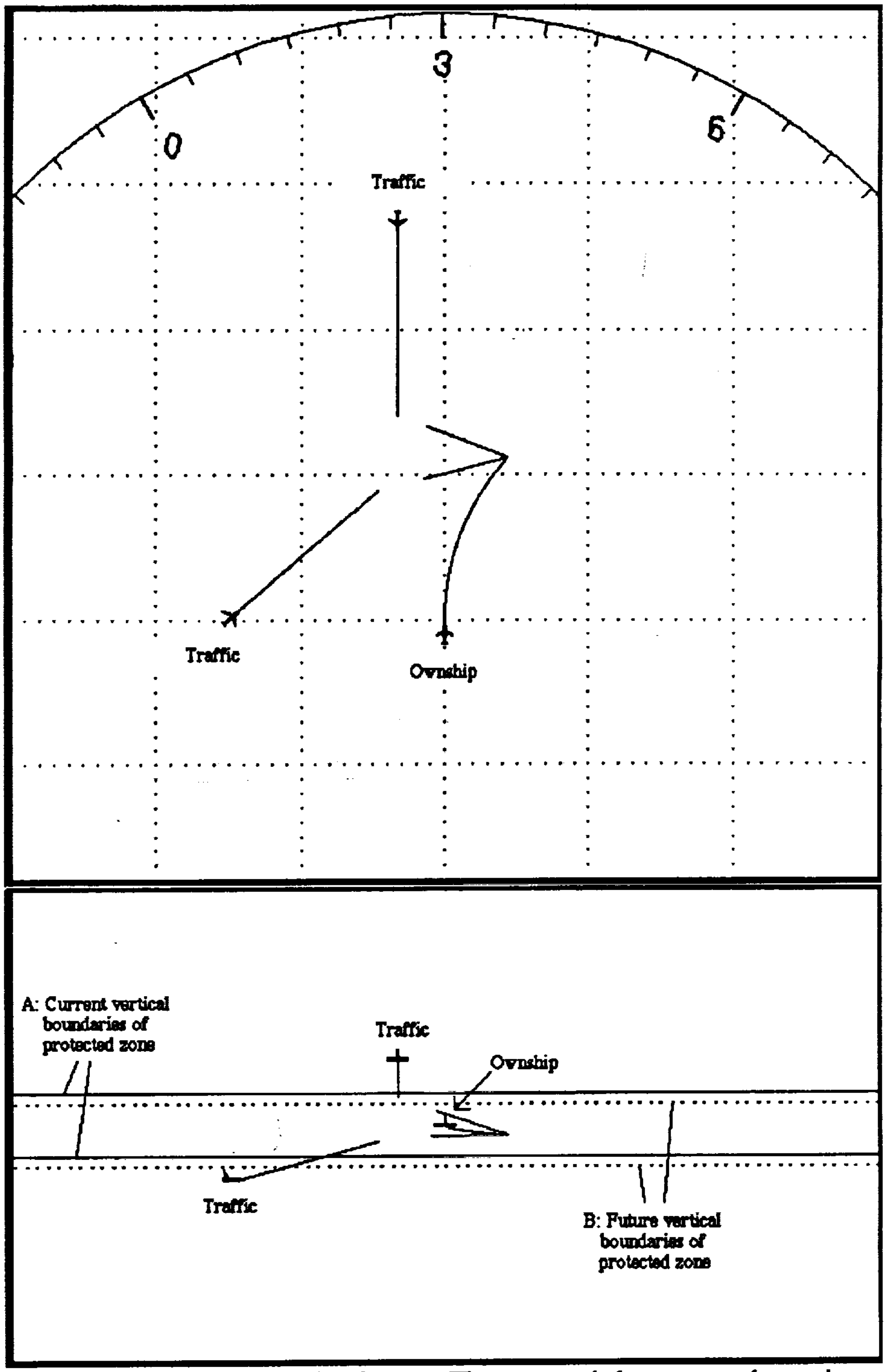


Figure 14. Depiction of the coplanar display format. The top panel shows a top-down view and the bottom panel represents a view from behind ownship (both panels are orthogonal projections). Each of the displays used in the study had a black background with colored lines used for symbology (see text). These augmentations relieve the pilot of having to estimate the relative altitude difference between other traffic and ownship's current and predicted positions, and offer comparable altitude information to the perceptual enhancements contained in the perspective display described below.

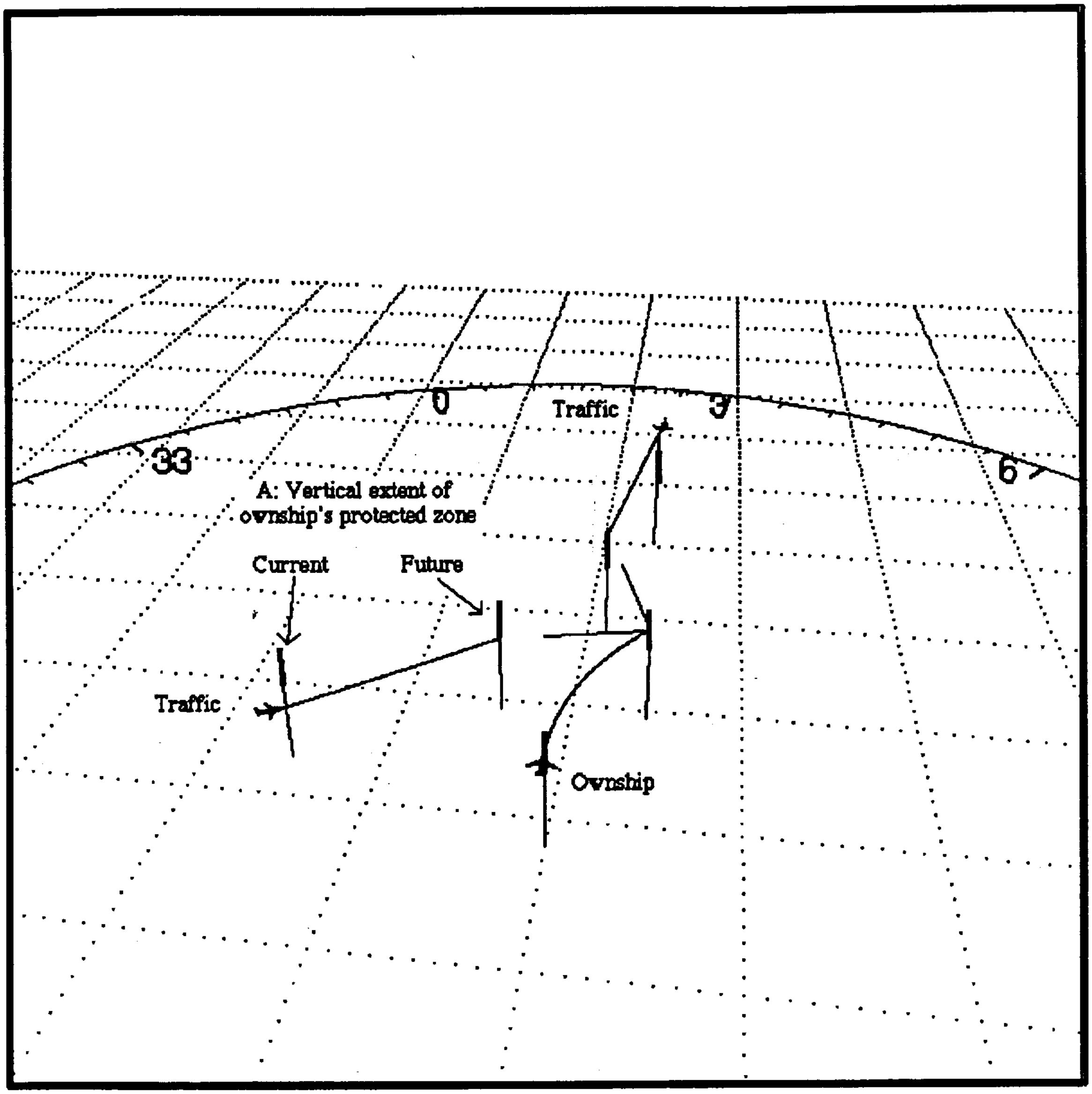


Figure 15. Depiction of the perspective display format with a 30 ° elevation viewing angle. The thicker line segments on the vertical reference lines indicating the vertical extent of ownship's protected zone are provided for explanatory purposes. On the displays used in the study, these line segments were color coded and were the same thickness as the rest of the reference line.

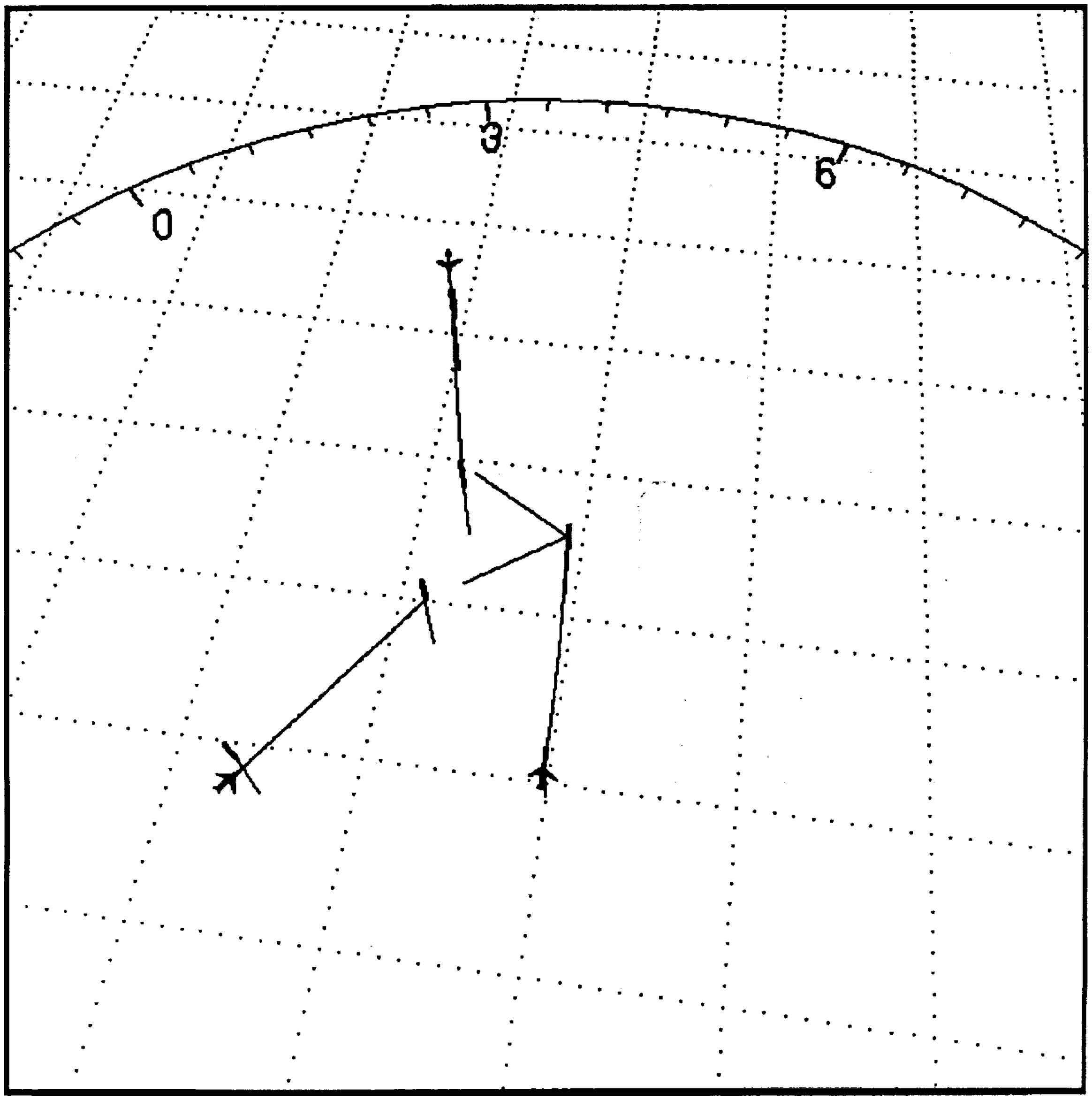


Figure 16. Depiction of the perspective display format with a 60 degree elevation viewing angle.

4.3 3D Perspective format

The perspective display (Figures 14 and 15) depicts an integrated view of the three spatial dimensions viewed from an exocentric position above and behind own ship. The information is displayed using a perspective projection with a vertical and horizontal geometric field of view of 40°. The elevation angle of the viewpoint (eyepoint) is either 30 (Figure 15) or 60° (Figure 16), with an azimuth offset of 5° in the clockwise direction (because of the track-up format, an azimuth offset is employed so that the predictive vector of ownship does not lie on the line of sight of the projection). The symbology used in the perspective display is the same as in the coplanar format, with the exception that reference lines are used to unambiguously show the horizontal positions of the aircraft icons and the ends of their predictive vectors. The reference lines extend to the grid, which is displayed at a constant, but adjustable vertical distance below ownship. The reference lines also contain yellow regions or bars, indicating the vertical boundaries of ownship's alert zone (shown by A on Figure 15). This symbology provides unambiguous relative altitude information that might otherwise be difficult to estimate from the perspective rendering, and is similar to the symbology used by Ellis and his colleagues (1987).

4.4 Simulation flight dynamics and apparatus

The simulation was run on a Silicon Graphics 4D/30 Super Turbo workstation and viewed on a Silicon Graphics 20 inch color display. The display had a screen resolution of 1280x1024 pixels and ran at a frequency of 60 hertz.

The simulation was controlled by relatively simple dynamics. Two-axis flight stick inputs were translated into first-order pitch and bank control, which resulted in second-order control of turn rate and vertical velocity. Maximum pitch angles were limited to 10 degrees and bank angles were limited to 45 degrees to avoid unusual attitudes. Airspeed was set to a constant value of 325 knots to ensure that the aircraft proceeded into the programmed traffic scenarios in a consistent manner, preserving the initial geometry and timing of the encounters.

4.5 Task and simulation

The task involved flying predefined routes in a series of trials, during which encounters with other aircraft occurred. The pilot was required to determine if deviations from the flight path would be necessary based on the position, bearing and speed of the other aircraft using the displays described above. Each trial began with the pilot flying a flight path to a navigational fix (the specific heading and altitude was displayed in an instruction window). The maximum deviation from the flight path was restricted by a hard limit which ensured that the aircraft entered preprogrammed encounters with other aircraft in a predictable and consistent manner. If the aircraft reached the limit, which can be thought of as an invisible box around the specified flight path, it was simply be prohibited from moving any further in the direction of the limit.

Subjects were instructed to fly the specified flight path unless the path brought the aircraft into conflict with other traffic. If pilots determined that a flight path deviation would be necessary to ensure separation, they would be able to indicate their intention to deviate by pressing a key, which disengaged the flight path deviation restrictions and allowed them to maneuver appropriately to resolve the conflict, with the general guideline that they should deviate only as much as was necessary to maintain separation. After the pilot determined that the conflict had been resolved, he or she was to return to a flight path which would intercept the original destination. The trial ended when the aircraft approached to within 3 miles of the navigational waypoint, while simultaneously attaining an altitude within 1000 ft. of the assigned altitude.

4.6 Independent variables

The hypotheses presented in section 3.6 were examined by manipulating the type of avoidance maneuver encouraged by a given traffic scenario. This was accomplished by systematically varying the geometry of the traffic encounters. The approach angle of the conflicting aircraft was varied horizontally and vertically (see Figure 17). The intruder approached from six different angles horizontally: 45 °, 90°, and 135 °, from the left and right. Additionally, the traffic approached ownship from the same flight level, from below and from above, creating level, ascending and descending encounters. Finally, the intruder was programmed to conflict with ownship's protected zone either in front of or behind ownship. Each of these variables was combined factorially to create a 3 (angle) X 3 (vertical) X 2 (left/right) X 2 (ahead/behind) design of within subject factors. Furthermore, a subset of these geometries was selected and adjusted so that they would create a variety of non-conflicting encounters. Each session contained 36 conflict trials and 24 non-conflict trials.

In addition to the constraints imposed by the approach trajectories of intruding aircraft, we also manipulated the number of aircraft present during the trial (one or two). This manipulation can be considered a dimension of complexity which brings its own constraints to the encounter. The second aircraft was located outside of ownship's protected zone, in a parallel flight path which effectively blocked one of the likely routes which could have been selected to avoid the primary intruding traffic. The second aircraft was located in one of six positions around ownship: on the right or left at the same flight level (constraining lateral maneuvers); above and slightly to the right and left (limiting climbing turns); and below and slightly to the right and left (limiting descending turns).

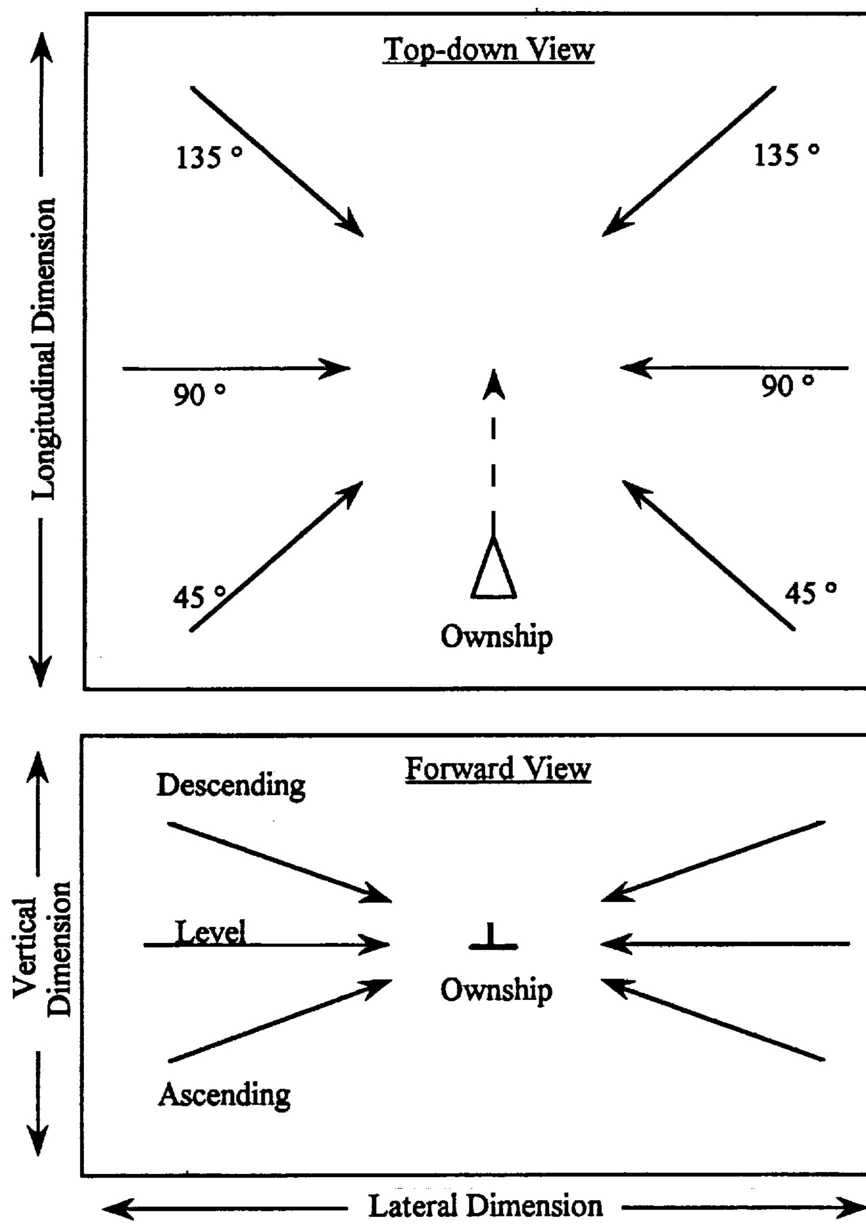


Figure 17. Diagram of intruder approach geometries. The top panel shows the horizontal parameters; the bottom panel shows the vertical parameters.

The placement of the second aircraft was not fully crossed with all of the primary intruder approach geometry factors, but was balanced across vertical and lateral approach trajectories of the primary aircraft. The intruder approach geometry and the presence of the additional non-conflicting aircraft were counter balanced and randomized within session. The first session involved trials with only the primary conflicting aircraft. The second session replicated the first in terms of the encounter geometries used, but included the second non-conflicting aircraft.

4.7 Dependent measures

Performance was evaluated in several ways. The dependent measures included: 1) the accuracy and latency in determining if ownship's alert zone was going to be compromised by the primary intruder aircraft; 2) the success in avoiding both predicted and actual conflicts if they were anticipated by the pilot; 3) the efficiency of the avoidance maneuver in terms of mean vertical and lateral deviations from the assigned flight path; 4) the spatial characteristics of the avoidance maneuver itself (e.g., the degree to which the vertical and horizontal dimensions were utilized; biases to maneuver to the left or right); 5) the proximity of ownship to the primary and secondary traffic at the point of closest pass during avoidance maneuvers. In addition to the performance variables recorded during the flight simulation trials, subjective measures of workload were also collected using the NASA-TLX workload rating scale (see Appendix 4). These measures were collected off line after each experimental session.

4.8 Design and procedure

A between subjects manipulation of display type was used to eliminate potential carryover effects from one condition to another. This is considered important because of the possibility that in this particular task, strategies might be formed from exposure to one of the display conditions which might persist throughout the experimental sessions, making interpretation of the results problematic. Refer to Figure 18 for a diagram of the experimental design. Participants completed two sessions on separate days. The first session included an introduction to the display configuration and practice on the task (Appendix 2 contains the written instructions given to subjects; Appendix 3 contains the verbal instructions, read by the experimenter, which pertain to the individual displays).

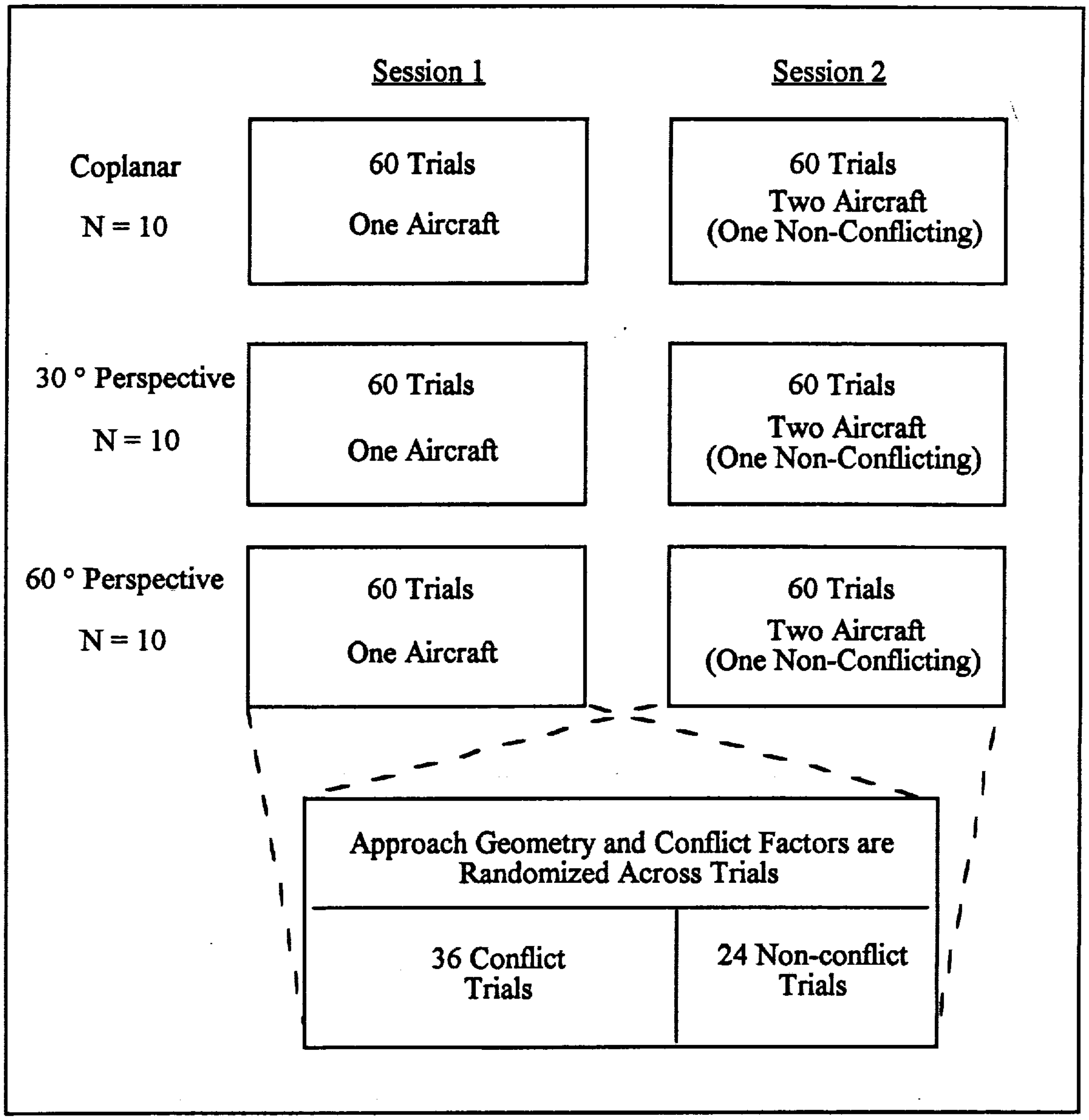


Figure 18. Diagram of the major between subjects and within subjects factors in the experimental design.

Time was provided for flying the simulation to become acquainted with the control dynamics of the system. Following this, participants received a series of practice trials which were representative of the types of traffic situations used in the experimental sessions. Subjects then completed the first session of the experimental trials, with the second session following on a subsequent day.

4.9 Participants

Thirty certified flight instructors (CFI) from the Institute of Aviation at the University of Illinois were paid $8/hr for their participation in the study. The mean of the pilots' total logged flight hours was 1,953hr (minimum=240; median=1,020; maximum=12,0000). The mean of the pilots' reported instrument flight time was 282hr (minimum=30; median=123; maximum =1,800).

5 RESULTS

5.0 Data Preprocessing

The results of the analyses performed on each of the dependent variables are presented in the following sub-sections. In each case, the distributions of the dependent variables were examined prior to analysis, to determine the appropriateness of the planned analysis techniques, as well as the suitability of the distributions themselves for the planned analyses. This involved a preliminary visual inspection for gross deviations from normality, as well as a check for extreme data points. None of the distributions required transformation as a result of this preliminary screening, nor were any data points removed due to extreme value. Some data points appeared to be unusually far from the mean of the distribution to which they belonged, but because of the rather small number of data points comprising the distributions, they did not meet generally accepted criteria for removal (i.e., three standard deviations from the mean).

Some of the analyses performed involved statistical models which included several main effect and interaction terms which were considered to be of lessor importance than others. Of primary interest was the main effect of display type, and the two-way interactions involving display type and the variables defining the geometric characteristics of the encounter, as well as the presence of the second non-conflicting aircraft. Higher-order interactions involving the display type variable were considered to be less important, both from a theoretical position, and because the likelihood of their presence was increased due to the large number of variables in the model. Therefore, unless there were theoretically interesting reasons for examining particular higher-order interactions, or the interactions showed some consistency across several measures, they will not be discussed.

In Section 4, a justification of the decision to use a between subjects design for the display variable was presented. The reasoning was that the task involved strategic components which, if developed using one display, might carry over to affect performance in another display in a way which would be difficult to predict or interpret. The use of a between subjects variable, however, introduces the problem of inter-subject variability, which can be particularly problematic if the pool of potential subjects is small, as is the case in the current experiment. In an attempt to reduce the influence of inter-subject variability on the results of this study, a number of questionnaire variables were collected from participants prior to their engagement in the experimental trials. This information included total flight time, total instrument flight time, and a series of questions which were designed to elicit traffic avoidance strategies which the pilots used in their routine flying (See Appendix 1 for an example of the questionnaire form used). These variables were later evaluated for their ability to reduce the error variance in the statistical analysis models. This was done by first computing correlations between the questionnaire variables and the dependent measures of interest (see Appendix 5 for the correlation matrices). Promising candidate variables were then included as covariates in the corresponding model. These covariates will be discussed where appropriate, in the sub-sections which describe the models in which they were used.

5.1 Conflict detection, false alarms and decision latency

In each trial of the experiment, subjects were first required to judge whether a conflict would occur, and to take appropriate action accordingly. As was described in Section 4, subjects indicated their response by pressing one of two buttons on the flight stick. Pressing the button which indicated a conflict present judgment removed the flight restrictions in the simulation and allowed the pilots to maneuver freely to avoid the conflict. Button presses for conflict absent judgments resulted in a color change of the 'RESTRICTED FLIGHT' text on the screen from amber to green, indicating that the pilot's response had been recorded but that the flight restrictions were still in place. This first part of each trial was essentially a signal detection task, and can be analyzed using techniques developed in the signal detection literature

(Green and Swets, 1988). For the purposes of this study, the following measures will be discussed: detection accuracy, false alarm rate, the sensitivity measure A' and response time. Each of these measures was analyzed separately using mixed within-between ANOVA models, using session as the within subjects variable (encounter geometries were collapsed for these analyses to provide sufficient response time data).

An analysis of the detection rate data which included two covariates (self-reported likelihood of using climbing, and climbing left avoidance maneuvers) revealed significant effects of display condition ($F_{2,25}=3.88$, $p.034$) and session ($F_{1,27}=7.68$, $p=.01$) on the dependent variable. Figure 19 shows the mean detection rates for the three displays plotted by session, which suggest an advantage for the coplanar display over the 60° perspective display, while the 30° perspective condition was associated with an intermediate level of performance. A post hoc comparison confirmed the difference evident in Figure 19 between the coplanar and 60° perspective display ($F_{1,25}=4.79$, $p=.038$). The data indicate generally very high detection rates, which is not surprising given that conflicts eventually became apparent as trials progressed. What is perhaps more surprising is that detection rates were not 100% in all conditions, suggesting that actual conflicts (indicated by a change in color of both ownship and the conflicting traffic, to red) were either not noticed or ignored in some trials.

An analysis of the false alarm rates did not reveal an effect of display condition ($F_{2,26}=1.67$, $p=.20$), suggesting that the differences observed in the detection rate data were not associated with a trade-off with false alarm rates (see Figure 20 for mean false alarm rates). That is, higher detection rates in the coplanar display condition were not coupled with higher false alarm rates, which would be the case if differences in detection rates between the display conditions resulted from different response criterion settings.

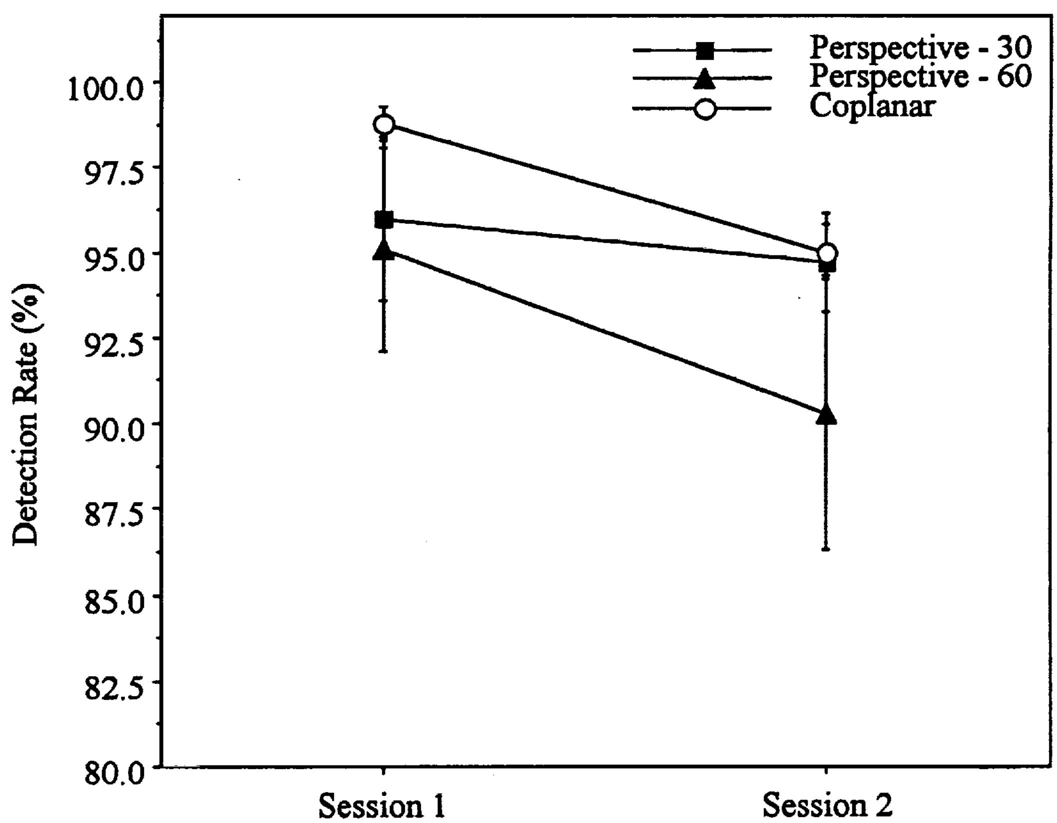


Figure 19. Plot of mean conflict detection rates (% detected) plotted by session.

To further examine the detection and false alarm rate data, the sensitivity measure A′ was calculated and analyzed. A mixed model ANOVA (which included the covariate measure of self-reported preference to select climbing avoidance maneuvers) revealed a marginal effect of display condition on A′ ($F_{2,25}=2.94$, $p=.07$). A post hoc comparison indicated that the display effect was caused by a difference between the coplanar and 30° perspective conditions ($F_{1,25}=5.6$, $p=.026$). Figure 21 shows the mean values of A′, in which the relatively higher sensitivity fostered by the coplanar display with respect to the 30° perspective display is apparent. Figure 21 also shows that the 60° perspective display condition supported values of A′ that were not substantially different from that of the 30° display in session one, or from that of the coplanar display in session two.

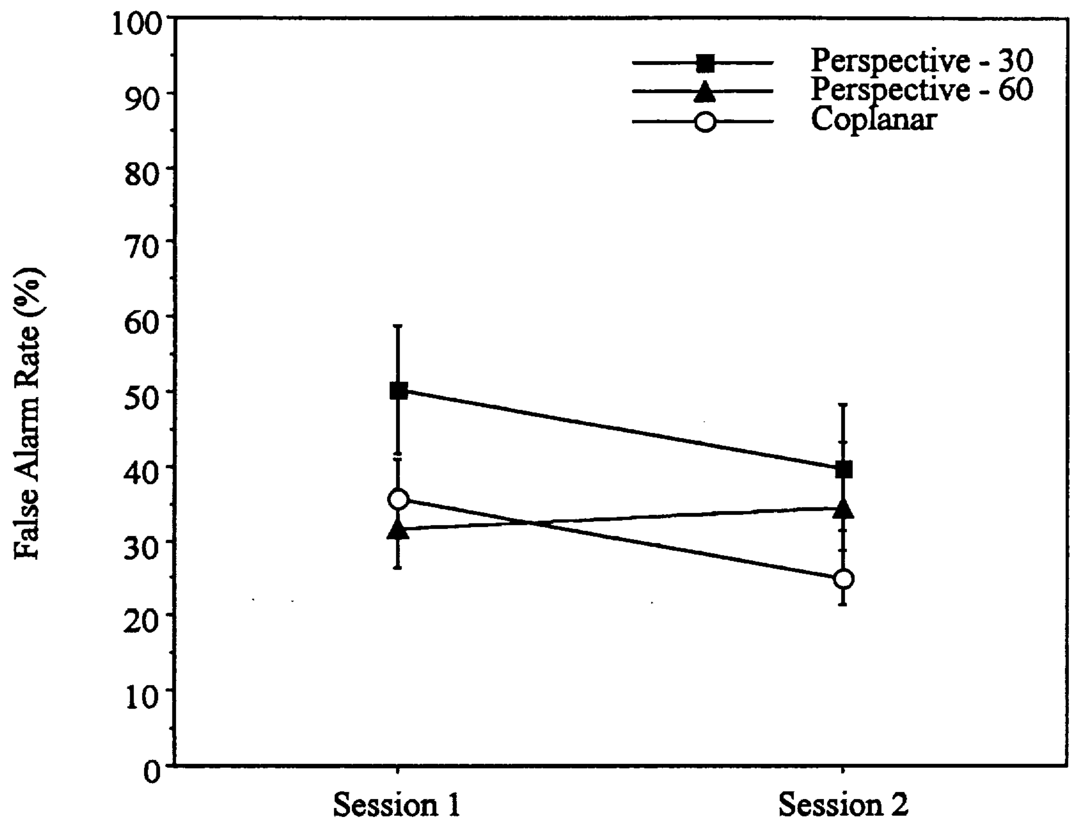


Figure 20. Plot of mean false alarm rates (%) for conflict detection task.

Estimates of the criterion measure Beta were also computed using the detection and false alarm rates for the three display conditions (Beta is the ratio of the normal ordinate corresponding to the detection rate to the normal ordinate associated with the false alarm rate). The estimated values of Beta are reported here, but were not submitted to analysis because of difficulties in analysis and interpretation of the statistic, especially when the size of the samples is small (Parasuraman, 1986). Estimates of Beta were *.20* for the coplanar display; *.29* for the 30° perspective condition; and *.37* for the 60° perspective display. These values suggest that the coplanar condition supported a greater willingness to report a conflict than did the 30°, and particularly the 60° condition, although caution is warranted in interpreting this assessment.

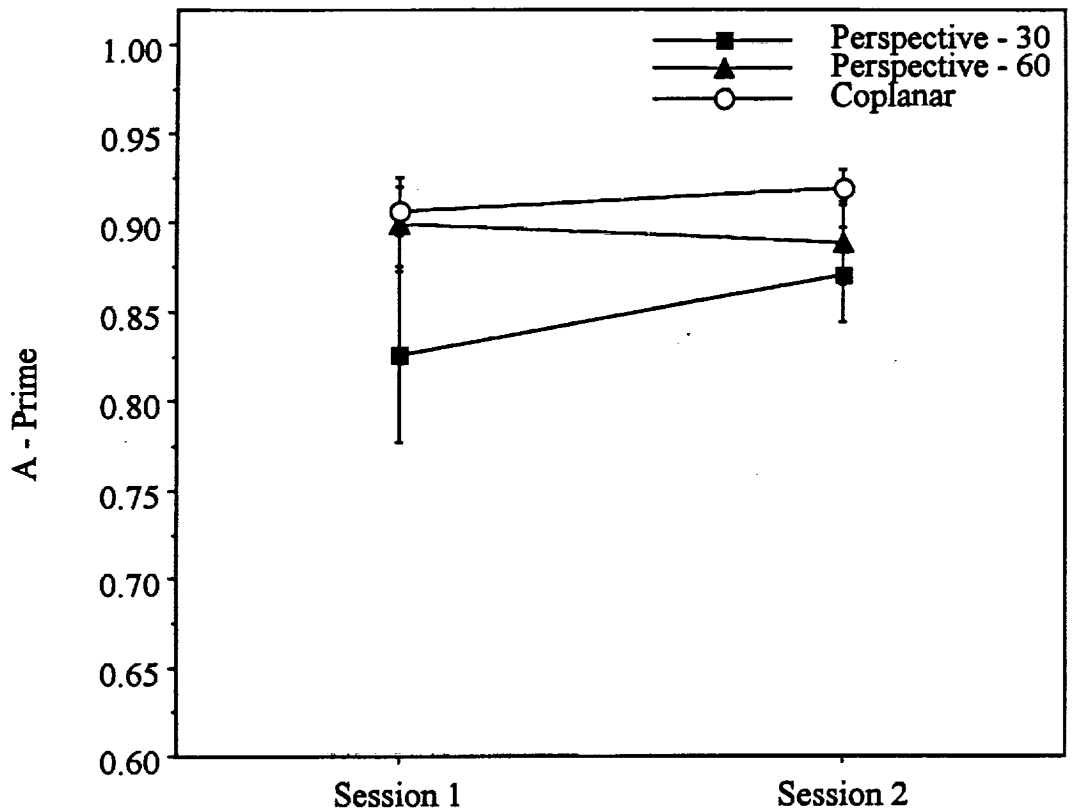


Figure 21. Plot of the mean values of A′ computed from detection and false alarm rates.

However, subjects in the coplanar format committed fewer false alarms than did those in the 30° format in particular, which suggests that the estimates of Beta were sensitive to the relatively higher detection rates for the coplanar display. Thus, the apparently less 'conservative' response criterion fostered by the coplanar display was not associated with more false alarms, but rather with more successful detections.

The response time data were analyzed using two mixed model ANOVAs. The first analysis included conflict present trials and indicated that response time was not significantly affected by display condition (F 2,26=.82, p=.45). Figure 22 shows the mean response times for correct conflict present judgments. The tight grouping of the response time data for conflict present judgments is likely due to the timing of the traffic encounters in the trials.

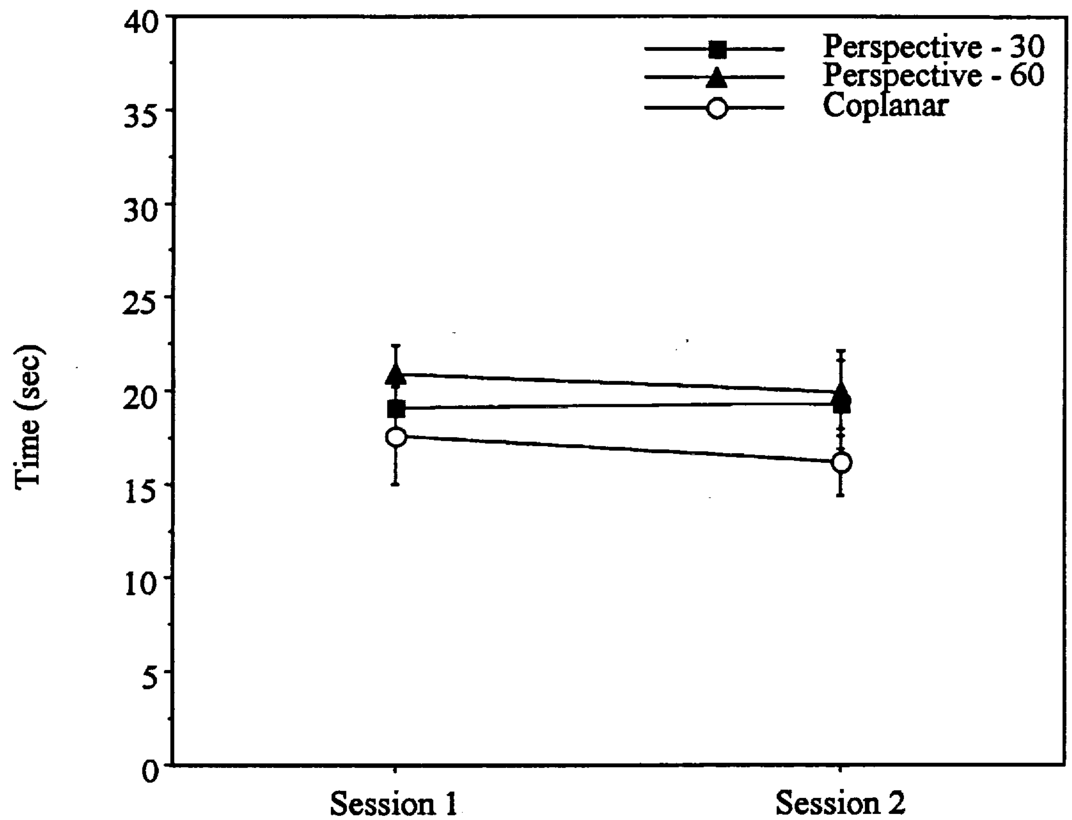


Figure 22. Plot of mean response times for conflict trials (correct detections only).

On conflict trials, the predictive vectors of ownship and the conflicting traffic intercepted after approximately 18 seconds, indicating a predicted conflict. The uncertainty of whether the trial would involve a conflict, therefore, ended after 18 seconds. This essentially created a ceiling for the response times on conflict trials, which is evident in the small standard error values of the means. Interestingly, none of the display conditions fostered responses which were made substantially sooner than the 18 second threshold, suggesting a generally adopted conservative strategy in which judgments were not made much before the predictive symbols from the two aircraft became quite close to one another.

An analysis of the response times for conflict absent judgments indicated a marginally significant effect of display condition (F 2,25=3.1, p=.06). This model included the covariate of total number of flight hours reported, which was significantly associated with response time (F 1,25=8.45, p<.008). Figure 23 shows the response time data for correctly identified conflict absent trials.

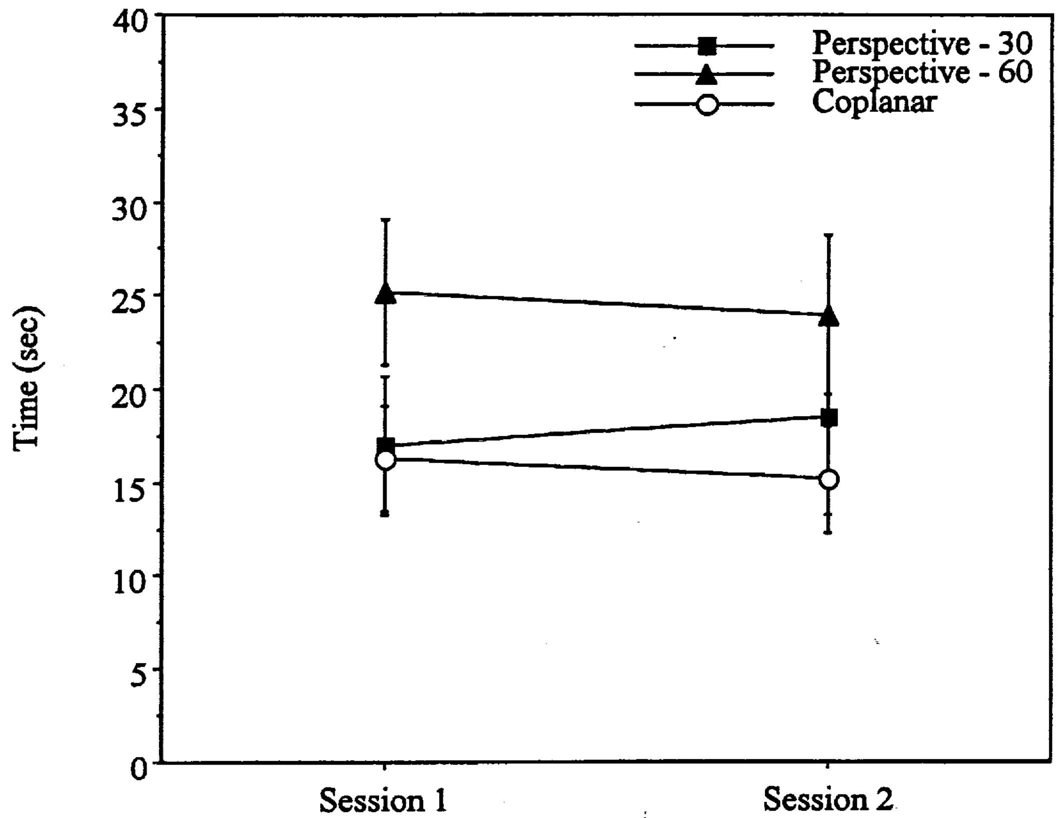


Figure 23. Plot of the mean response times for conflict absent trials (correct responses only).

The data in Figure 23 suggest a relative disadvantage for the 60° perspective condition with respect to the other two display conditions. The visually apparent differences in Figure 23 were confirmed in a post hoc comparison in which the 60° perspective condition was found to be significantly different from both the coplanar display ($F_{1,25}=4.25$, $p=.049$) and the 30° perspective display ($F_{1,25}=5.11$, $p=.033$).

5.2 Conflict Avoidance

The results from the conflict detection task presented in section 5.1 provide important data on the initial assessment of the traffic encounter scenarios, but are limited in that they do not indicate how effectively the pilots managed the evolving situation once they made a decision either to continue on their prescribed flight path or to initiate an avoidance maneuver. To examine the pilots' performance with respect to the critical task of maintaining safe separation from traffic, we utilized a mixed within-between multivariate analysis of variance (MANOVA) model which included the between-subjects factor of display type, the three within-subjects factors which defined the geometry of the encounter, and the presence of the second non-conflicting aircraft in session 2. Therefore, a 3 (display type) X 3 (horizontal approach angle) X 3 (vertical approach angle) X 2 (approach side: left or right) X 2 (point of conflict/closest pass: in front or behind) X 2 (session: presence of second aircraft) MANOVA model was used for this analysis. None of the questionnaire variables was highly correlated with the dependent variables, and therefore no covariates were used in the model.

Two dependent variables were included in the analysis: (1) the proportion of trials in which the pilot's flight maneuver triggered a "predicted conflict"; and (2) the proportion of trials in which the pilot actually failed to maintain safe separation from the traffic, precipitating an "actual conflict." Although the experimental instructions advised that predicted conflicts should be avoided, they nevertheless occurred rather frequently. Predicted conflicts were triggered when ownship's threat vector symbology contacted another aircraft's predictive vector, indicating that a conflict would occur within 45 seconds if the current flight parameters were maintained. Actual conflicts occurred when traffic closed to within three miles laterally and 1000 ft. vertically of ownship, and as expected, occurred only rarely.

Figure 24 shows the mean proportion of predicted conflicts for each display type in sessions 1 and 2 A univariate ANOVA performed on the proportion of predicted conflicts with the primary traffic indicated a marginal effect of display type ($F_{2,27}=3.06$, $p=.06$). Figure 24 indicates a trend in which relatively more predicted conflicts occurred in the 60 degree perspective display condition than in the 30°, and particularly, the coplanar display condition. A post hoc comparison was then performed to determine the locus of the marginal effect of display type on the proportion of predicted conflicts.

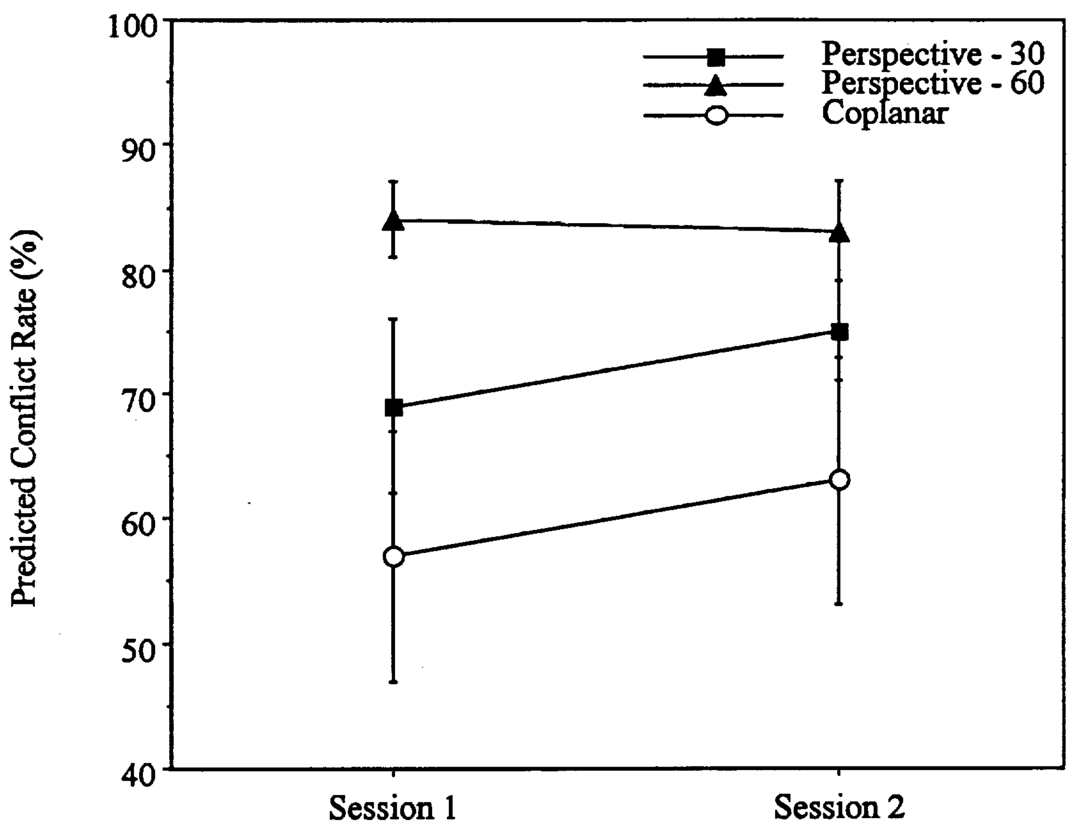


Figure 24. Plot of the mean rates for predicted conflicts triggered during all trials.

This test confirmed the visually apparent difference in Figure 24 between the means for the 60 degree perspective display and the coplanar display ($F_{1,27}=6.11$, $p=.02$).

Figure 25 shows the mean rate of actual conflicts for each display condition in both sessions, which was not significantly affected by display type ($p=.59$). Interestingly, the means for the coplanar display appear lower than either of the two perspective displays in Figure 25, which mirrors the data for predicted conflicts shown in Figure 24.

As was discussed in section 4, the first experimental session involved only one intruding aircraft. The second session, however, included a second non-conflicting aircraft which flew parallel to ownship and was used to effectively limit the pilot's options in selecting an appropriate maneuver to avoid the primary conflicting intruder.

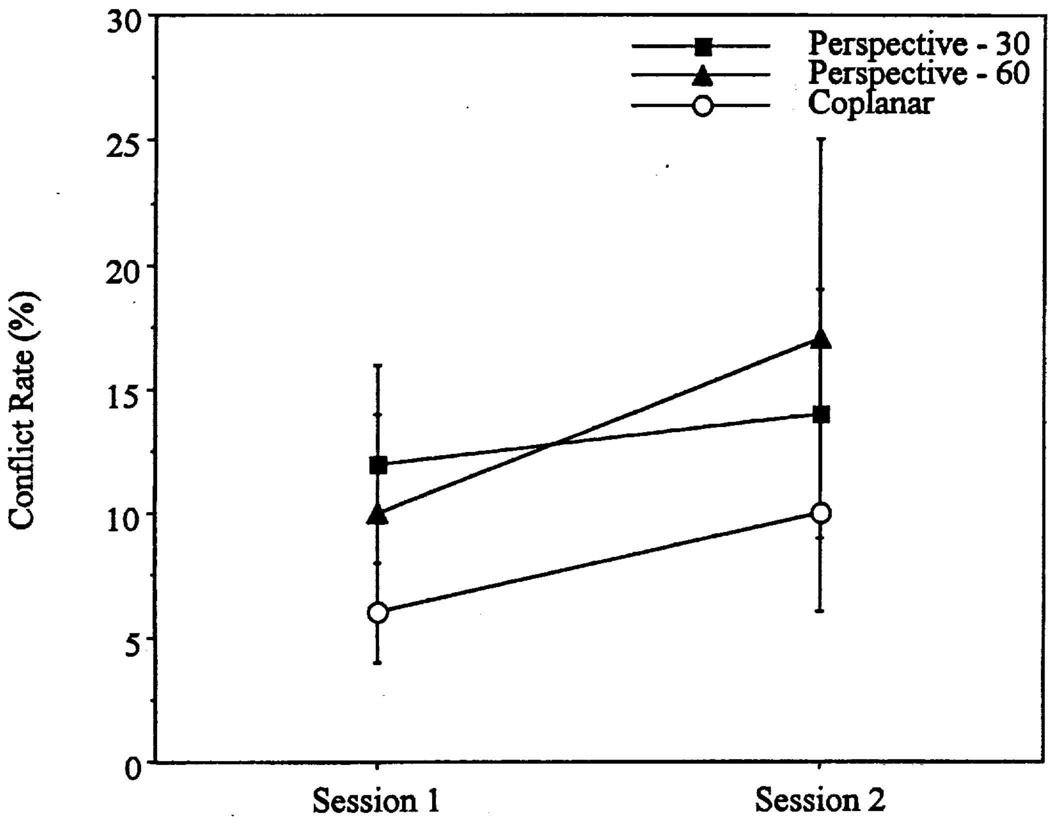


Figure 25. Plot of the mean rates for actual conflicts triggered during all trials.

During these trials, pilots sometimes lost separation with the second aircraft while maneuvering to avoid the primary (intruder) aircraft. The reason for including the second aircraft in the experimental paradigm was to assess the effectiveness with which pilots could integrate the constraints imposed by the presence of the second aircraft with the information required to avoid the primary intruder. To examine this issue, two ANOVAs were performed on the proportion of predicted and actual conflicts with the second (initially non-conflicting) aircraft in session 2.

An ANOVA performed on the proportion of actual conflicts with the second aircraft revealed a significant main effect of display type on the dependent variable ($F_{2,27}=6.55$, $p=.005$), as well as an interaction between the vertical approach behavior of the primary traffic and display condition ($F_{4,52}=3.78$, $p=.01$). A second ANOVA performed on the proportion of predicted conflicts with the second aircraft indicated a non-significant trend for the display effect ($F_{2,27}=2.69$, $p=.086$). Figure 26 shows the effect of display type on actual conflicts, as well as the non-significant trend for predicted conflicts, suggesting an advantage for the coplanar display in avoiding the secondary air traffic. Post hoc tests confirmed the relative advantage of the coplanar display format. This advantage was most pronounced when comparing the coplanar display with the 30° perspective display. Significant differences were found between the coplanar and 30° perspective displays for actual conflicts ($F_{1,27}=12.48$, $p=.002$) as well as predicted conflicts ($F_{1,27}$=4.84, p=.036). A significant difference was also observed between the two perspective display conditions for actual conflicts ($F_{1,27}$=5.98, p=.02), while a similar comparison between the coplanar and the 60° perspective display did not indicate a difference for actual conflicts ($F_{1,27}$=1.18, p=.29). Unlike the primary intruder conflict data from session two in Figure 25 which indicate poorer performance in the 60° perspective condition, the results of this analysis show worse performance with the 30° perspective display.

The interaction between the vertical approach behavior of primary traffic and display type for actual conflicts with the second aircraft is shown in Figure 27. Referring to Figure 27, each of the three display conditions supported poorer performance on trials which involved primary traffic that was climbing or descending. However, the 30° perspective display showed substantially worse performance on trials in which the primary intruder was changing its vertical position than did the coplanar, and to a lessor extent the 60° perspective display.

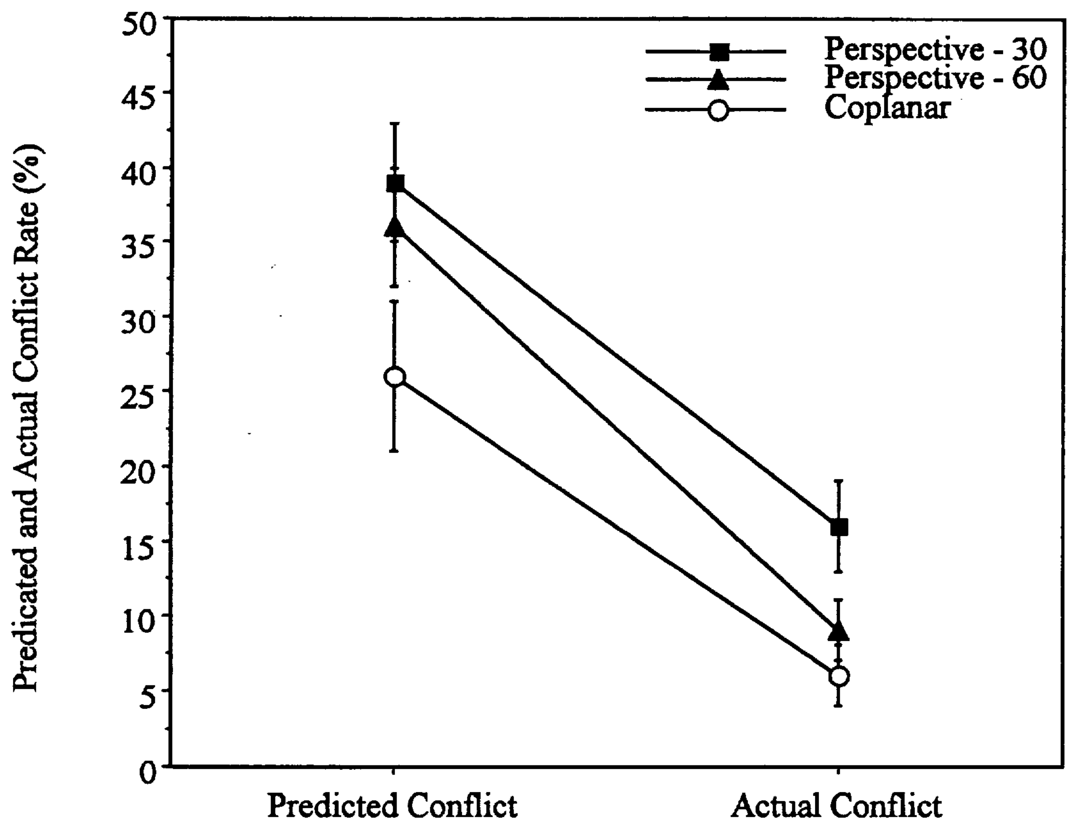


Figure 26. Plot of the mean rates for predicted and actual conflicts with the second, non-conflicting aircraft in session 2, summarized over all within-subjects factors.

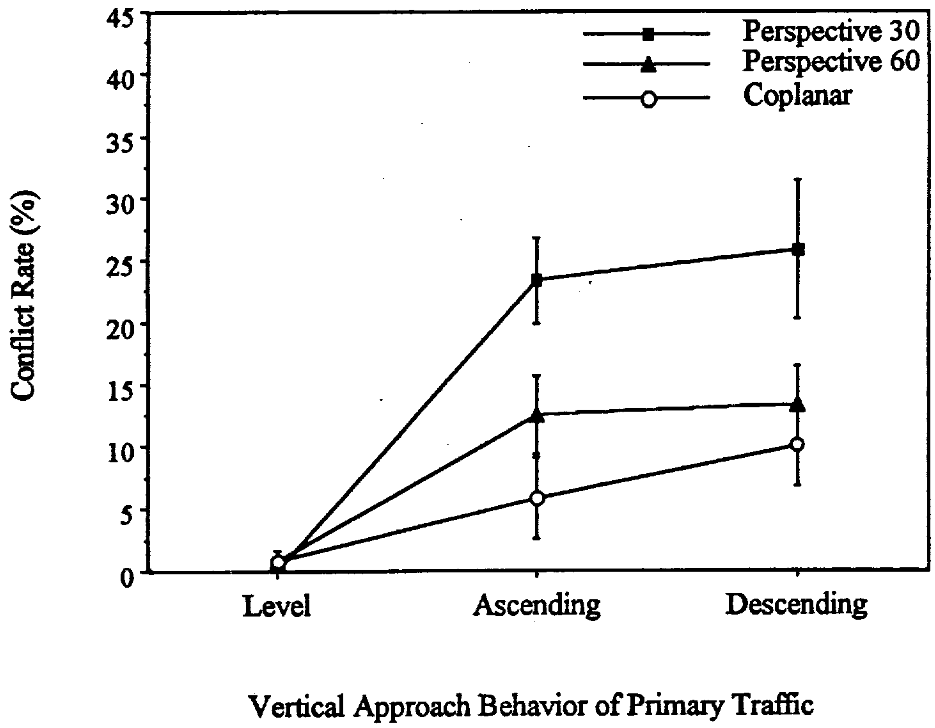


Figure 27. Plot of the mean rates for actual conflicts with the secondary aircraft in session 2, showing the interaction between the vertical approach behavior of the primary traffic and display condition.

5.4 Avoidance Maneuver Characteristics

An examination of the types of avoidance maneuvers chosen by the pilots was carried out using a MANOVA to analyze the mean vertical and horizontal position of ownship during trials which required avoidance maneuvers. Our primary interest was in detecting any general biases toward one or the other types of maneuvers that might be induced by the display formats, including interactions with the geometry of the traffic encounters. The two dependent variables in the analysis were the vertical and lateral position of ownship averaged over the flight trajectory tracked during the first 80 seconds of each conflict trial. Flight path data collected after 80 seconds were not included in the computation of these variables because pilots occasionally flew extremely circuitous routes to intercept the navigational waypoint after maneuvering to avoid the traffic. Also, the distinguishing characteristics of the avoidance maneuvers were evident during the first 80 seconds of the trial.

Additionally, flight path data from trials in which pilots failed to indicate that an avoidance maneuver was necessary were omitted from the analysis. On these trials, pilots either failed to detect or ignored the conflict, and as a result were not released from the flight path restrictions. Therefore, no maneuvers were initiated on these trials, which represented approximately 5% of the conflict trials. Figures 28 (session 1) and 29 (session 2) are plots of individual data points representing the mean lateral and vertical position of ownship relative to the assigned flight path (defined at 0 miles laterally and 10,000 ft vertically) during conflict trials: each data point represents one trial, as flown by a single pilot. The plots are provided to show the distributions of avoidance maneuvers for the three display types collapsed over all of the encounter geometry factors.

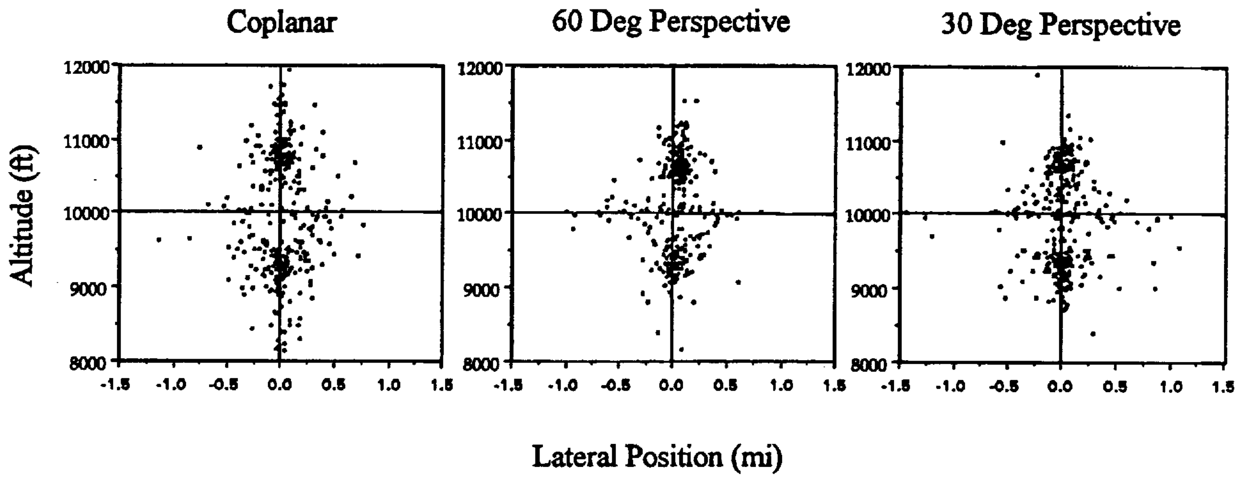


Figure 28. Plot of vertical and lateral position of ownship on individual conflict trials in session 1.

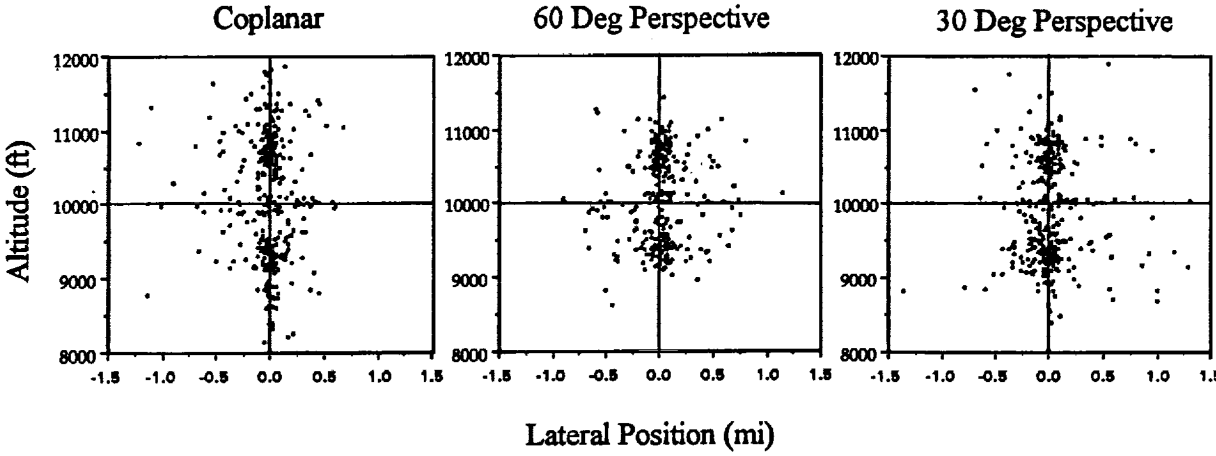


Figure 29. Plot of vertical and lateral position of ownship on individual conflict trials in session 2.

An overview of Figures 28 and 29 reveals a few general visualizable features. The greater variability in the vertical dimension of both figures for data in the coplanar panel with respect to the two perspective displays suggests differing biases in the selection of avoidance maneuvers in the coplanar and perspective display formats. This accentuation of vertical components of maneuvers for the coplanar display is particularly evident in Figure 29. The 60° perspective display seems to have fostered less variability in general as compared to the coplanar and 30° perspective displays, as evidenced by the relatively more compact clusters in the 60° panels in the middle of each figure. The horizontal 'line' at 10,000ft altitude (evident in the 60° panel of Figure 28) depicts exclusively horizontal maneuvers. The clusters of data points in each panel, centered on the intersection of the vertical and horizontal lines referencing the assigned flight path indicate trials in which substantial maneuvers were not made. In these cases, it is likely that actual conflicts occurred.

The statistical analyses performed confirmed some of the observations reported above. A covariate was included in the MANOVA model which modestly reduced the error variance. The covariate was the number of instrument flight hours flown as reported by the pilots in the pre-experimental questionnaire. This covariate accounted for a marginally significant amount of the variance in the model ($F_{2,25}=2.97$, $p=.069$). With the covariate included, the MANCOVA indicated a significant main effect of display type on the combined vertical and lateral position of ownship during trials in which avoidance maneuvers were required ($F_{4,50}=2.86$, $p=.03$). This result was due to an effect on the vertical position of ownship ($F_{2,26}=4.67$, $p=.02$); display type did not significantly affect lateral position in this analysis ($F_{2,26}=1.44$, $p=.25$). Figure 30 shows the mean position data collapsed over all of the within subject factors for the three display conditions.

As can be seen in Figure 30, the mean vertical position of maneuvers made in the 30° perspective condition was substantially lower than those initiated in 60° perspective condition and modestly lower than those made with the coplanar display. A post hoc comparison revealed that the mean vertical position data for the two perspective displays was significantly different ($F_{1,26}=9.02$, $p=.006$). While not contributing to a reliable effect on lateral position, the two perspective displays appear to foster lateral components to the avoidance maneuvers which are biased somewhat to the right of the flight path, while the data for the coplanar display does not suggest this bias to the right. To further examine this apparent difference, the lateral position data for the two perspective displays were combined and compared to the data from the coplanar display; this comparison yielded a marginally significant difference ($F_{1,28}=3.08$, $p=.09$). This trend may have resulted from the viewing vector azimuth offset of 5 degrees to the right used for the perspective display implementation. This offset would have caused ownship's predictive vector to align toward a more parallel relationship with the viewing plane during banking maneuvers to the right. This could have enabled more precise estimates of the future position than if the predictive vector remained extended in a position more closely aligned with the viewing vector, along the line of sight. Banking maneuvers to the left would cause ownship's predictive vector to extend even more along the line of sight viewing vector, making estimates of position on the longitudinal dimension more difficult.

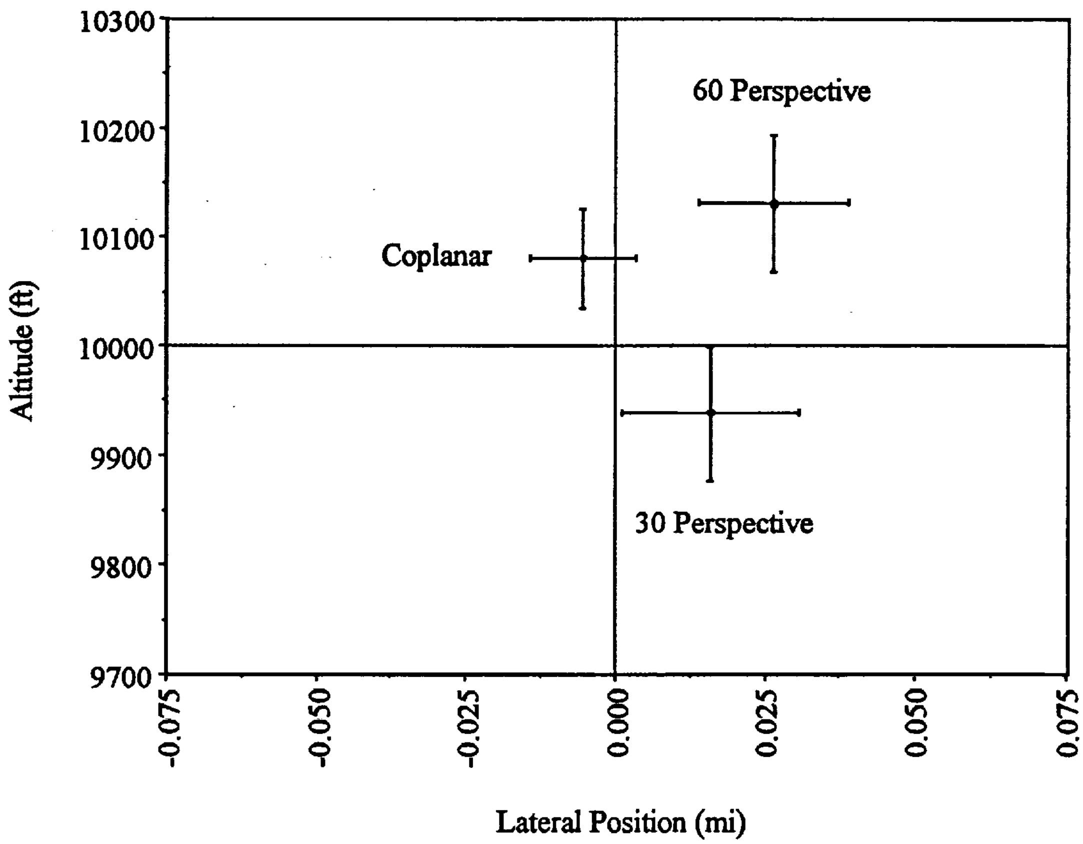


Figure 30. Plot of the mean position of ownship during conflict trials summarized over within factors.

In addition to the main effect of display on the mean vertical position of ownship, a significant two-way interaction was found between display type and the vertical approach behavior of the intruder (i.e., level, ascending into protected zone, or descending into protected zone) on the combination of dependent variables ($F_{8,106}=6.4$, $p<.0001$). Each of the dependent variables was significantly affected by the interaction. However, the mean vertical position of ownship was slightly more sensitive than was the mean horizontal position to the interacting effect ($F_{4,54}=9.13$, $p<.001$; and $F_{4,54}=4.08$, $p<.006$, respectively).

The interaction is evident in Figure 31, which shows the mean positions of ownship for each of the three conditions defining the vertical approach behavior of the traffic.

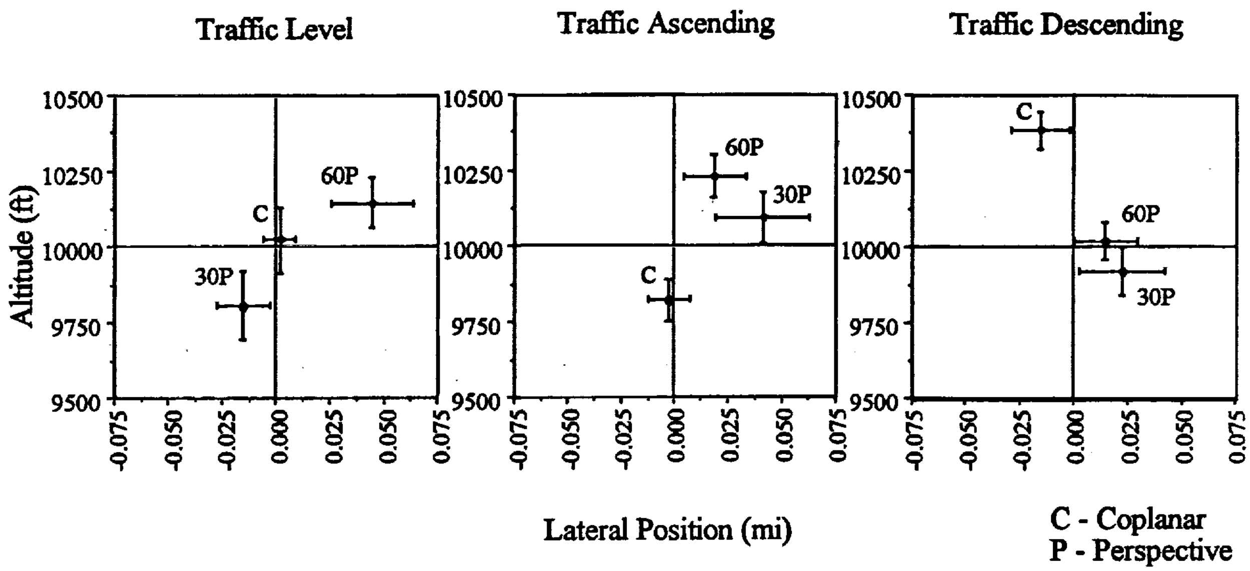


Figure 31. Plot of the mean vertical and horizontal positions of ownship during conflict trials in which the traffic was approaching at the same flight level (left panel), ascending from below (middle panel), or descending from above (right panel). Note the interaction between display type and the vertical approach characteristics of the traffic (see text).

In the left panel of Figure 31, the data point for the coplanar display occupies a central position with respect to the assigned flight parameters while the two perspective displays indicate maneuver tendencies which are either above and to the right (60° display) or below and to the left (30° display) of center. The two panels on the right side of Figure 31 are most revealing, however. When faced with ascending traffic (middle panel), the coplanar display fostered a tendency to <u>descend</u> to avoid, while the two perspective displays appear to support relatively more <u>ascending</u> maneuvers. The opposite trend is apparent in the far right panel of Figure 31. In this case, descending traffic promoted ascending avoidance maneuvers in the coplanar condition, while maneuvers made in the two perspective display conditions are lower as compared to their responses to ascending traffic.

One potential source for this finding is the relative ease with which vertical trend information can be extracted from the coplanar display as compared to the two perspective displays. The bottom panel of the coplanar display provides an unambiguous representation of the vertical dimension, without being distorted by the integration of the other two spatial axes. The integration of the vertical and longitudinal (and to some degree, the lateral) dimensions in the two perspective displays creates some perceptual ambiguity which can be overcome, with some effort, by comparing two graphically connected, but spatially separated symbols (the vertical reference lines extending from the ends of the predictive vectors; see Figures 14 and 15). For both display formats the angle or slope of the intruder's predictive vector is an efficient graphical representation of the intruder's vertical trend. The coplanar display supports the direct, unambiguous perception of the vertical extent of the predictive vector because it is mapped to the XY space of the planar display. The slope of the predictive vector is less perceptible in the perspective displays because of dimensional integration, and the perceptual biases which accompany it. Hence, users of the perspective displays will be more inclined to rely on the current <u>position</u> of the intruder aircraft (rather than its vertical trend) to select the maneuver; if the intruder is below (although climbing) the response is to climb. If the intruder is above (although descending) the response is to descend.

5.5 Efficiency of avoidance maneuvers

The mean absolute vertical and lateral deviations from the assigned flight path were computed for two purposes: the first was to measure the efficiency of the conflict avoidance maneuver; the second was to examine differential tendencies to choose lateral versus vertical deviations. Biases for selecting vertical versus lateral maneuvers cannot be adequately examined from the signed deviations from the flight path (presented in the preceding section), because the position measures are sensitive to right/left and climb/descend strategies. The absolute deviation data, on the other hand, are only sensitive to the magnitude of the vertical and lateral components of the maneuvers.

Figures 28 and 29, as well as Figure 31 suggest a greater use of the vertical dimension by those pilots using the coplanar display than those using either of the perspective formats. However, little support for this observation was found in the results of a MANOVA which included vertical and lateral deviations from the flight path as the dependent variables, and considered each display type as a unique level of the display variable. No covariates were used in this model. The analysis did not reveal a significant effect of display type on the combination of the two dependent variables ($F_{4,52}=1.06$, $p=.38$), however a non-significant trend was observed for vertical deviations ($F_{2,27}=2.01$, $p=.15$). The mean values of the vertical and lateral deviations for the three displays are shown in Figure 32. As seen in Figure 32, the coplanar display led to higher, but more variable values in vertical deviation than either of the two perspective displays. The means for the perspective displays are relatively close to each other in value, particularly on the vertical dimension. A second analysis was undertaken in which the data for the two perspective formats were grouped together, creating a two level display variable in the MANOVA model. This analysis indicated a moderately stronger trend than was found in the three-level analysis for an effect of display on the combination of vertical and lateral deviations ($F_{2,27}=1.98$, $p=.15$). Similarly, a univariate test showed a marginally significant effect of display type on vertical deviations from the flight path ($F_{1,28}=4.12$, $p=.05$), offering somewhat stronger support to the observations drawn from Figure 32 than were found in the previous, three-level analysis. That is, the coplanar display encouraged more vertical maneuvering.

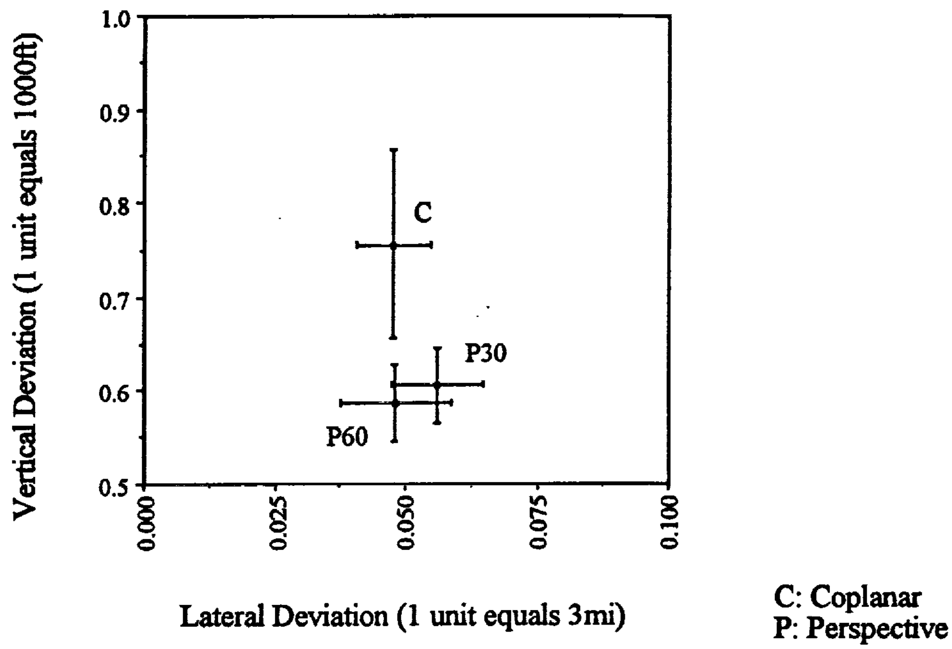


Figure 32. Plot of the mean vertical and lateral deviations from the assigned flight path during avoidance maneuvers. The data are plotted in units of protected zone minimum separation distance to show the relatively greater use of the vertical dimension (i.e., as a function of the protected zone dimensions). Vertical distance is represented in units of 1000ft; horizontal distance is plotted in units of 3 miles (see text).

In addition, a significant three-way interaction was found between the lateral approach angle, vertical approach angle and display condition for the combination of vertical and lateral deviations ($F_{8,21}=2.68$, $p=.03$). Figure 33 depicts this interaction, in which the relationship between the vertical and lateral deviations of the coplanar and perspective displays changes across encounter geometries. Most noticeable in Figure 33 is the shift in the relative deviation values between the two display formats for 90° encounters. This shift is evident in the changing slope of the 90° line from the left panel to the right panel. For encounters in which the traffic was approaching at the same flight level (left panel), the coplanar display fostered relatively greater vertical deviations, and relatively smaller lateral deviations than did the perspective displays. On trials in which the traffic was ascending toward ownship (middle panel), the coplanar format led to greater lateral deviations than with level traffic, although these deviations were still slightly smaller than those initiated in the perspective display conditions. This increase in lateral deviations for the coplanar format was not, however, accompanied by decreased vertical deviations.

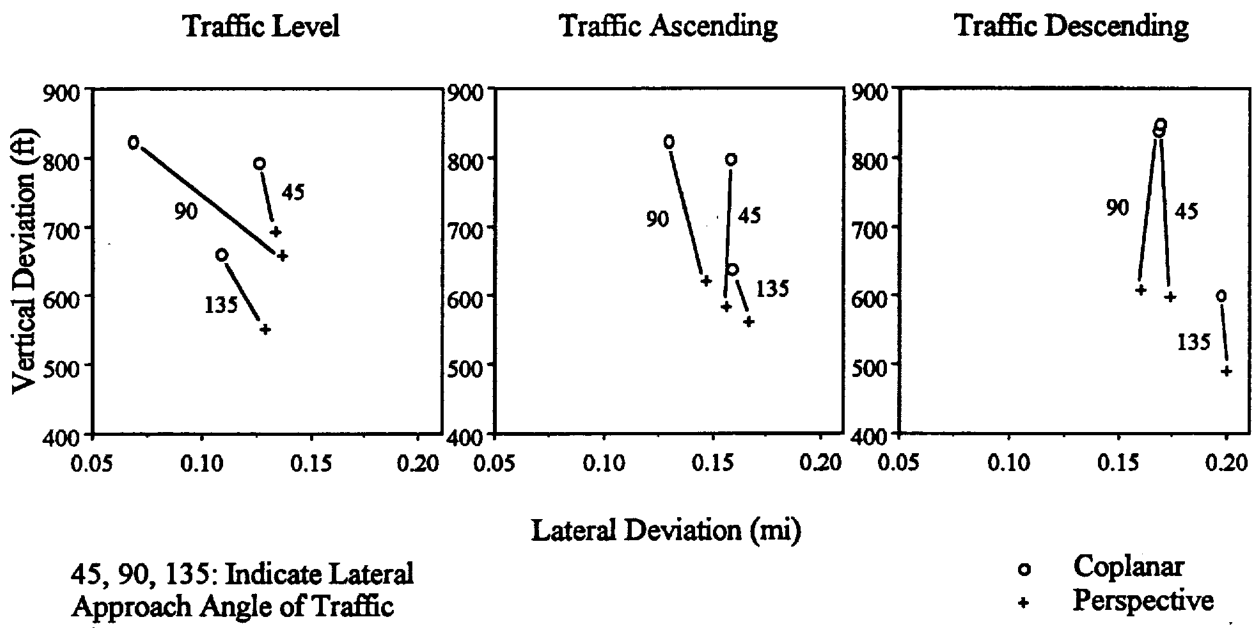


Figure 33. Plot of the mean vertical and lateral deviation data for the coplanar and perspective (grouped) displays. The panels indicate the type of vertical approach behavior of the traffic; the lines connecting data points within the panels describe the lateral approach angle of the traffic (see text).

Finally, on trials in which traffic was descending, the coplanar format led to slightly greater lateral deviations than did the perspective displays. The changing slope of the 90° line across the three panels is in contrast to the 45° and 135° lines representing the relative proportions of vertical and lateral deviations for the coplanar and perspective display conditions. The slopes for the 45° and 135° lines remain relatively consistent across the three panels of Figure 33.

5.5 Proximity to Traffic

An important characteristic of the avoidance maneuver data which is not adequately captured by the conflict rate, position or deviation data is the proximity of the pilots' maneuvers to the traffic. To examine this issue, values were computed for both the mean and minimum distances between ownship and the primary intruder in session one, and between ownship and both aircraft in session two. Data were collected for the horizontal (radial) distance and for the vertical distance between the aircraft. The minimum distance data were computed when the direct, line of sight distance between the aircraft was at a minimum (when the aircraft were closest to each other in three-dimensional space). The two measures were then scaled by the dimensions of the protected zone on their respective axes so that they could be compared. That is, the data for the horizontal distance were divided by the radius of the protected zone (3mi); the vertical data were divided by the minimum allowable vertical separation distance (1000ft). This converted the mean and minimum distance data into units of protected zone distance, which makes interpretation of the data more meaningful when the two dimensions are compared within the same graph, as well as across graphs.

The results of analyses performed on mean distance to traffic data did not reveal any significant main effects or interactions involving display condition. This was not surprising given the large separations between ownship and traffic at the beginning and towards the end of trials. However, several interesting findings were observed in the results from analyses of the minimum distance to traffic data, and will therefore be presented here.

The minimum horizontal and vertical distance between ownship and the primary intruder at closest pass were analyzed together using a MANOVA model which included each of the between subjects factors. The first analysis considered the display variable as a three level factor, in which the two perspective displays represented unique levels of the factor. The session variable and the variable defining whether the traffic passed in front of or behind ownship were not found to interact with the other variables of interest, and were therefore dropped from the model. The resulting analysis did not reveal a reliable main effect of display type on the combination of horizontal and vertical distance at the point of closest pass with the primary traffic ($F_{4,52}=1.22$, $p=.31$). Figure 34 shows the mean values of the two dependent measures for the three display conditions collapsed over the between subjects factors.

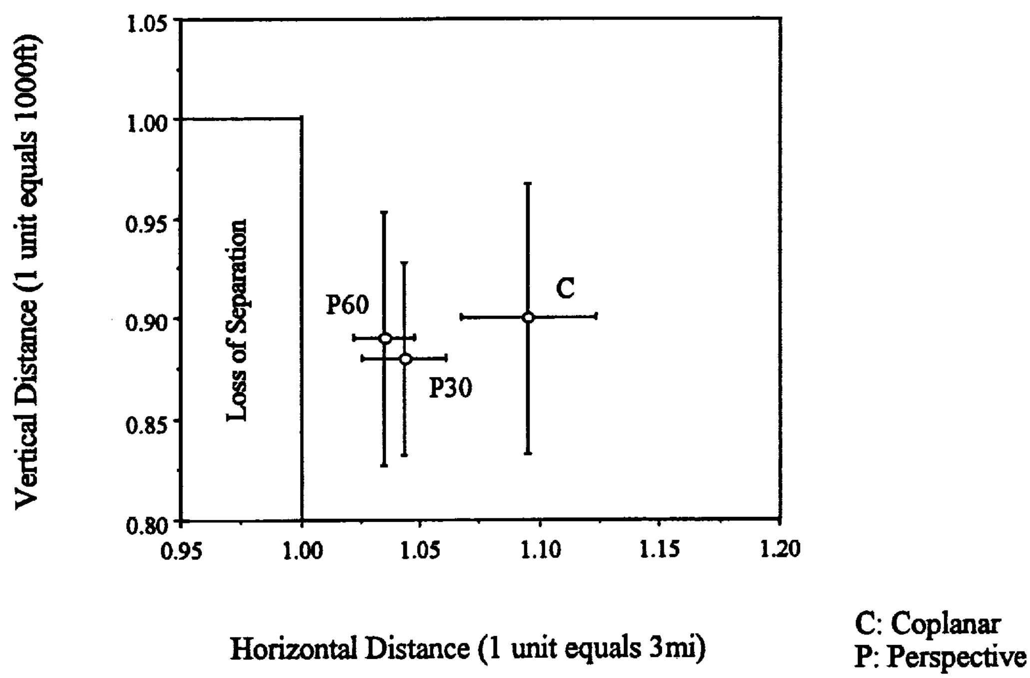


Figure 34. Plot of the mean values for the vertical and horizontal distances between ownship and the primary traffic at the point of closest pass. The data are plotted in units of protected zone minimum separation distances. Note that the range of values on each axis are the same size, but are shifted due to the general bias of maintaining greater separation on the horizontal dimension than on the vertical dimension.

Modest two-way interactions were also found between lateral approach angle and display ($F_{8,48}=1.78$, $p=.10$), and between vertical approach angle and display ($F_{8,48}=1.90$, $p=.08$). These interactions were modified in a follow-up analysis which is described next.

Based on visual inspection of the means from the three level analysis (see Figure 34), which indicate greater differences between the perspective displays and the coplanar format than between the perspective displays themselves, a second analysis was performed in which the two perspective formats were grouped together and compared with the coplanar display (the means for the two-level analysis are shown in Figure 35).

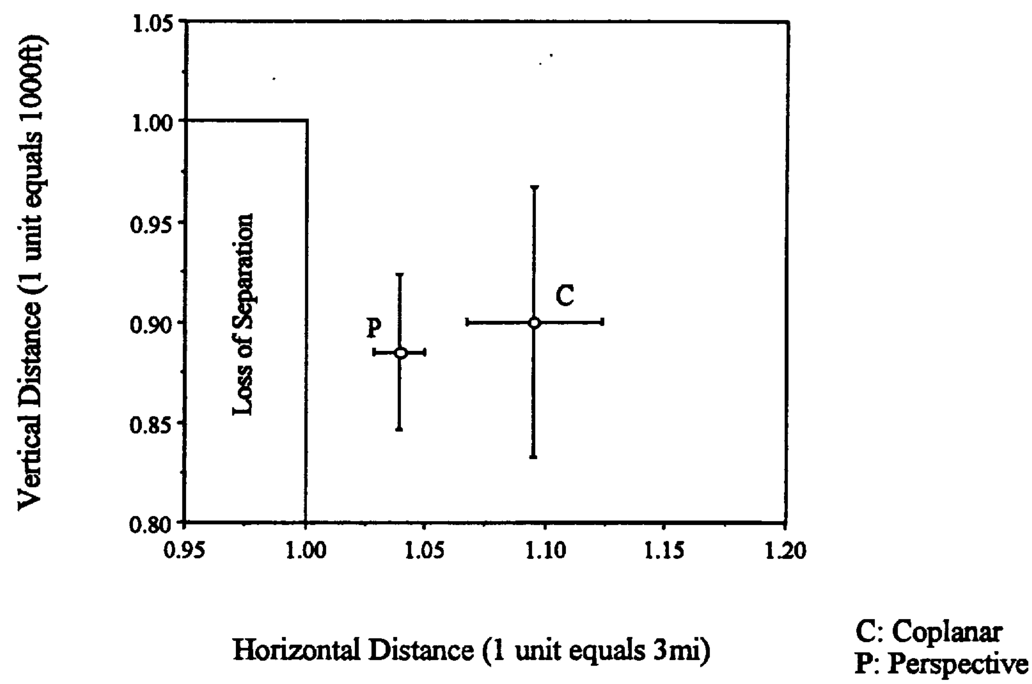


Figure 35. Plot of the minimum distance data for the two-level display variable analysis (i.e., the perspective displays were grouped together), showing the main effect of display on the horizontal separation at the point of closest pass between the aircraft. The region on the left side of the plot indicates insufficient minimum separation values.

This analysis revealed a considerably more reliable main effect of display on the combination of the dependent variables(F 2,27=2.61, p=.09). A univariate test confirmed that the source of the main effect of display was proximity on the horizontal dimension (F 1,28=5.41, p=.03). The coplanar display format supported maneuvers which created greater separation from primary traffic at the point of closest proximity; and this separation was due to a larger horizontal distance between ownship and the traffic.

In addition to the main effect of display, the marginal two-way interaction between the lateral approach angle and display condition observed in the first, three-level MANOVA, strengthened considerably (F 4,25=3.74, p=.02), while the interaction between the vertical approach of traffic and display condition from the first analysis failed to reach statistical significance at the p=.10 level. Figure 36 shows the interaction between display condition and lateral approach angle. Referring to Figure 36, for encounters in which the traffic approached laterally from either 90 or 135 degree angles (i.e., directly from the side, or from the front and side), the coplanar display supported maneuvers which had greater vertical separation from traffic than maneuvers selected in the perspective conditions. The opposite case was true, however, for 45° encounters in which the traffic was approaching from the side, but more closely paralleling the forward path of ownship. In these situations the coplanar format supported maneuvers which had less vertical separation from traffic than did those in the perspective display conditions.

A possible explanation for this interaction could be the effect of perspective distortion (40° geometric field of view) in the two perspective displays (see, for example, Figures 3 and 6). For the perspective displays, traffic which approached from a 45° angle was closer to the center of projection (COP) at the beginning of the trial. Because of the perspective distortion, spatial relationships are expanded as distance to the COP decreases, resulting in increases in the displayed sized of objects in the foreground of the represented space. The symbology associated with traffic approaching from 45° appeared larger at the beginning of a trial than did symbology associated with traffic approaching from 135°. The increased size of the traffic symbology may have induced larger deviations in response. In particular, the yellow bar representing the vertical extent of ownship's protected zone displayed on the vertical reference line of the traffic icon's symbology would appear longer at the beginning of the trial. This could have induced a response in the pilots to ascend or descend more rapidly to avoid the encounter.

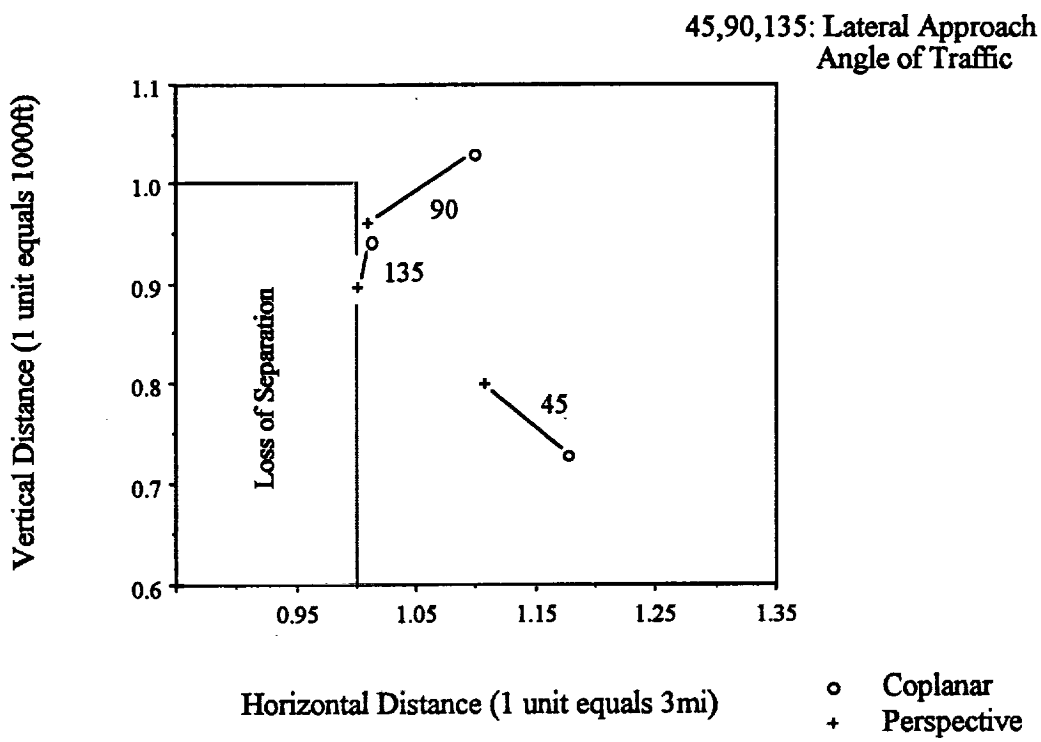


Figure 36. Plot of the mean vertical and horizontal distances between ownship and the primary traffic at the point of closest pass. This figure shows the interaction between the lateral approach angle of the traffic and display condition (the two perspective displays were grouped together for this analysis).

Another possible explanation is the proximity of traffic approaching from 45°. Traffic approaching from this angle was closer to ownship at the beginning of the trial, because it approaches more slowly than traffic on a nearly head-on course. The ambiguity inherent in the perspective displays may have interacted with the proximity of the 45° traffic to induce more extreme maneuvers than those initiated in response to traffic approaching from farther away.

Similar analyses were performed on the data from session two in which the distances between ownship and the second, non-conflicting aircraft were computed. The first analysis considered each of the three displays as a unique level of the display factor, and included the vertical and horizontal distance at closest pass as dependent variables in the MANOVA model. The results from this analysis revealed a moderate effect of display condition on the combination of the two dependent variables (F 4,52=2.48, p=.05). Vertical distance to the traffic made the strongest contribution to the overall effect (F 2,27=5.55, p<.01), while the effect on horizontal separation was substantially weaker (F 2,27=2.34, p=.10). Figure 37 shows the mean values for the vertical and horizontal separation from traffic at the point of closest pass. The data in Figure 37 show that each display format supported maneuvers which created greater separation on the vertical axis than on the horizontal axis (note the values on the ordinate and abscissa). However, the coplanar display fostered maneuvers which maintained substantially greater vertical separation, and somewhat less lateral separation between ownship and the second aircraft in session 2, than did either of the perspective displays. A noticeable difference between the two perspective displays on the vertical dimension is also evident. A post hoc test comparing the two perspective displays offered some evidence for this observation (F 1,27=2.98, p=.10). The differences between the displays in the vertical and lateral separation from traffic are in contrast to the data on the separation from the primary traffic (Figures 36, 37). While the coplanar display supported relatively greater lateral separation from the primary traffic than did the perspective displays, it supported relatively greater vertical separation from the secondary traffic.

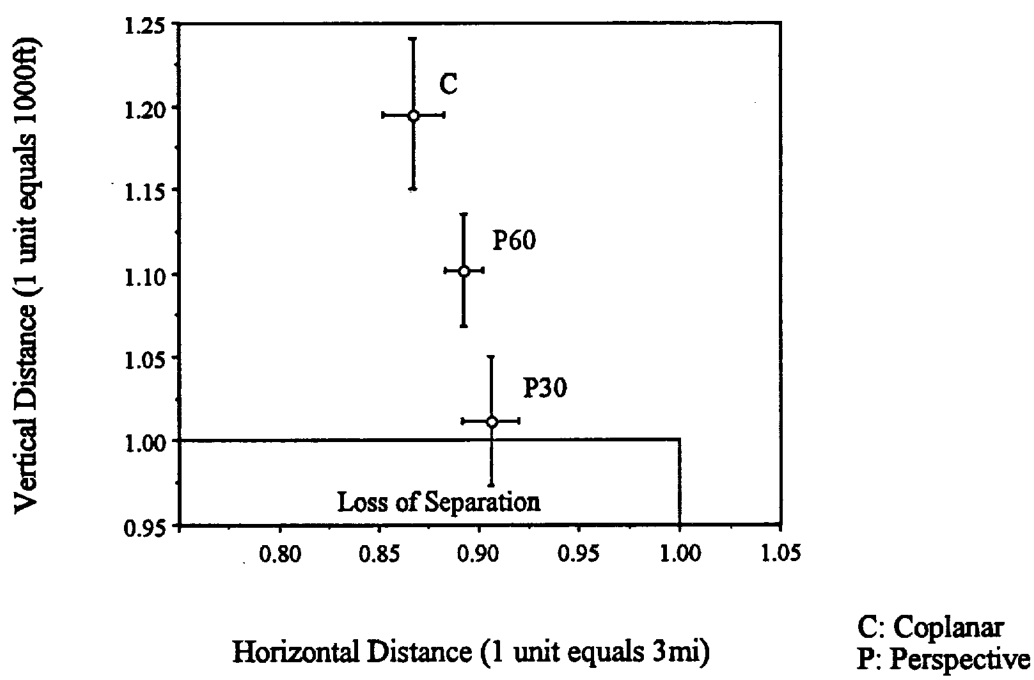


Figure 37. Plot of the mean vertical and horizontal separations at the point of closest pass between ownship and the second, non-conflicting aircraft in session 2. Axes are plotted in units of minimum allowable separation (see text). The region on the bottom of the plot indicates insufficient minimum separation values. Note that the range of the two axes are the same size, but represent different regions on the dimensions.

In addition to the main effect of display, a significant two-way interaction was also found between display type and the vertical approach behavior of the primary traffic ($F_{8,48}=2.39$, $p=.03$). This interaction can be seen in the two graphs in Figure 38. The left panel in Figure 38 shows the relationship between the three display conditions on the dependent measures for trials in which the primary traffic was approaching from the same flight level. While all of the display conditions fostered maneuvers which created greater horizontal separation than vertical separation from the secondary traffic, the perspective displays supported maneuvers which maintained relatively larger vertical separations from the secondary traffic than did maneuvers generated in the coplanar display condition. The absolute differences were small, however, due to the placement of the secondary traffic on trials which contained primary traffic approaching from the same flight level. The coplanar format led to somewhat greater horizontal separation than did the 30° display, and slightly greater separation than did the 60° display. This relationship changed dramatically for trials in which the primary traffic was either ascending or descending toward ownship.

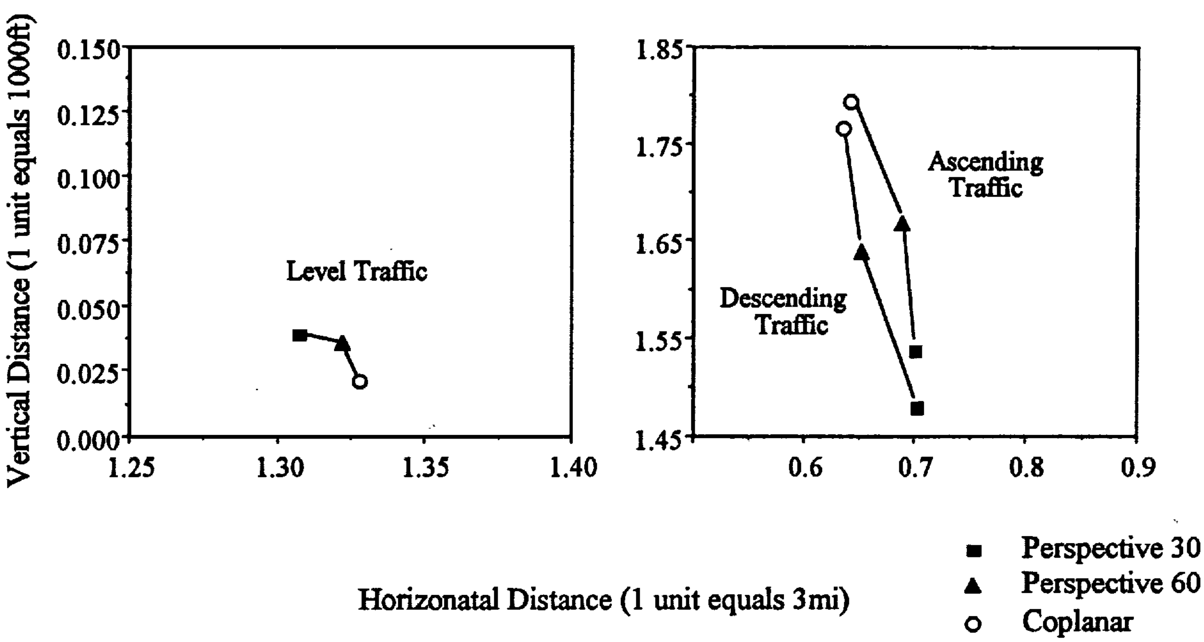


Figure 38. Plot of the mean values of vertical and horizontal separation at closest pass with the secondary traffic in session 2. The data indicate an interaction between display condition and the vertical approach behavior of the primary traffic. Note that the scales of the axes in the two plots are different. However, the range of the vertical and horizontal axes are the same size within each plot, so that line slopes can be compared across plots.

First, referring to the axes on the right panel of Figure 38, all of the displays supported maneuvers which created greater vertical than horizontal separation, reversing the relative balance of vertical and horizontal separation seen in the left panel of Figure 38. The coplanar format, however, contributed to this reversal to a greater extent than did the two perspective displays. This is evident in the relative positions of the data points in the right panel of Figure 38. The coplanar display, which supported relatively smaller vertical separation from the secondary traffic when confronted with a level intruder, fostered greater vertical separation than did the perspective displays on trials which involved ascending or descending primary traffic.

5.6 Subjective Workload Ratings

After completion of each experimental session, pilots provided ratings on the level of subjective workload experienced performing the task using the NASA TLX scale. These data were submitted to a 3 (display) X 2 (session) mixed within-between ANOVA model. The results of the analysis revealed a significant effect of session (F 1,27=14.35, $p<.001$). This effect is apparent in Figure 39, which shows the mean ratings for the 3 display types in sessions 1 and 2. Each of the 3 display groups reported higher workload ratings in session 2 than in session 1. A trend is also visible in the ordering of the means for the 3 display types. The coplanar display had the lowest mean workload ratings, followed by the 30 degree perspective display, with the 60 degree perspective display associated with the highest workload ratings. This trend, however, did not represent a statistically significant effect (F 2, 27=1.86, $p=.18$). The addition of a relatively highly correlated covariate did not reduce the error variance in the model enough to overcome the loss of 2 degrees of freedom, and therefore is not reported here. However, the non-significant trend shows a similar ordering of the three displays to that seen in the proportion of predicted conflict data described previously (see Figure 24), and the means for the two perspective displays are relatively close to one another as compared to the means for the coplanar format. A second test was then performed in which the coplanar format was compared to the combined data for the perspective displays. The results of this comparison indicated a marginally significant difference between the coplanar and perspective displays (F 1,28=3.64, $p=.067$).

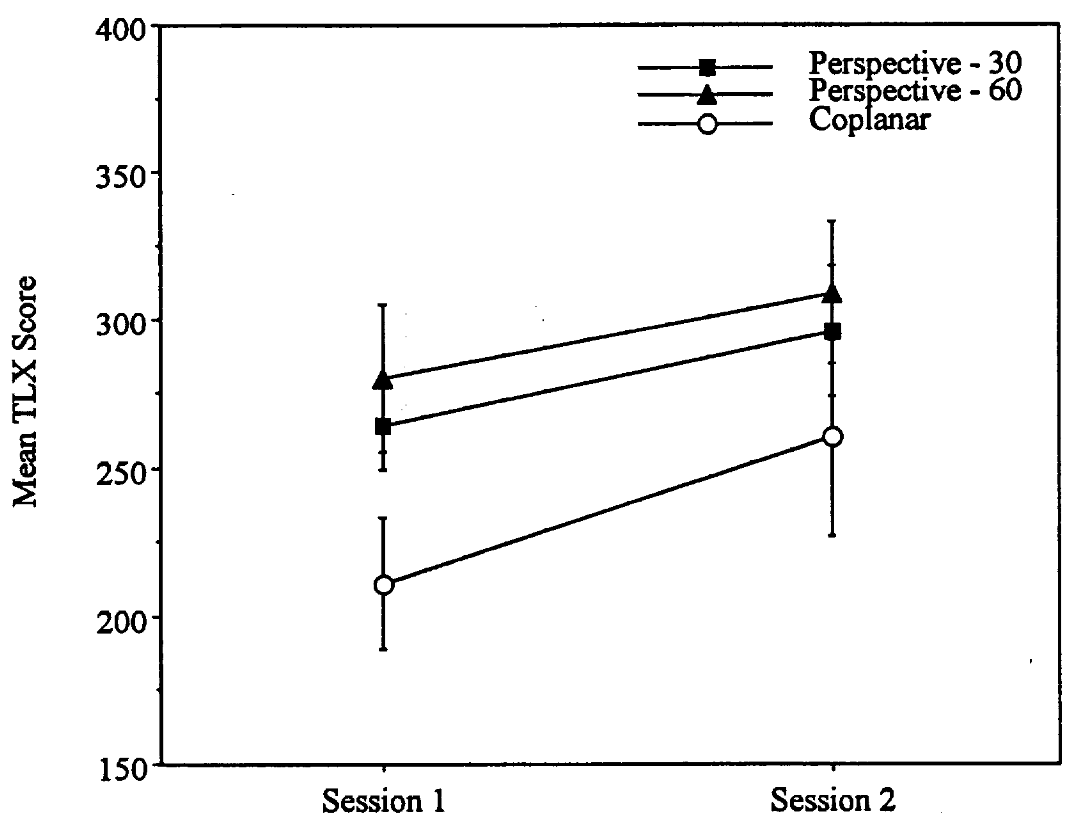


Figure 39. Plot of the mean subjective workload ratings collected using the NASA TLX rating scale. The means represent sums of the unweighted scores on the individual dimensions of the TLX scale.

5.7 Global effects of traffic approach geometry

The primary focus of the current work was to examine the influence of display factors, including the main effects of display format and the interactions between display format and the non-display factors (i.e., approach geometry, number of aircraft). However, our results also speak to some general maneuver tendencies exhibited by the pilots in all of the display conditions.

Several of the factors defining the approach geometry of the traffic encounters influenced the pilot's maneuvering strategies as well as their objective performance. Specifically, the frequency of actual conflicts with the primary traffic varied with traffic's lateral approach angle (45°, 90°, 135°), approach direction (from the left or the right side) and relative position at the programmed point of closest pass (ahead, behind ownship). The effect of lateral approach angle is evident in Figure 40, which shows the mean rates of actual conflicts for the three lateral approach angles ($F_{2,27}=3.61$, $p=.040$). The 135° approach angle in which the intruder is approaching from the front was the most difficult as evidenced by its high conflict rate; the 45° angle (rear quarter) was associated with the lowest absolute conflict rate, while the 90° approach angle resulted in an intermediate level of performance. The relative difficulty of the 135° approach angle is possibly due to the high closure rates associated with its more 'head-on' approach; the closure rates were lowest in the 45° encounters.

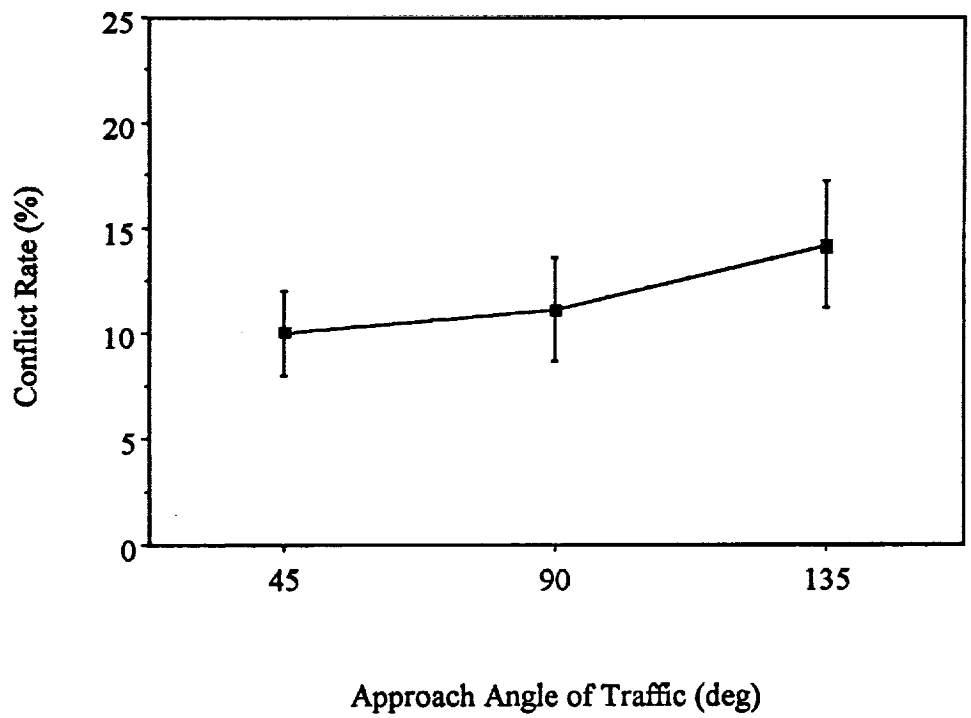


Figure 40. Plot of the mean actual conflict rates for the lateral approach angles of the primary traffic summarized over the display formats.

The approach direction of the traffic also influenced the pilots' ability to avoid loss of separation ($F_{1,28}=6.35$, $p=.017$). Figure 41 shows the mean conflict rates for trials in which the traffic approached from the left and the right. As is evident in Figure 41, trials in which the traffic approached from the left were more difficult than those in which traffic approached from the right. A possible explanation is the tendency of the pilots to favor maneuvers to the right (see below), which would prevent turn-behind maneuvers in some situations. The turn-right tendency is likely due to the influence of FAA regulations which stipulate right-turning avoidance maneuvers in response to head-on traffic, and has been observed in other traffic avoidance simulation paradigms (Beringer, 1978).

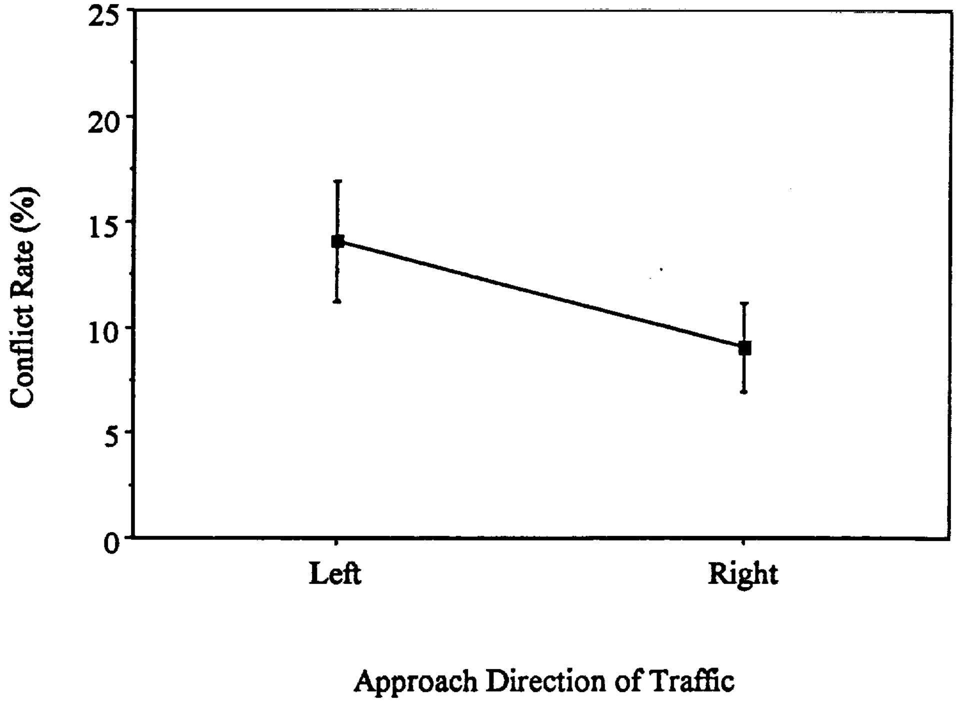


Figure 41. Plot of the mean actual conflict rates for the approach direction of the primary traffic summarized over the display formats.

The position of the traffic at the point of closest pass, ahead or behind ownship (assuming no corrective action was to be taken) exhibited a moderate influence on the pilots' ability to avoid conflicts ($F_{1,28}=3.78$, $p=.06$). Figure 42 shows the mean rates of conflicts for 'ahead' and 'behind' encounters. As can be seen in Figure 42, encounters in which the traffic would pass ahead of ownship resulted in poorer performance than did those trials in which traffic would pass behind . The maneuvering tendencies for ahead and behind encounters were dramatically different (see Figure 43 below), suggesting a possible source for the performance differences.

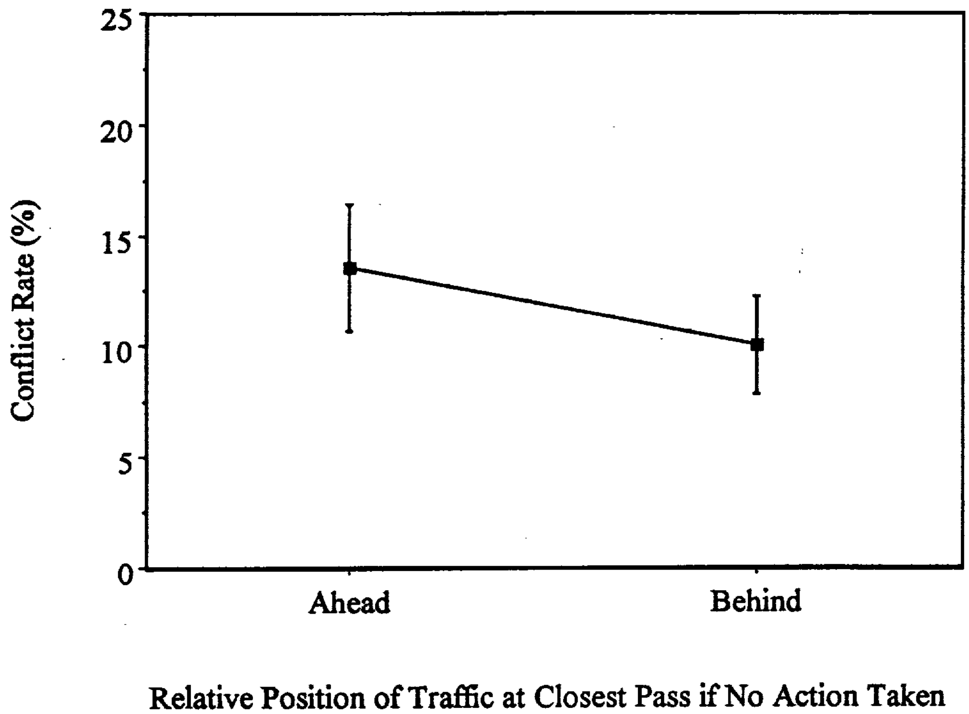


Figure 42. Plot of the mean actual conflict rates for the relative positions of the primary traffic at the point of closest pass, summarized over the display formats.

Figure 43 shows the mean lateral and vertical positions of ownship for the four combinations of left, right, ahead and behind encounters. The two factors exhibited main effects on the vertical and lateral position of ownship (direction: vertical [$F_{1,27}=4.58$, $p=.04$], lateral [$F_{1,27}=8.82$, $p=.006$]; relative position: vertical [$F_{1,27}=43.94$, $p=.0001$], lateral [$F_{1,27}=3.96$, $p=.056$]), and interacted to affect ownship's lateral position ($F_{1,27}=14.34$, $p=.001$). Several interesting patterns are evident in Figure 43. First, maneuvers initiated in response to ahead encounters are sensitive to the direction from which the traffic is approaching, clearly indicating a strategy of turning toward, and then behind the intruder which would then pass safely in front of ownship, a technique which was generally quite effective in creating increased separation as the trial progressed. Additionally, the ahead encounters were associated with a moderate bias to remain near the command altitude or to descend slightly. Behind encounters, however, do not elicit this response, but rather appear to induce predominantly vertical climbing maneuvers. Finally, there seems to be a general tendency to maneuver to the right, a finding which echoes the results of Beringer (1978), and likely reflects FAA rules to turn right when faced with head-on encounters.

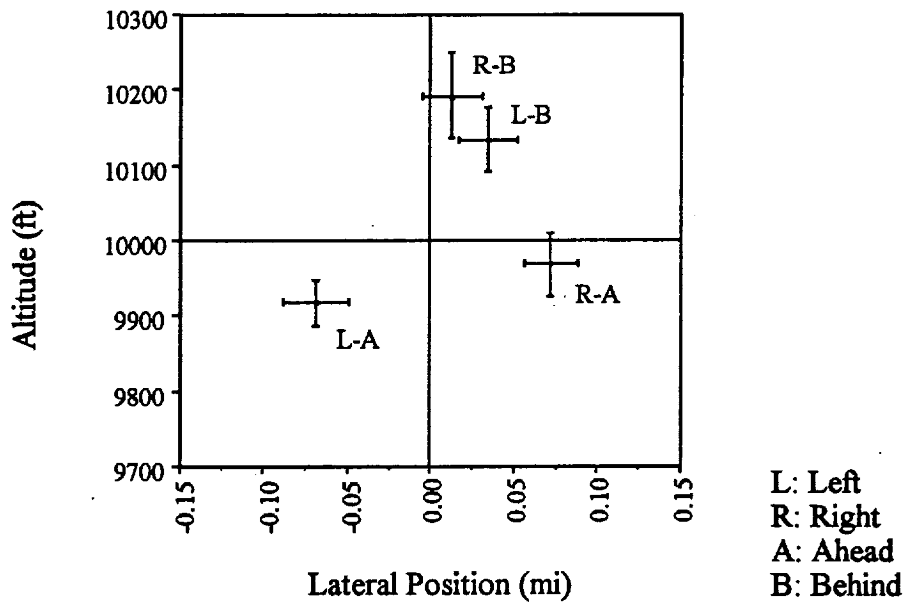


Figure 43. Plot of the mean vertical and lateral position of ownship during conflict trials summarized over the display conditions.

6 DISCUSSION

A number of mechanisms, which were summarized in the hierarchical task description presented in Figure 11, were hypothesized to affect various task elements in the current experiment. Evidence for the nature of the influence these mechanisms might exert on performance in the display conditions tested here was offered in the discussion of previous research which has examined the use of perspective, planar and coplanar formats in a variety of task domains. Collectively, the previous work has produced ambivalent results, primarily because of the wide variety of experimental paradigms and display techniques used. While it has been shown that perspective formats can support better performance than planar formats in some instances, perspective displays often induce unwanted perceptual biases (e.g., Ellis, McGreevy and Hitchcock, 1987; McGreevy and Ellis, 1986; Barfield, Hendrix and Bjorneseth, 1995). Furthermore, the few studies which have directly compared perspective and coplanar formats have found conflicting results (e.g., Wickens, Merwin and Lin, 1994; Jasek, Pioch and Zeltzer, 1995). The findings of the current experiment provide further evidence for the mediating influence the factors identified in Figure 11 can have on the performance of tasks requiring the judgment of three-dimensional positional relationships in spatial information instruments. The following discussion is organized by the major influencing factors which appear to have affected, either positively or negatively, performance on the dependent variables in the current paradigm.

6.1 Perspective Ambiguity and Orthogonal Precision

The ambiguity of positional information inherent in perspective display formats has been shown to adversely impact performance in a variety of tasks, particularly when monocular depth cues are used exclusively to support depth judgments (Wickens, Todd and Seidler, 1989; Wickens, 1995; McGreevy and Ellis, 1986; Barfield, Hendrix and Bjorneseth, 1995). In the current paradigm, perspective ambiguity was hypothesized to negatively impact the perception of spatial relationships between traffic and ownship, thereby impairing the evaluation of critical separation parameters necessary to determine if maneuvers would be required to maintain safe separation (letter d in Figure 11). The relative performance levels observed in the perspective and coplanar conditions on several of the dependent measures suggests that perspective ambiguity likely played a role in the current paradigm.

Conflict detection. Taken together, the findings from the conflict detection task show that the coplanar display supported better performance than did the perspective displays. The coplanar format fostered higher detection rates than did the 60° display; higher sensitivity, as measured by A-prime, than did the 30° display; and did not induce more false alarms than did either of the perspective displays. Unlike the findings reported by Wickens and Prevett (1995) and Wickens et. al. (1995), the greater accuracy supported by the coplanar display was not purchased at the cost of increased latency. The coplanar display supported decision times which were as fast as those observed for the two perspective displays on conflict trials, and faster than those found for the 60° display on non-conflict trials.

The most probable source of the performance differences found in the conflict detection data is ambiguity in the perspective displays, which likely impaired the accurate judgments of future position of the traffic with respect to ownship (i.e., the positions of the predictive reference lines). This explanation is supported by a growing collection of research which has found inaccurate performance in tasks which require the estimation of position along one or more spatial axes from an exocentric viewpoint using monoscopic perspective displays (McGreevy and Ellis, 1986; Tharp and Ellis, 1990; Kim et al., 1987; Barfield and Rosenberg, 1995; Wickens, 1995b,c; Wickens and May, 1994; Yeh and Silverstein, 1992; Boyer et al., 1995). According to this justification, the uncertainty created by the ambiguous judgments of depth relations fostered the relatively higher false alarm rates observed in the 30° display condition, while also contributing to the relatively lower detection rate found for the 60° display. Why the ambiguity in the two perspective display formats affected performance in different ways (i.e., increased false alarm rates for the 30° display, and decreased detection rate for the 60° display) is not entirely clear. It is possible that pilots in the two perspective conditions used different criterion settings in making their judgments, and that these differences resulted in the observed patterns. The criterion measure Beta was estimated for each of the three display groups, and did indicate absolute differences between the displays (.20 for coplanar; .29 for 30°; .37 for 60° perspective). The two perspective groups were found to have different criterion settings based the values of Beta, but whether these differences were the cause or the effect of performance levels is impossible to determine. Also, issues regarding the difficulty in analyzing the measure Beta caution against drawing conclusions from it (Parasuraman, 1986).

An alternative explanation for the differences observed between the two perspective formats is that the different elevation viewing angles in the two perspective conditions modulated the ambiguous depth relations in the displays; a factor which is suggested by the results of Yeh and Silverstein (1992), and Barfield, Hendrix and Bjorneseth (1995). The 30° display compressed the longitudinal axis more than the vertical axis, while the opposite relationship was true for the 60° display. These differences, however, did not interact with the approach geometry of the traffic to affect performance in the detection task, suggesting that the ambiguity present in both displays impacted detection performance in similar ways. The supporting symbology which indicated horizontal position and relative vertical position could have mediated the influence of the line of sight ambiguity such that uncertainty on the compressed axis was reduced by the supporting symbology (i.e., the relative altitude symbols reduced the vertical ambiguity in the 60° display, while the reference lines' intersections with the floor grid reduced longitudinal ambiguity in the 30° display condition). Therefore, the contrast in performance between the perspective displays and the coplanar format suggest that the ambiguity in the perspective formats was not sufficiently compensated by the monocular depth cues available (e.g., linear perspective, relative size, height in the visual field), to support spatial judgments that were as accurate as those observed in the coplanar format. However, the detection data do not effectively discriminate between the two perspective displays for different types of traffic encounter geometries, and therefore, do not offer insight into the differential effects that line of sight ambiguity might have exerted on the 30° and 60° elevation viewing vector conditions.

The results of the detection task are in contrast to findings reported by Wickens et al. (1996), in which planar and perspective air traffic control displays were compared in their ability to support a number of tasks, including conflict detection. Their results showed no differences between the display formats. The planar display used in their study, however, did not include a second planar panel showing the vertical dimension in an analog-graphical format, but coded altitude data alphanumerically. Results from a similar experiment by Wickens et al. (1993) indicated no substantial differences between planar and perspective displays, although altitude data were also coded alphanumerically. However, Boyer and Wickens (1994) did compare a coplanar format with a perspective display in a task which required the planning of maneuvers around weather phenomena. Their results, consistent with those reported here, indicated more efficient routing in the coplanar display format, although no other differences in performance between the two displays were observed. The pattern of results in the current study are also in agreement with the findings of Jasek, Pioch and Zeltzer (1995), in which coplanar display formats supported better conflict detection performance than did a number of different perspective displays.

Given these previous findings and the results from the current experiment, there appears to be an advantage in conflict detection for coding the vertical axis in the analog-graphic display code of linear extent, over using an alphanumeric code superimposed on the X-Z plane. This conclusion is based on the relative advantages seen for coplanar displays over perspective formats (e.g., the current study; Jasek, Pioch and Zeltzer, 1995), as compared to the results from studies which found no better, or worse performance for planar-alphanumeric formats with respect to perspective displays (e.g., Wickens, 1995; Wickens et al., 1995; Ellis, McGreevy and Hitchcock, 1987). Considering the results from the previous research and the findings from the present study, it is clear that the detrimental effects of perceptual ambiguity are not always apparent when compared to performance using a planar display in which the vertical dimension is coded alphanumerically. The incompatible display codes used in the planar-alphanumeric displays could have reduced performance to levels below those observed for perspective displays (Ellis, McGreevy and Hitchcock, 1987; Wise, Garland and Guide, 1993). By comparing perspective displays to coplanar formats in the present study, the disadvantage of incompatible display codes inherent in the planar-alphanumeric format was eliminated, thereby allowing the relative advantage of precise judgments on compatibly coded dimensions to support higher levels of performance with respect to the perspective displays.

Further evidence for the effects of perspective ambiguity were observed in the data which define how successful pilots were in maintaining separation from the conflicting traffic. The two measures collected which indicated the success of the avoidance maneuvers were the rates of predicted and actual conflicts. Predicted conflicts are distinguished from actual conflicts in that the former indicate that an actual conflict will eventually occur within 45 seconds if no changes in the flight parameters are made, but that an actual conflict is not occurring at the present time. Actual conflicts occurred when separation between the aircraft was simultaneously less than 1000ft vertically and 3mi horizontally. The pilots were informed that they should avoid both predicted and actual conflicts, but that actual conflicts were to be avoided at all costs.

The results of the analysis of these data show a clear advantage for the coplanar display for avoiding predicted, but not actual conflicts with the primary conflicting traffic (see Figures 24 and 25). A similar advantage was found for predicted and actual conflicts with the second, non-conflicting aircraft in session two (Figure 26). The coplanar format supported better performance than did the 30° perspective display for both predicted and actual conflicts, but the coplanar display fostered better performance than did the 60° format for predicted conflicts only. These results, like those observed in the conflict detection data, are in contrast to the findings of Ellis, McGreevy, and Hitchcock (1987), and Wise, Garland, and Guide (1993); two experiments which used planar-alphanumeric formats. The current data are, however, in agreement with the results of Jasek, Pioch, and Zeltzer (1995), a study in which coplanar displays were compared to perspective formats.

Additional evidence for the effects of ambiguity caused by the compression of the vertical axis in the perspective formats is suggested by the secondary conflict data, where an interaction between the vertical approach behavior of the primary traffic and the display condition was found (Figure 27). The display formats differed in the percentage of actual conflicts with the second aircraft, but only on trials in which the primary intruder was either climbing or descending toward ownship. On these trials, the 30° display fostered more actual conflicts with the second aircraft than did the 60°, and particularly, the coplanar display. Again, a probable explanation for the relative advantage of the coplanar display over the 30° perspective display, is the difference in altitude representation in the two formats. The vertical trend of the primary intruder was unambiguously displayed on the orthogonally projected X-Y panel of the coplanar display by the slope of the intruder's predictive vector. Accurate vertical trend information could not, however, be obtained from the slope of the predictive vectors in the perspective displays (because of the integration of the axes) if the linear perspective and relative size cues present in the displays were not sufficient to support veridical perception of the predictive vector's slope in three-dimensional space (i.e., because of ambiguous mappings of position on the three axes). Although the supporting display symbology indicating the extent of ownship's protected zone in the vertical dimension was located on the current and future vertical reference lines (yellow regions on the posts), these two symbols have to be compared to ascertain the vertical trend of the intruder. Assuming that this comparison process must be made to accurately obtain the vertical trend of the traffic, then it is reasonable to suggest that judgment of the vertical trend would be either slower, less accurate or both in the perspective displays than in the coplanar format. Such vertical trend extraction is unnecessary when the encounter aircraft is flying level.

What is less clear is the reason for noticeably different levels of performance in the two perspective conditions in Figure 27. It was expected that due to the greater compression of the vertical axis in the 60° display than in the 30° display, resolution of fine differences between objects in the vertical dimension would be more ambiguous in the 60°, than in the 30° display (Yeh and Silverstein, 1992; Barfield and Rosenberg, 1995; Rosenberg et al., 1995). However, the extent of the influence of vertical axis compression could have been reduced by the inclusion of the supporting symbolic elements (i.e., the yellow regions on the references lines indicating the altitude of ownship), as well as the presence of the depth cue of relative size. The findings from both the altitude separation data between ownship and the second aircraft (Figure 38), and the conflict rates with the second aircraft (Figure 27) show clearly that the 60° display supported more, and more effective separation from the second aircraft on trials which involved climbing or descending primary traffic.

The conflict avoidance data are in similar agreement with the detection results. Again, there are advantages for the coplanar format, and mixed results for the perspective displays. These findings are in contrast to the results reported by Ellis, McGreevy, and Hitchcock (1987) and Wise, Garland, and Guide (1993), in which perspective displays supported better performance than that observed in planar-alphanumeric conditions; however the findings here are consistent with the results of Jasek, Pioch and Zeltzer (1995) who employed the coplanar technique. As was discussed with respect to the detection data, here again a probable explanation for the differences in the findings of the two experiments is the addition of the X-Y panel in the current study, which coded altitude data analogically. Following this logic, the analog-graphical code of linear extent supported more efficient processing of the vertical relationships or trends between the aircraft, than did the alphanumeric code used in the planar display of Ellis, McGreevy, and Hitchcock (1987).

In summary, the relatively lower levels of performance observed in the perspective conditions with respect to the coplanar format, on the dependent variables which measured pilots' abilities to successfully detect and avoid traffic conflicts indicates that the perspective displays did not support judgments of spatial relationships which were as precise as those made in the coplanar condition. Based on the evidence offered by previous work on the perception of spatial information presented in monoscopic perspective displays, and the nature of the pattern of results discussed above, it is likely that the ambiguity caused by the integration of the three axes was the source of the performance costs associated with the perspective displays.

6.2 Perspective-induced Biases: Perceived Vertical Expansion and Occlusion

In addition to ambiguity in perspective formats, two other factors identified in Figure 11 which may have contributed to effects observed in the current results are the tendency to overestimate differences in the vertical separation between objects, and the inherent problem of superimposition of symbology, or occlusion. Previous work has shown that the compression of the vertical axis in perspective displays results in a perceived expansion of the vertical dimension when viewing vector elevation angles are substantially greater than 0° (e.g., Barfield, Hendrix, and Bjorneseth, 1995; McGreevy and Ellis, 1986). Furthermore, the impact of occluding symbology is potentially quite detrimental to the process of accurately judging spatial relationships in the current paradigm, both in terms of identifying the presence of conflicting targets, as well as maintaining separation while performing avoidance maneuvers. The influence that these two factors may have had on the selection of avoidance maneuvers in the perspective conditions is discussed below in the context of the dependent measures which characterized avoidance maneuver strategies.

Equally important to the critical performance measure of maintaining separation from conflicting traffic, is how the three displays mediated the selection and performance of different types of maneuvers when pilots were confronted with a variety of conflict scenarios. The findings of Ellis, McGreevy, and Hitchcock (1987), which showed that a perspective display format supported greater use of vertical maneuvering and an equal amount of lateral maneuvering to avoid traffic, relative to a planar display which used alphanumeric coding for the vertical dimension, were not replicated in the current study. The conflicting results, however, are not surprising given that the vertical dimension was coded alphanumerically in the study by Ellis, McGreevy, and Hitchcock, while altitude information was represented in an analog-graphic format in the current experiment. While all of the display formats in the present experiment fostered even greater use of the vertical than horizontal dimension (i.e., as a proportion of protected zone units; see Figure 32), when the data from the perspective displays were grouped together and compared to the data from the coplanar display, a marginally significant effect on vertical maneuvering was found; the coplanar display fostered greater use of the vertical dimension than did the perspective displays (Figure 32). These results are also in contrast to the findings of Wise, Garland, and Guide (1993), in which pilots selected more vertical maneuvers to avoid obstacles when using a perspective display, than when using either a 2D paper or 2D electronic map. Again, the presence of the X-Y plane explicitly showing a graphical analog representation of the vertical dimension in the current experiment is the probable reason for the additional vertical maneuvering in the coplanar format in the present study. Considering the results of Ellis, McGreevy, and Hitchcock (1987), Wise, Garland, and Guide (1993), and the findings reported here, it appears that perspective formats support more vertical maneuvering only when compared with displays which code altitude data alphanumerically or with symbolic icons. The current study suggests that an analog representation of linear extent, even if it is not integrated spatially with the other axes, can support more vertical maneuvering than a perspective format in a traffic avoidance simulation.

It is relatively clear why the coplanar display supported effective vertical maneuvering in the present study, but it is somewhat surprising that it fostered greater use of the vertical dimension than did the perspective displays (Figure 32). A possible source of this effect is the well-known bias to overestimate differences in the vertical dimension of perspective displays when viewing from an exocentric viewpoint (McGreevy and Ellis, 1986; Barfield and Rosenberg, 1995; Barfield et al., 1995; Wickens, Todd, and Siedler, 1989). In the current study, this bias (which leads to a perceived expansion of the vertical dimension) may have caused pilots to believe that they had gained or lost more altitude, or that they had provided more vertical separation between themselves and the traffic, than they actually had. The coplanar display did not induce this perceptual bias because the X-Y panel was projected in parallel, and therefore would not have led to the overestimation of relative altitude differences prevalent in perspective projections. This explanation is consistent with the data for vertical separation from the second aircraft at closest pass shown in Figures 37 and 38. On trials which had vertically maneuvering primary intruders, the two perspective displays (and the 30° display in particular) supported maneuvers which provided less vertical separation from the second aircraft than did maneuvers in the coplanar condition, as if pilots overestimated their vertical separation with the perspective displays.

In addition to the vertical and horizontal avoidance preferences, we were also interested in the signed deviations from the flight path which indicate whether pilots were biased to avoid to the right or left, or use climbing versus descending maneuvers to resolve conflicts. The results of the analyses on these position data revealed a number of interesting patterns. The two perspective displays supported maneuvers which differed substantially in the vertical dimension (Figure 30; left panel of Figure 31). Referring to the left panel of Figure 31, when faced with traffic approaching from the same flight level, the 60° display fostered maneuvers whose mean altitude was higher than the original flight path, indicating a preference to fly over traffic. The 30° format, however, supported maneuvers which had a mean vertical position lower than the flight path, signaling a preference to fly under traffic.

The descending maneuver bias observed in the 30° format was probably caused by an increased likelihood of overlapping or occluding symbology when ascending maneuvers were initiated. Display elements that are beyond ownship on the longitudinal axis (i.e., farther from the viewer along the depth axis) and that are at the same altitude, appear higher than ownship on the display screen because of the perspective parameters which support the depth cue of height in the visual field (Figure 15). However, if the pilot ascends to an altitude greater than that of the traffic in front of ownship, the symbolic icons representing the two aircraft could align along the line of sight viewing vector, creating an occlusion or superimposition of the two aircraft icons. This could be avoided by using a descending maneuver, which would cause the traffic icon to remain above the ownship icon on the display until the two aircraft had passed each other. The 60° elevation viewing angle would not have supported this descending bias because the more top-down view of the 60° format created occluding situations only when ownship was nearly directly above or below a traffic icon (Figure 16). Therefore, there would be little advantage to attempt to avoid an occlusion with a vertical maneuver; rather, horizontal maneuvers would offer a better opportunity to avoid such an occlusion.

The ascending bias of the 60° display could be related to the relatively greater compression of the vertical axis than was present in the 30° condition. Two results of a climbing maneuver in the perspective formats are an elongation of the vertical reference lines of the traffic icons, and a relatively higher position of the yellow, ownship-altitude regions located on the traffic icons' vertical reference lines. Because of the greater y-axis compression in the 60° format, the vertical reference lines are contracted so that precise judgments of vertical position are difficult (see Figure 16). Thus, the judgment of the relative vertical positions of the intersection of the traffic's predictive vector with its vertical reference line, and the yellow ownship-altitude region on the reference line (a critical element of the task of predicting future altitude separation), was likely impaired relative to similar judgments made with the 30° display.

The ability to make these judgments could have been improved by initiating a climbing maneuver which extends the length of the traffic's vertical reference lines. The reason for this is found by noting what happens to the vertical reference lines of the traffic icons when ownship is at a higher altitude. The yellow segments on the traffic's vertical reference lines extend above the traffic's predictive vectors. This makes it easier to assess the relative positions of the ends of the predictive vectors and the associated yellow segments on the vertical reference lines because an additional cue can be used to make the judgment (i.e., the length of the line segment which extends above the point of intersection between the predictive vector and the vertical reference line). Provided that the length of the protruding line segment is greater than the length of the yellow region, the traffic is positioned at least 1000ft below ownship. The additional cue of the protruding section of the vertical reference line is not available when ownship is below traffic. In these cases, the only method to unambiguously determine vertical separation is to compare the color boundaries on the reference line with the intersection point of the predictive vector, which is made more difficult by the greater compression of the vertical reference lines in the 60° display with respect to the 30° format.

A related pattern of maneuver biases is seen in the strong interaction between the vertical approach behavior of the traffic and display format (Figure 31). In response to ascending traffic, the coplanar display supported more descending maneuvers, while the two perspective displays fostered maneuvers which tended to have more ascending components. A similar pattern is seen in the data for descending traffic, in which the coplanar format encouraged more ascending maneuvers, while the perspective displays led to more descending maneuvers. This pattern can be explained by the different ways in which vertical trend information was obtained from the display formats.

As was described above, the coplanar format provided an unambiguous, single source for vertical trend information (i.e., the slope of the traffic's predictive vector). Perception of the slope of predictive vectors in the perspective displays was not necessarily veridical because of the projection of three-dimensional information onto the 2D display plane. To the extent that the depth cues of linear perspective and relative size did not disambiguate the slope of the predictive vectors, pilots would have had to compare two sources of relative altitude information to obtain accurate slope estimates (i.e., the yellow regions on the vertical reference lines and the intersection point of the predictive vectors with the reference lines; see Figures 14 and 15). It is reasonable to assume that vertical trend information was not as readily available in the perspective displays as in the coplanar format. Because of the difficulty in obtaining accurate slope information in the perspective displays, pilots may have been responding to the current altitude information for the traffic (rather than climbing or descending trends) which was available from the current position reference lines of the traffic icons (Figures 14 and 15). When confronted with traffic that was currently below ownship, pilots in the perspective display conditions tended to climb (relative to the mean behavior in the specific perspective condition), and similarly tended to descend more than usual in response to traffic which was currently above their position (Figure 31).

The two perspective displays also supported maneuvers which were biased toward the right of the flight path on trials involving vertically maneuvering traffic, while the lateral position data for the coplanar display do not show this effect (Figure 31). The viewing vector azimuth offset of 5° to the right of the flight path during straight flight may have contributed to this bias. The slight rotation of the viewing vector about the vertical axis causes ownship's predictive vector to align more closely with the line of sight viewing vector during banking turns to the left. However, turns to the right rotate ownship's predictive vector into a position that is closer to parallel to the line of sight viewing vector. This explanation assumes that the perception of the extent of ownship's predictive vector is important for the task, which is a reasonable assumption given the demands of the task components.

In summary, the patterns of maneuvering behavior exhibited in the perspective conditions with respect to that which were observed in the coplanar format suggest that the influencing factors of occlusion and vertical axis compression may have contributed to the maneuvering biases discussed above. The tendency for pilots using the perspective displays to make smaller vertical deviations than those using the coplanar format is evidence for perceptual expansion of the vertical axis; while the bias of pilots using the 30° perspective display to descend, and of those using the 60° format to climb, suggest the influence of occlusion and vertical axis compression, respectively.

6.3 Visual Scanning and Planar Integration

The primary disadvantages which were predicted to negatively impact performance in the coplanar format were the requirement to visually scan between the two planes of data, and mentally reconstruct the three-dimensional space from the two two-dimensional planes. One line of evidence for these mechanisms would be increased latencies in evaluating potentially conflicting encounters. Latency costs were not observed in the coplanar condition (Figures 22 and 23). In fact, the coplanar format supported significantly faster response times for the identification of non-conflicting encounters than did the 60° perspective display. A potential reason for the absence of relative latency costs in the coplanar format vis-a-vis the perspective conditions could be that the ambiguity in the perspective displays required pilots using those displays to visually scan between the two vertical reference lines which served to disambiguate the horizontal and vertical positions of the aircraft. If this is the case, then any advantage which might otherwise have been gained through the integration of the three spatial axes in the perspective displays was lost due to the need to visually scan within the perspective displays themselves.

Support for the adverse influence of having to mentally reconstruct or integrate the separate display planes in the coplanar format would be found in comparatively worse performance in the two-aircraft encounters in the second session, with respect to the perspective displays (i.e., an interaction between the number of aircraft present and display format, in which a coplanar advantage over the perspective displays would be smaller, or a disadvantage would be larger, in the second session). The reason for this is that the number of aircraft icons in the coplanar format increases by a factor of two over the number of aircraft icons present in the perspective formats. This evidence was not found, suggesting that the process of integrating information displayed separately on the two, two-dimensional panels did not exert a negative effect on performance in the coplanar condition compared to the perspective format. Furthermore, it might be expected that cognitive integration or additional 'cognitive scanning' between the two planar displays in the coplanar format with respect to the perspective displays, would result in greater reported levels of workload in the coplanar condition (e.g., Haskell and Wickens, 1993). This effect was not found; in fact, the coplanar display supported moderately lower levels of subjective workload than did the two perspective displays (i.e., when the two perspective displays were combined for analysis). The absence of evidence for planar integration costs for the coplanar display might have been due to the relatively small number of aircraft present in the simulation. Had more aircraft been displayed, the costs which were not found in the present study might have emerged; this is a condition (i.e., a greater number of aircraft) which should be examined in future experiments.

6. 4 General maneuvering biases

Several maneuvering tendencies were observed which were common to all of the display conditions. The most general tendency was for pilots to make much greater use of the vertical dimension than of the horizontal dimension. Potential reasons for this strategy include the ease with which separation could be ensured by quickly gaining adequate vertical spacing (the simulation dynamics supported high rates of vertical speed). Controlling vertical position is also easier from a manual control perspective: altitude control approximates a second-order control task, while controlling horizontal position involves third-order control dynamics. Vertical spacing is important from an air traffic control perspective as well; emphasis of tight altitude control is implicit in IFR operations. Finally, it should be noted that conflict maneuver analysis carried out by Krozell (1996) revealed vertical maneuvers to be the most flexible at all times leading up to a conflict. Our results are consistent with this optimal prescription

Another interesting finding was the general bias to utilize right-turning maneuvers (this is most apparent in Figure 43). This finding is consistent with the results of a study on collision avoidance stereotypes carried out by Beringer (1978), which indicated that pilots initiated right turns on 75% of trials in which traffic was approaching from head-on or slightly to the left or right of center. Both the current findings and those of Beringer appear to reflect the influence of FAA rules, which require aircraft that are heading directly toward one another to both turn right. This response, however, may be inappropriate when the aircraft are not approaching directly head-on, as was the case in the current study.

Beyond the general tendencies for pilots is use predominantly vertical maneuvers and to favor right turns, more specific biases were found in response to the geometric characteristics of the encounters. For example, the tendency on "ahead" conflicts to turn toward the aircraft (Fig. 43), probably represents the pilot's habitual tendency in visual flight to bring the intruder aircraft into the forward field of view (even though this view was not simulated in the current study). The greater difficulty, as evidenced by higher conflict rates, observed in the 135° approach angle trials suggests that the pilots were less able to deal with the relatively higher closure rates implicit in such encounters. Scallon, Smith and Hancock (1996) also found that conflict avoidance strategies and success rates were greatly influenced by the type of traffic scenarios used. In partial contrast to the current study, they found that converging (similar to the 45° condition in the current study) and overtaking traffic encounters led to relatively higher conflict rates than did crossing traffic scenarios (similar to 90° encounters in the current study). However, the methodology used by Scallon, Smith, and Hancock involved more complex scenarios with a greater number of aircraft than was present in the current study.

In addition to the relatively more difficult 135° encounters, traffic approaching from the left created more problems than did traffic approaching from the right, a finding which could be due to the right-turning bias described above. Furthermore, pilots tended to maneuver laterally and turn behind traffic which would pass in front of ownship, while making predominantly vertical, climbing maneuvers in response to traffic which would pass behind ownship. The cause of the different response biases for ahead and behind encounters is not clear, but reflects a flexible strategy which should be investigated in future experiments.

6.5 Conclusions

The results of the current study provide important data which should be considered in the design of traffic displays for the cockpit. Although the generalizability of the findings reported here is somewhat limited due to the constraints of the simulation and subject population, the data do offer insight into how experienced general aviation pilots might use perspective and coplanar CDTI displays for maintaining separation in an environment which places responsibility for traffic separation on the pilot, rather than with air traffic control. One of the implications of the current findings is that perceptual and cognitive factors can interact with information formatting techniques to impact the behavior of pilots in this type of simulation. Importantly, the use of an integrated perspective format which exclusively uses monocular depth cues may impair the ability of pilots to detect and avoid conflicts with other air traffic, relative to a separated coplanar format which projects each of the three spatial axes orthogonally onto the display screen. Furthermore, the use of coplanar formats should be considered as an alternative to planar displays which code the vertical dimension with alphanumeric or symbolic codes. The integration of information from the two planar displays in the current experiment was accomplished with higher levels of performance, and without increased latencies or greater levels of subjective workload than were observed in the perspective conditions. These findings are in partial contrast to previous research which has compared planar-alphanumeric displays with perspective formats; and indicate the need for orthogonally projected scales of linear extent for altitude representation in cockpit traffic displays.

Currently, the procedures which will govern the future National Airspace System are not fully developed, and will certainly make use of increasing levels of automation, both in the cockpit, in air traffic control and in airline operations centers. While it is recognized that pilots may not be required to 'hand fly' aircraft based on the information displayed on a cockpit traffic display, it is nevertheless important to provide pilots with information regarding the traffic situation around them which can be accurately and efficiently processed. The use of the current generation TCAS system has shown that pilots' behavior is influenced not only by commands issued by automated agents, but also by the graphical information displayed on cockpit instruments. Based on the assumption that pilots will continue to use, and benefit from spatial information instruments on the flight deck, research studying how these instruments affect behavior is critically important. The work reported here offers evidence which argues for the careful selection and implementation of traffic display formats in the cockpit. Future research must continue to examine the issues which relate directly to the use of graphical instruments in concert with semi-automated systems, in which humans are required to make judgments based on their perception of spatial information.

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APPENDIX 1

Pilot Questionnaire - Traffic Avoidance

1) Total flight hrs. (approximate) ___________
2) Total Instrument hrs. (sim & actual) ___________
3) Do you use specific strategies to avoid traffic assuming the other pilot IS NOT aware of your presence?

   YES ___________ NO ___________

   If YES, describe them below:

   ____
   ____
   ____
   ____
   ____

4) Indicate on a scale from 1 to 5 the relative frequency with which you use the following types of avoidance maneuver assuming the other pilot IS NOT aware of your presence (1 is least often compared to the others, 5 is most often compared to the others). Indicate relative frequencies for each group (A, B, C, D) independently.

A) VERTICAL______ HORIZONTAL ______ COMBINED VERT & HORIZ______
B) CLIMB ______ DESCENT______
C) LEFT TURN______ RIGHT TURN ______
D) CLIMBING LEFT TURN______ CLIMBING RIGHT TURN______
   DESCENDING LEFT TURN______ DESCENDING RIGHT TURN______

APPENDIX 2

Experimental Instructions:
Cockpit Display of Traffic Information: Conflict Detection and Avoidance Simulation

Introduction

The FAA and NASA have recently undertaken a research effort to examine specific ways to improve the efficiency of the National Airspace System. This program has been referred to as *Free Flight*, and involves providing airspace users with increased flexibility in selecting routes to their destinations. New systems are currently being developed to provide safe separation of traffic while supporting more flexible flight paths. *Free Flight* has in fact been described as a system in which VFR flexibility is provided under IFR protection. A potential result of *Free Flight* is that ATC will have less control over traffic in the enroute phase of flight than it does today. Because of this, pilots may be expected to take a greater role in monitoring their own separation from traffic; or more likely, monitoring the automated system that is providing separation (i.e., the current TCAS system). The present study examines several issues involved in presenting traffic information in the cockpit.

Task Overview

In this study you will be asked to fly a series of short (1 to 2 minute) trials using a desktop IFR flight simulator which contains an experimental traffic display. The traffic display provides information about the relative position, heading and altitude of nearby air traffic. During each trial you will be asked to fly a prescribed heading and altitude to a navigational waypoint while monitoring the traffic display for potential conflicts, which are defined as penetrations of the protected zone around your own aircraft. The primary goal of your task is to reach the waypoint as efficiently and rapidly as possible while maintaining safe separation from traffic. You will receive several practice trials before beginning the experiment, during which time the experimenter will answer any questions you may have. The process of completing a trial is outlined below:

- Fly the prescribed heading and altitude toward navigational waypoint - the presence of the "restricted flight" text on the right side of the display indicates that you will be prevented from straying off course too much. Specifically, you will need to stay within 150 ft of your command altitude and within 2 miles laterally of your course (unless an avoidance maneuver is required - see below).

- Monitor the traffic display for anticipated conflicts - the experimenter will explain the symbology on the traffic display provided to assist you in detecting future conflicts, after you read these instructions. The other traffic in the display will always maintain their heading and vertical velocity, and will not react to your own aircraft's behavior.

- As soon as you determine that a conflict will occur, press the button on top of the joystick (this will turn the "restricted flight" text off so that you can maneuver freely) and maneuver around the conflict, returning, as soon as you have avoided the conflict, to a heading and altitude that will intersect the navigational waypoint presented on the traffic display. Maneuvers should be as "efficient" as possible without compromising separation. That is, you should try to deviate as little as possible from your prescribed heading and altitude while safely maneuvering around the conflict. You may use any type of maneuver (other than a change in airspeed, which is constant) that you feel is appropriate for the situation (i.e., there are no restrictions on the type of maneuvers you may select).

- As soon as you determine that a conflict will not occur, pull the trigger on the joystick (this will turn the "restricted flight" text to green) and maintain the prescribed heading and altitude. This trigger press is important because it records the time at which you determine that a conflict will not occur. However, if you later decide that a conflict will in fact occur, you can press the top button on the joystick and maneuver to avoid the conflict.

- The trial will end when you get within 3 miles of the waypoint and within 1000 ft of your prescribed altitude.

- More than half of the trials will involve conflicts

Schedule

Day 1: Practice trials - 60 experimental trials with one other plane
Day 2: 60 experimental trials with two other planes

APPENDIX 3

Description of CDTI Symbology
(Read by Experimenter and used in conjunction with hard copy images of traffic displays)

Basic description of the formats

2D Planar

The top-down view shows our aircraft and other traffic in a traditional map format; bottom view shows the same airspace information from behind rather than from the top (each dot on the top-down display represents one mile). Altitude is presented on the Y axis in the bottom display. (Indicate where the planes are in each display.)

Predictor line

The line extending from each aircraft indicates the path that the aircraft will travel over the next 45 seconds, based on the current heading, pitch and bank. You can use this predictor line to anticipate where your aircraft will be in relation to where the traffic will be in the near future. (Show the predictor line on both the top-down and forward views.)

Relative altitude indicators

The solid horizontal yellow lines in the forward view indicate the vertical boundaries of our protected zone, the top line is 1000ft above, the bottom line is 1000ft below our current altitude. The dashed yellow lines indicate the vertical boundaries of our protected zone when our aircraft reaches the end of its predictor line (45 seconds in the future).

3D Perspective (30 and 60)

This represents a "3D" view of the airspace around our aircraft and other traffic, indicating where the planes are and how they are positioned on vertical "posts" which are connected to the grid lines 5000ft below our aircraft (each dot on the display represents one mile). The vertical posts provide information about the horizontal positions of aircraft, as well as their relative vertical altitudes.

Predictor line

The line extending from each aircraft indicates the path that the aircraft will travel over the next 45 seconds, based on the current heading, pitch and bank. You can use this predictor line to anticipate where your aircraft will be in relation to where the traffic will be in the near future. (Show the predictor line on both the top-down and forward views.)

Relative altitude indicators

The Yellow bars on the posts indicate the vertical extent of your protected zone. The yellow bars on posts which extend from each aircraft symbol indicate the current boundaries of your protected zone. The yellow bars on the posts which extend from the ends of each aircraft's predictor line indicate the future boundaries of your protected zone (45 seconds in the future).

All Display Formats

Threat vector

This line indicates where the nearest threat is predicted to be when you reach the threat vector, so you can use the vector to determine how close other aircraft will come to your protected zone. The threat vector will move toward your aircraft symbol as the time until the threat is closest decreases. Also, the end of the threat vector indicates the edge of your protected zone. Therefore, if the threat vector reaches another aircraft's predictor line, a conflict is predicted to occur (at the time that the threat vector reaches your aircraft), unless you deviate from your current course. You will know that this has occurred because your aircraft as well as the aircraft that is predicted to conflict with you will be highlighted. You should avoid triggering predicted conflicts (this is when ATC would intervene to resolve the situation), as well as actual conflicts.

APPENDIX 4

NASA-TLX WORKLOAD RATING SCALE

MENTAL DEMAND

PHYSICAL DEMAND

TIME PRESSURE

OWN PERFORMANCE

FRUSTRATION LEVEL

MENTAL EFFORT

APPENDIX 5

Matrix of Pearson correlation coefficients for questionnaire variables and dependent measures. Top numbers are Pearson coefficients; bottom numbers are probability > |R| under Ho: Rho=0, N = 30.

	Total Flight Hrs	Instrument Flight Hrs	Preference Vertical Man	Preference Horiz. Man.	Preference Combined Man.
Predicted Conf. with 1ST A/C	0.12377 0.5146	-0.18434 0.3295	0.09788 0.6068	-0.08429 0.6579	0.01765 0.9263
Actual Conf. with 1ST A/C	0.17664 0.3504	0.04838 0.7996	0.21439 0.2553	0.02180 0.9090	-0.20092 0.2870
Predicted Conf. with 2ND A/C	0.31758 0.0872	0.11445 0.5470	0.09311 0.6246	-0.04812 0.8007	-0.03151 0.8687
Actual Conf. with 2ND A/C	0.29468 0.1139	0.01242 0.9481	0.06664 0.7264	-0.10624 0.5763	0.05964 0.7542
Detection Accuracy	-0.10920 0.5657	0.02106 0.9120	0.12433 0.5127	-0.11658 0.5396	0.03378 0.8593
Decision Time Conflict	0.09068 0.6337	-0.00425 0.9822	0.23072 0.2200	-0.38547 0.0354	0.23760 0.2061
Decision Time No Conflict	0.41359 0.0231	-0.08093 0.6707	0.10114 0.5949	-0.21483 0.2543	0.15981 0.3989
Horizontal Position	0.23504 0.2112	-0.28249 0.1304	-0.18332 0.3322	0.24505 0.1918	-0.12414 0.5134
Vertical Position	-0.17008 0.3689	0.26274 0.1607	0.04222 0.8247	0.03654 0.8480	-0.07046 0.7114
Horizontal Deviation	0.11011 0.5624	0.11548 0.5434	-0.06890 0.7175	0.18635 0.3241	-0.16421 0.3859
Vertical Deviation	0.15633 0.4094	0.16589 0.3810	-0.00449 0.9812	-0.14233 0.4531	0.15922 0.4007
Min. Distance Line of Sight	0.21738 0.2485	0.18757 0.3209	-0.02572 0.8927	-0.10969 0.5639	0.14305 0.4508
Min Distance Vertical	0.23767 0.2060	0.09048 0.6344	-0.02184 0.9088	-0.05953 0.7547	0.09717 0.6095
Min. Distance Horizontal	-0.01134 0.9526	0.21651 0.2505	-0.05272 0.7820	-0.15627 0.4096	0.19674 0.2974

Workload Session 1	0.01671 0.9301	-0.05474 0.7739	0.12374 0.5147	0.36931 0.0446	-0.50869 0.0041
Workload Session 2	0.00774 0.9676	-0.07021 0.7124	0.28627 0.1251	0.16216 0.3919	-0.40832 0.0251

	Preference Climb Man.	Preference Descend	Preference Left Man.	Preference Right Man.	Preference Climb Left
Predicted Conf. with 1ST A/C	-0.06020 0.7520	0.05528 0.7717	-0.07846 0.6803	0.07846 0.6803	0.07916 0.6775
Actual Conf. with 1ST A/C	-0.23020 0.2210	0.22532 0.2313	0.03877 0.8388	-0.03877 0.8388	-0.05424 0.7759
Predicted Conf. with 2ND A/C	-0.16094 0.3955	0.15199 0.4227	0.05995 0.7530	-0.05995 0.7530	0.10239 0.5903
Actual Conf. with 2ND A/C	-0.11465 0.5463	0.10948 0.5647	0.17393 0.3580	-0.17393 0.3580	0.03654 0.8480
Detection Accuracy	0.31398 0.0911	-0.31063 0.0948	0.21978 0.2432	-0.21978 0.2432	0.34729 0.0601
Decision Time Conflict	0.10277 0.5889	-0.10670 0.5746	-0.17836 0.3457	0.17836 0.3457	0.15836 0.4033
Decision Time No Conflict	0.24133 0.1989	-0.24259 0.1965	-0.31979 0.0849	0.31979 0.0849	0.20172 0.2851
Horizontal Position	-0.20904 0.2676	0.21067 0.2638	-0.04212 0.8251	0.04212 0.8251	-0.22595 0.2299
Vertical Position	0.10108 0.5951	-0.10034 0.5978	-0.33665 0.0689	0.33665 0.0689	-0.03797 0.8421
Horizontal Deviation	0.14567 0.4424	-0.14643 0.4400	-0.03997 0.8339	0.03997 0.8339	-0.07263 0.7029
Vertical Deviation	-0.05671 0.7660	0.06240 0.7432	0.01447 0.9395	-0.01447 0.9395	0.06004 0.7526
Min. Distance Line of Sight	0.10743 0.5720	-0.10188 0.5921	-0.11013 0.5624	0.11013 0.5624	0.11726 0.5372
Min. Distance Vertical	0.07386 0.6981	-0.07034 0.7118	-0.05675 0.7658	0.05675 0.7658	0.11780 0.5353

Min. Distance Horizontal	0.11992 0.5279	-0.11484 0.5457	-0.15543 0.4121	0.15543 0.4121	0.05983 0.7535
Workload Session 1	0.44588 0.0135	-0.45059 0.0125	-0.03641 0.8485	0.03641 0.8485	0.35166 0.0567
Workload Session 2	0.35537 0.0540	-0.35885 0.0515	-0.04756 0.8029	0.04756 0.8029	0.20342 0.2810

	Preference Climb Right	Preference Desc. Left	Preference Desc. Right
Predicted Conf. with 1ST A/C	-0.01786 0.9254	0.07763 0.6835	-0.12250 0.5190
Actual Conf. with 1ST A/C	-0.19942 0.2907	0.16657 0.3790	0.08458 0.6568
Predicted Conf. with 2ND A/C	-0.12041 0.5262	0.12631 0.5060	-0.08605 0.6512
Actual Conf. with 2ND A/C	-0.18268 0.3339	0.18131 0.3376	-0.01111 0.9535
Detection Accuracy	0.10298 0.5882	-0.17506 0.3548	-0.21534 0.2531
Decision Time Conflict	0.11058 0.5608	-0.11682 0.5387	-0.15406 0.4163
Decision Time No Conflict	0.22494 0.2320	-0.13106 0.4900	-0.28380 0.1286
Horizontal Position	-0.24036 0.2008	0.25349 0.1765	0.19431 0.3035
Vertical Position	0.20920 0.2672	-0.06002 0.7527	-0.13180 0.4875
Horizontal Deviation	-0.06480 0.7337	0.06991 0.7136	0.05480 0.7736
Vertical Deviation	0.11718 0.5374	-0.16501 0.3836	-0.01699 0.9290
Min. Distance Line of Sight	0.24531 0.1914	-0.26640 0.1547	-0.10210 0.5913

Min. Distance	0.22495	-0.24155	-0.10061
Vertical	0.2320	0.1985	0.5968
Min. Distance	0.17305	-0.18908	-0.06139
Horizontal	0.3605	0.3170	0.7473
Workload	0.21646	-0.21129	-0.30398
Session 1	0.2506	0.2624	0.1024
Workload	0.06232	-0.07300	-0.15931
Session 2	0.7435	0.7014	0.4004