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Tactical Displays for Combat Awareness: An Examination of Dimensionality and Frame of Reference Concepts and the Application of Cognitive Engineering

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Three prototype displays are contrasted for aircraft navigation and tactical hazard awareness: a conventional 2-D coplanar display, an exocentric (God's eye) 3-D display, and an immersed (pilot's eye) 3-D display coupled with a small scale global display. Strengths and weaknesses of each display type are discussed, related particularly to the ambiguity of perspective displays and to attention allocation problems with dual-display suites. In Experiment 1, 8 pilots flew with each of the displays around an airspace populated by waypoints, hazards, and traffic. Performance measures revealed the anticipated costs and benefits of each display type. In Experiment 2, cognitive engineering techniques of performance and cognitive task analysis were applied to remediate the weaknesses of each display type. Emphasis was placed on display enhancements to resolve 3-D ambiguity and visual momentum and cueing techniques to facilitate attention allocation and switching. Analysis of performance of 27 additional participants in flight path tracking and hazard awareness measures re-

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vealed success in application of the cognitive engineering principles, greatly attenuating the weaknesses of each display.

Rapid advances in computer graphics technology have made feasible a variety of possible formats of dynamic 3-D graphics for aviation displays. By *3-D* we mean the incorporation of any of a set of perceptual depth cues (e.g., motion parallax, stereo, linear perspective) to convey a sense of 3-D volume of the displayed environment (Wickens, Todd, & Seidler, 1989). Options may include panoramic displays (Busquets, Parrish, Williams, & Nold, 1994), pathway in the sky displays (Barfield, Rosenberg, & Furness, 1995; Fadden & Wickens, 1997; Flohr & Huisman, 1997; Haskell & Wickens, 1993; Nordwall, 1997; Reising, Barthelemy, & Hartsock, 1989; Theunissen, 1995), virtual cockpits (Haas, 1992), or somewhat more conventional 3-D electronic maps (Olmos, Liang, & Wickens, 1997; Wickens, Liang, Prevett, & Olmos, 1996; Wickens & Prevett, 1995). On the one hand, the concept of 3-D displays makes intuitive sense because the pilot's world is a very 3-D one. Yet empirically, whether the benefits of 3-D displays, relative to their more conventional 2-D counterparts (e.g., paper maps), outweigh their costs turns out to be a complex issue depending on the particular 3-D rendering chosen, the nature of the task, and the structure of the information to be displayed (Wickens, 1999). We consider these issues in turn.

DISPLAY VIEWPOINTS

We first note that there are two qualitatively different viewpoints offered by 3-D displays (see Figures 1a and 1b). The "immersed" or fully egocentric viewpoint (Figure 1a) presents the world much as a pilot's eyes might see it from the cockpit (Flohr & Huisman, 1997; Jensen, 1981; Theunissen, 1995). Such a view has also been characterized as an *inside–out* or *pilot-referenced* view. The exocentric viewpoint (Figure 1b) presents a view from behind and above ownship. The displaced viewpoint may allow it to be characterized as an *outside–in* viewpoint, but it should not necessarily be considered as *world-referenced* (i.e., in contrast to pilot-referenced), as such a label depends on the extent to which movement of ownship through space also changes the viewpoint (Wickens, 1999). In many respects, these two 3-D viewpoints are as different from each other as both are from the more conventional 2-D display (Figure 1c) with which they are often compared. However, we note that any fair comparison of 3-D with 2-D viewpoints must provide the latter with two orthogonal views of the airspace so that all viewpoints are provided with a spatial analog representation of the vertical axis (Fadden, Braune, & Wiedemann, 1991). Therefore, we refer to this as the *coplanar view*. Such a coplanar view may either rotate in the direction of travel, in which case azimuth an-

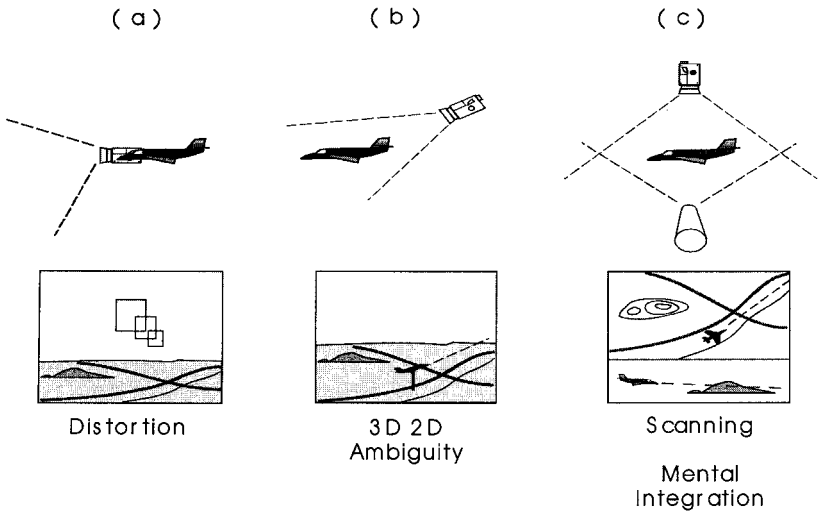

FIGURE 1 Three canonical viewpoints for aviation displays and the resulting display depiction are (a) egocentric or immersed, (b) exocentric or tethered, or (c) a 2-D display that lists the associated human perceptual or cognitive costs.

gle is pilot-referenced, or be fixed (typically in a north-up orientation), in which case it is world-referenced (Wickens, Liang, Prevett, & Olmos, 1996).

TASKS

One may distinguish at least three categories of spatially relevant aviation tasks that the aforementioned viewpoints must serve: (a) *Local guidance,* typical of aviation instrument navigation, simply requires adherence to a flight path leading forward from the nose of the aircraft; (b) *navigational checking* or *pilotage* in visual meteorological conditions requires cross-referencing map information with visual information in the forward view to ascertain congruence between the two (Hickox & Wickens, 1999), thereby establishing that the pilot is geographically oriented or that a target specified on the map can be seen in the forward view; and (c) *spatial* or *hazard awareness,* a subset of the more generic concept of situation awareness (Endsley, 1999) requires knowledge of the location, orientation, and trend of entities (i.e., weather, other traffic, no-fly zones, terrain) lying within a much broader sphere of the surrounding airspace. Hazard awareness can be broken down in terms of the degree of precision with which location and trend must be determined. For example, a traffic display for collision avoidance must yield very precise location and trend information. In contrast, a combat display for general strategic planning,

or a weather display for route planning, imposes less precise requirements. We distinguish precise from imprecise hazard awareness because different display viewpoints have different implications for the two categories of tasks.

Information

The information itself, on which the previously discussed tasks are dependent, may vary in its distribution across a 3-D volume in ways that appear to influence the effectiveness of different display viewpoints. Such information may lie along constrained 2-D planes (e.g., a flat segment of terrain or the flight path of a level aircraft) or may be distributed as less constrained 3-D volumes or trajectories (e.g., the 3-D volume of a hazardous weather region, radar coverage envelope, or the 3-D flight path of an attacking hostile aircraft). In the former case, if the dimensional constraints are assumed by the user perceiving the display, then he or she may impose some level of top-down perceptual processing. In the latter case, these constraints cannot be imposed.

Empirical Data

Different display viewpoints appear to be differentially effective for the different tasks as modified sometimes by the information structure. The most robust finding regarding the costs and benefits of the three prototype display viewpoints shown in Figure 1 is that the immersed pathway in the sky display is superior to the other two prototypes for guidance tasks (Barfield et al., 1995; Haskell & Wickens, 1993; McCormick, Wickens, Banks, & Yeh, 1998; Wickens & Prevett, 1995). The advantage for guidance appears to result both from the compatibility or congruence between the location of the display viewpoint and the axis of control rotation and because of the higher gain by which rotational motion is represented on the display. Such an increase in display gain offers greater sensitivity to error from the desired flight path. However, the same immersed viewpoint appears to be inferior as a means of providing hazard awareness information. This inferiority results either because the display provides only a “keyhole” view of the world behind and around ownship (Woods, 1984) or because an expanded geometric field of view (designed to address the keyhole phenomenon) severely distorts the perceived position of hazards (Wickens & Prevett, 1995).

In contrast to the clearly demarked findings for the immersed display, the differences between coplanar and exocentric formats are more subtle, as they depend on a trade-off between two information processing operations or processing costs. On the one hand, the coplanar format imposes on the pilot a visual scanning requirement to fixate the two views, and an added cognitive load required to men-

tally integrate them. On the other hand, the exocentric format suffers from the ambiguity with which the 3-D location of entities is collapsed onto the 2-D viewing surface (Gregory, 1973; McGreevy & Ellis, 1986). Location of either ownship or hazards is imprecisely determined along the line of sight, and the perceived orientation and length of the vector connecting the two (i.e., the azimuth, elevation angle, and distance from ownship to a hazard) will be degraded by the imprecise estimates of both endpoints of the vector (McGreevy & Ellis, 1986).

Our research findings have indicated that the contributions of either scanning or ambiguity to the costs and benefits of coplanar versus exocentric displays will be modulated by a number of other task and information factors. For example, to the extent that the combined implications of change on all three dimensions is relevant, the scanning costs of the coplanar display appear to impose a greater penalty (McCormick et al., 1998; Wickens, Merwin, & Lin, 1994). But to the extent that there is a need for precise estimation of 3-D position (e.g., estimating the position and trajectory of air traffic), the 3-D ambiguity costs begin to dominate, as revealed by our findings in air traffic control (May, Campbell, & Wickens, 1996; Wickens, Miller, & Tham, 1996) and cockpit traffic displays (Merwin, O'Brien, & Wickens, 1997). However, even this 3-D ambiguity cost for precise location estimation appears to be mitigated by the information, that is, the extent to which the viewer assumes that properties within the environment constrain the ambiguity of positions (e.g., knowledge that all points lie along a level surface or flight path). This explains why 3-D ambiguity problems in trajectory estimation are not observed with level traffic in either air traffic control displays (Wickens, Miller, et al., 1996) or cockpit traffic displays (Merwin et al., 1997), but only when traffic is either climbing or descending.

Finally, in circumstances in which there is not a requirement for high precision of spatial estimates, and in which some constraints on 3-D spatial behavior are present (e.g., the continuous and predictable descent of an aircraft on approach to landing), it is not surprising that our results have revealed rough equivalence between the two display types (Wickens, Liang, et al., 1996; Wickens & Prevett, 1995), and have sometimes revealed a trend in favor of the 3-D display with its reduced scanning requirements (Olmos et al., 1997). This has been particularly true for the navigational checking task typical of pilotage (Hickox & Wickens, 1999; Schreiber, Wickens, Renner, Alton, & Hickox, 1998).

Many of the empirical comparisons between 2-D and 3-D displays, to support both guidance and hazard awareness, have been carried out in the context of civil aviation in which maneuvering performance is relatively constrained by "rules of the airspace." For example, aircraft are typically assigned to, or fly at, fixed altitudes, and when they climb or descend (as in standardized departure and approach routes around an airport), these are typically accomplished while on a straight leg. However, in many aspects of combat tactical maneuvering, such constraints are entirely absent, suggesting two competing alternatives. On the one hand, it is possible that a high degree of 3-D maneuvering may impose a greater cost of scanning

and cognitive integration with the coplanar display, rendering it inferior. Such an interpretation can be offered to explain the navigational superiority of 3-D over coplanar displays in data visualization experiments carried out by Wickens et al. (1994) and by McCormick et al. (1998). This superiority was absent for the exocentric 3-D displays in the more constrained (airport descent path) flying examined by Wickens, Liang, et al. (1996). On the other hand, it may be that when the 2-D constraints on information location and trajectories are removed, this will amplify the ambiguity costs associated with 3-D (perspective) displays in hazard location awareness. Indeed, McCormick et al. found specific evidence for such 3-D ambiguity with precise judgments of location, even as the 3-D displays provided overall benefits for navigation in the unconstrained space.

To investigate these issues in the context of the less constrained 3-D environment of the fighter pilot, two experiments are reported here that evaluated the relative merits of the three display prototypes in supporting 3-D flight path tracking and tactical hazard awareness regarding the 3-D volume of airspace around a simulated combat aircraft. In Experiment 1, we compare performance of the three baseline displays. However, we make one important and necessary modification to the egocentric viewpoint (Figure 1a). Because the keyhole effect associated with this viewpoint is unacceptable for hazard awareness in air-to-air combat (hostile targets in the rear quarter often represent the greatest hazards), the immersed forward view (a local display) was coupled with a large scale (but small resolution) global display positioned in the lower portion of the viewing area. Hence, we refer to this as the *split screen* display as shown in Figure 2. Thus, all three displays depict the same region of airspace on the same display screen size, but from different viewpoints (or combinations of viewpoints). In Experiment 1, participants flew to a set of waypoints positioned at different altitudes among a series of hazards and were required periodically to orient to air targets. We anticipate the experimental data to reflect the strengths and weaknesses of each display type for the set of tasks employed, as previously discussed. Then, in Experiment 2, we attempt to apply cognitive engineering principles (Rasmussen, Pejtersen, & Goodstein, 1995) formulated on the basis of analyses of human information processing and designed to address the inherent weaknesses of each display type, without simultaneously encumbering them with alternative shortcomings. We describe these principles in the introduction to Experiment 2.

EXPERIMENT 1: BASELINE COMPARISON

Participants

Participating in the experiment were 30 University of Illinois Institute of Aviation personnel, all licensed pilots, each receiving payment of $5 per hour. Flight experience varied from 65 hr to 2000 hr with a median time of 250 hr. Participants ranged

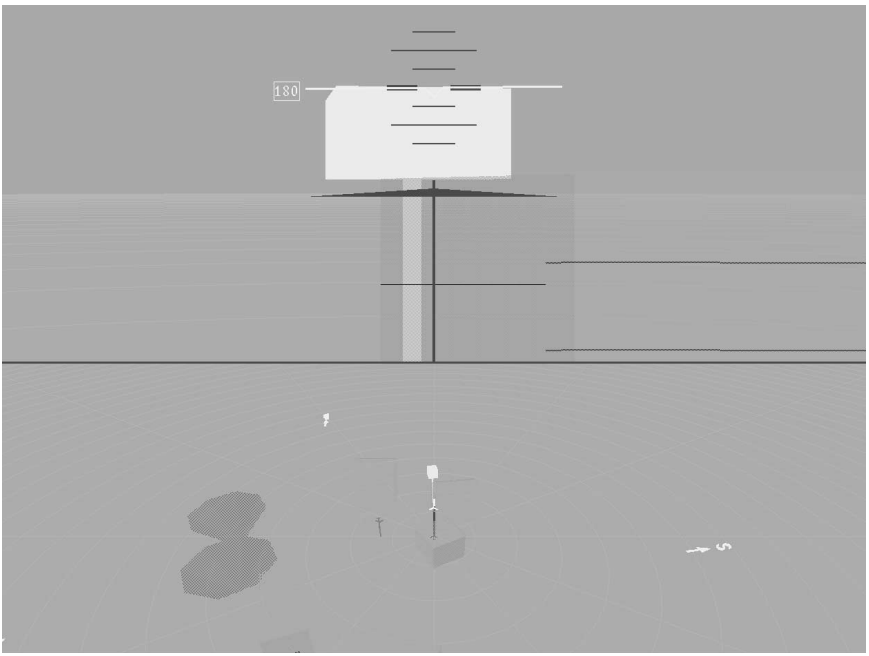

FIGURE 2 3-D split screen display. The upper panel is the immersed egocentric view.

from 18 to 45 years of age. All participants flew with all three display formats. However, before flying with each unique display condition, participants were given a short practice session to familiarize themselves with the display format. All participants received the same instructions and performance measures.

Apparatus and Flight Dynamics

The study was conducted at a Silicon Graphics IRIS workstation with a 16-in. diagonal screen. Navigation was controlled with a 2 *df* joystick that was attached to the right arm of the participant's chair. Relatively generic light aircraft aviation dynamics were employed. These were chosen, rather than combat aircraft-specific dynamics, so that they would not require any specialized training for our general aviation participant population. In these dynamics, pushing forward on the joystick caused the aircraft to pitch down with a subsequent loss of altitude, whereas pulling back on the joystick caused the aircraft to pitch up, thereby increasing aircraft altitude. The degree of pitching up or down directly controlled the rate of altitude change. Moving the joystick to the right or left made the aircraft bank right or left, respectively, at a rate proportional to joystick deflections. Bank angle was directly

proportional to the rate of heading change, and the aircraft was not allowed to roll past 90° in either direction. As in standard aircraft dynamics, pitch and bank were directly coupled such that for a given bank angle the aircraft would have a proportional tendency to pitch down. Power was held constant, although airspeed was allowed to vary from 180 kt at level flight to a minimum of 160 kt in a climb and a maximum of 190 kt in a descent. There were no throttle or rudder controls.

Display

The world in which the pilots flew, with respect to the location of both terrain and hazard volumes, was the same across all display conditions. Terrain was represented with transparent geometric wire frame objects, and hazard volumes were depicted by inverted radar coverage cones (Figures 2, 3, and 4). To reduce any carry-over effects across display conditions, each session with a new display began with the aircraft in a different location and at a different altitude. In addition to changing aircraft location, the location of the various waypoints was also altered for each

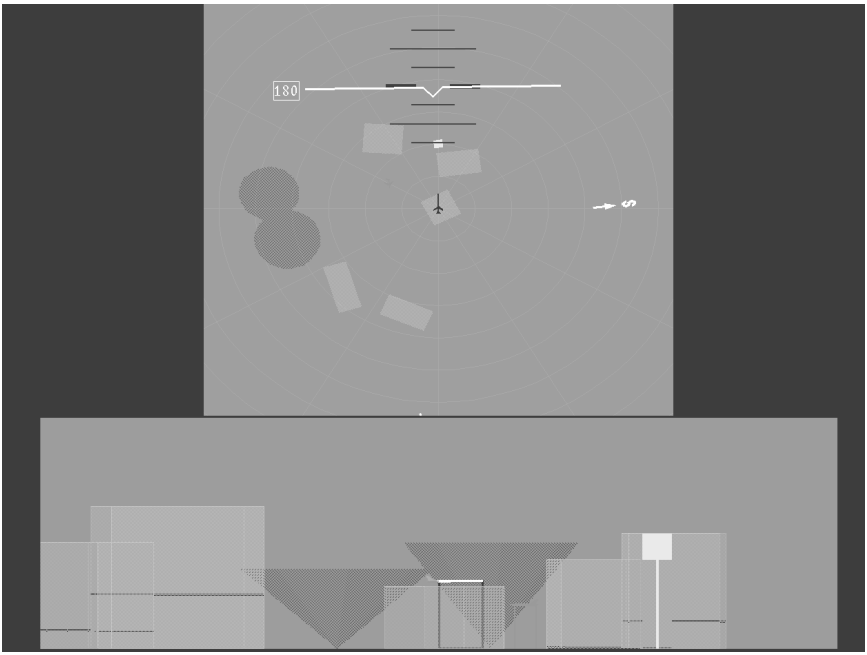

FIGURE 3 2-D coplanar display. The particular viewpoint shown in the vertical display is that used in Experiment 2, with a 0° azimuth angle (i.e., behind the aircraft).

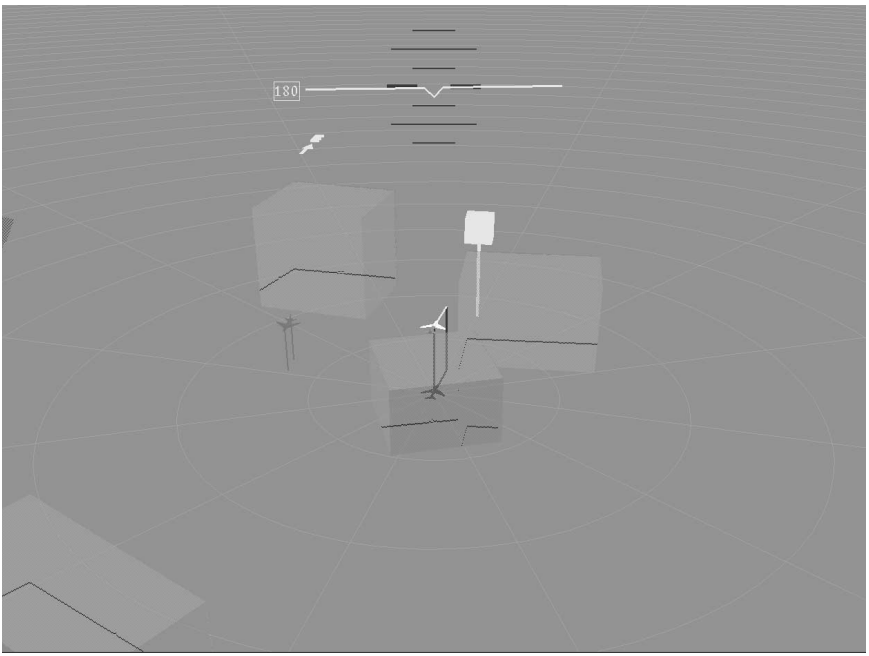

FIGURE 4 3-D exocentric display. The next waypoint is shown by the cube mounted on the pole ahead of the aircraft.

unique display condition. A rotating (track up) map was employed for all three display formats.

2-D coplanar display. For the 2-D display (Figure 3), both a planar and a profile view were provided to present lateral and vertical information, respectively. The planar (horizontal situation) view was placed at the top of the display and presented information from a 90° look-down perspective; hence, no vertical information was provided in this viewpoint. To ensure depiction of threats in front of and behind ownship, the participant's aircraft was placed at the center of the display. The profile view was placed at the bottom of the display and presented vertical information from a viewpoint orthogonal to the aircraft's moment-to-moment location, with a 90° azimuth angle (perpendicular to the fuselage and momentary heading), and at an elevation angle of 0°. As with the plan view, the pilot's aircraft was placed at the center of the profile view to ensure adequate threat depiction. To aid vertical control, a predictor in the form of two poles, one at the front and one at the rear of the aircraft and extending to a grid surface below the aircraft, was added to the aircraft icon.

3-D exocentric display. The 3-D exocentric display (Figure 4) combined lateral and vertical information into a single display by employing a tethered exocentric viewpoint (Wickens & Prevett, 1995). The display viewpoint was placed at a distance above and behind the aircraft. A vertical predictor similar to that used in the 2-D condition was used to help provide altitude information. To ensure that the predictor did not lie along the line of sight of projection, and hence become invisible, an azimuth offset of 15° to the right was used. A geometric field of view of 50° was employed to help with the depiction of threats beside and behind ownship. An elevation angle of 30° was also used to assist the participants with vertical judgments. These projection parameters for the exocentric viewpoint are schematically depicted in Figure 5.

3-D split screen display. The split screen display (Figure 2) combined two differing perspective viewpoints, both of which employed a 50° geometric field of view. The first viewpoint, placed at the top of the display panel, was a fully egocentric, immersed perspective similar to what would be seen by a pilot looking out of the windscreen (Wickens & Prevett, 1995). The second viewpoint, placed at the bottom of the display screen, was presented from an exocentric perspective similar to that of the 3-D display previously discussed. However, to provide a more global view of the world, the viewpoint distance with the exocentric display was increased and the elevation angle was increased from 30° to 45°. Also, because participants would presumably use the egocentric viewpoint for primary flight control, the azimuth offset in this display was decreased from 15° to 0°.

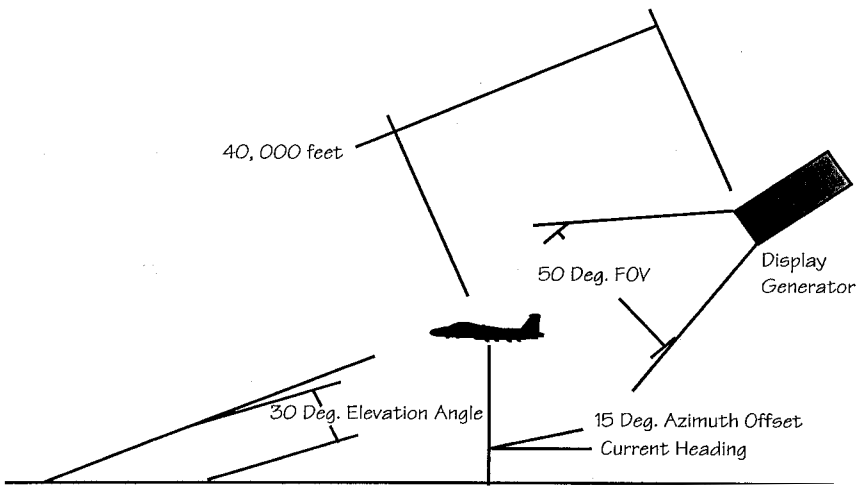

FIGURE 5 Projection parameters of the exocentric viewpoint.

To aid the participants in their navigation task, there were three additional augmentations to the standard displays previously described: (a) An attitude indicator was placed at the top of each display to aid inner-loop flight control, (b) a digital readout of the aircraft's current airspeed was also placed to the left of the attitude indicator, and (c) a series of concentric rings (set at one mile apart) was created to help participants quickly orient to the next waypoint, and lines emanating from the aircraft formed a "dart board" that surrounded the aircraft.

Task

For each display condition, all participants were asked to navigate as quickly and directly as possible to a specific waypoint that was depicted in the environment by a flashing yellow cube. To aid altitude encoding, a reference line, extending from the bottom of the cube to the grid below, was added to each waypoint (Ellis, McGreevy, & Hitchcock, 1987). For each navigation leg only one waypoint appeared in 3-D space. As a result, once the participant successfully intercepted the specified waypoint it vanished and a second waypoint appeared. Participants were asked to navigate to a total of eight waypoints for each display format. All waypoints were separated by a distance of 24,000 ft and all were positioned randomly in both location (360° around ownship) and altitude (between 3,000 ft and 6,000 ft above or below ownship). Once the eighth waypoint was intercepted, the session would terminate. Hence, the only break that occurred was between display conditions.

These eight legs within each flight were composed of the following:

1. Two straight legs: For these legs, no excessive lateral or vertical maneuvers were required to reach the next waypoint. For example, for a given straight leg participants needed only to descend or climb to reach the next waypoint. That is, no hazard volumes or terrain were present in the participant's path.
2. Six maneuvering legs due to permanent hazards: To reach the next waypoint as quickly as possible, participants needed to circumnavigate permanent hazards that were present in their path. This would necessitate a decision on the participant's part as to whether a climb, descent, turn, or combination climbing turn and descending turn would result in the shortest navigation time to the next waypoint. Of the six maneuvering legs, two could be navigated most rapidly with a lateral maneuver, two with a vertical maneuver, and two required a combination of lateral and vertical maneuvers.

In addition, within the six maneuvering legs there were two legs in which an external threat, in the form of a red aircraft icon, appeared at some random position that was in the view for all three displays, and two within which a hazard volume appeared in the participant's path. The appearance of a hazard volume (the in-

verted radar coverage cone) required some added maneuvering in addition to that which was required due to the presence of a permanent hazard.

Performance Measures

Total time for each leg. The timing for the individual legs began when the next waypoint began flashing and ended when the participants intercepted the specified waypoint. Participants were encouraged to fly the shortest route possible to each waypoint. Hence, because airspeed was constant (other than effects of altitude change), excessive time measures would indicate a deficiency in local guidance, as well as difficulties in efficiently circumnavigating the hazards.

Contact with surrounding terrain or hazards. The total number of contacts was measured within each leg, and the total time within the terrain or hazard volume was also measured for each leg. If contact did occur, participants were immediately alerted with a beeping tone. For each particular display condition, this measure was designed to assess participants' awareness of surrounding hazards.

External threat identification. At unexpected times during the navigation task an external aircraft threat appeared on the participant's display. Participants were asked to verbally identify the location of the external threat as quickly as possible according to the following format:

1. O'clock position—1 through 12.
2. Altitude:
   High—meaning the threat is higher than current altitude.
   Level—the threat is at current altitude.
   Low—the threat is below current altitude.
3. Trend:
   Closing—the threat is approaching.
   Opening—the threat is receding.

The experimenter encoded the verbal responses onto the computer. Both the latency of the first word of the vocal utterance and the accuracy of response was measured for each individual response. Accuracy of response was collected by comparing the participant's actual response to the ideal response. The ideal response was based on the pilot's XYZ position and trend at the moment the threat appeared.

Pop-up conflicts. As with the external threats, at unexpected times during the navigation task, a hazard volume would appear in the participant's path. The participant's task was to decide on a maneuver that would circumnavigate the hazard as quickly as possible. When an appropriate maneuver was decided on, partici-

pants keyed a button on the joystick and immediately commenced the maneuver. A time measure was recorded in seconds for both length of decision time and length of maneuvering time around the hazard. Both measures began at the moment the hazard volume appeared. There were two pop-up conflicts that appeared for each display format. To circumnavigate the pop-up hazard as quickly as possible, one required a lateral maneuver, whereas the other required a vertical maneuver.

Flight path position. The participant's XYZ position was recorded every 5 sec. This was done to later determine the quality of maneuvers (i.e., climb, turn) that was used to navigate around the hazards presented.

Design

A repeated measures design with counterbalancing was used so all 30 participants were randomly broken into six groups, each of which were randomly assigned to one of six display condition orders. These were defined by cycling twice through the three display conditions, each time in a different order. Thus, each display was encountered equally often at each of the six sequential positions.

Procedure

On arrival, participants were given instructions explaining the purpose of the experiment and the tasks they would encounter. After reading the instructions, participants were seated in a dimly lit room in front of the IRIS workstation. Three practice sessions and three experimental sessions were conducted in a 1-day experiment. During each of the practice sessions, participants were encouraged to fly the shortest route possible to each waypoint. The experimenter ensured that participants understood the different features shown with each particular display format. After completing the practice session, the experimenter left the room and the experimental session began. During each of the experimental sessions, participants experienced two external threat identification tasks and two pop-up conflict tasks. The location of the external threats and hazard volumes was altered for each experimental session with a new display format.

Results: Experiment 1

An initial analysis of variance including display and counterbalancing order as factors failed to reveal a significant interaction between these factors. If such an interaction had been observed, it may have suggested some degree of asymmetric transfer (Poulton, 1974) in this repeated measures design.

The data for Experiment 1 are shown in Figures 6 through 9 in the white bar graphs. (The dark bar graphs represent the data for Experiment 2 and will be de-

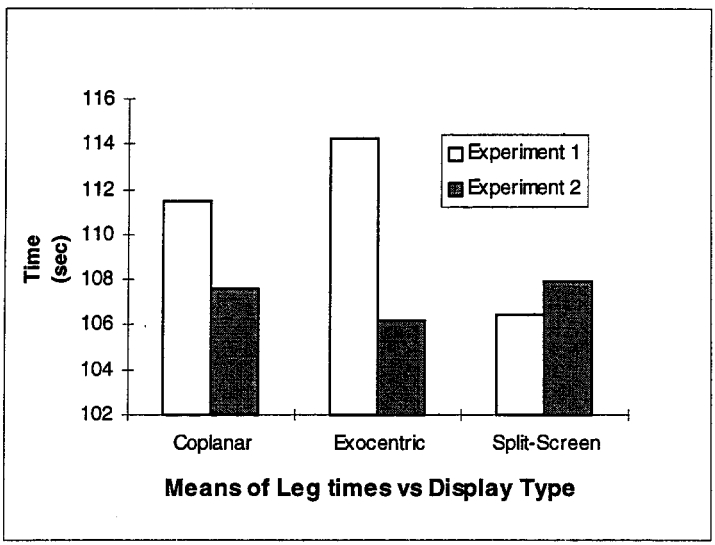

FIGURE 6 Mean travel time per leg. White bar graphs represent data from Experiment 1. Black bar graphs represent data from Experiment 2.

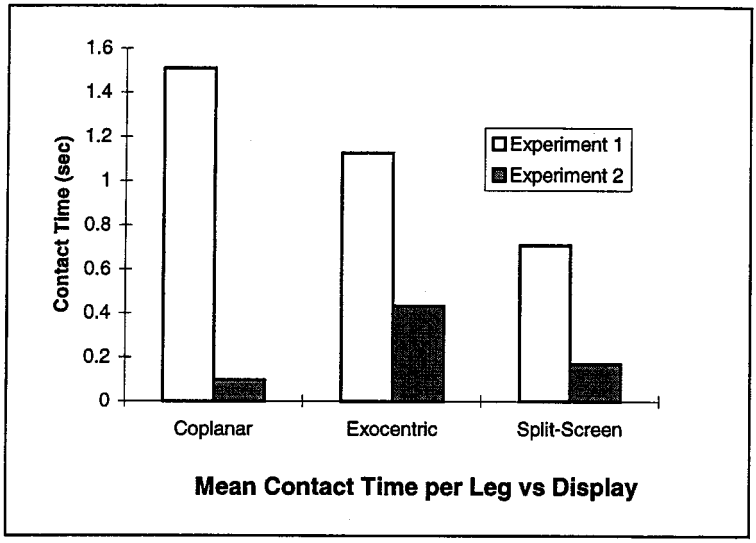

FIGURE 7 Mean time contacting hazard volumes per leg.

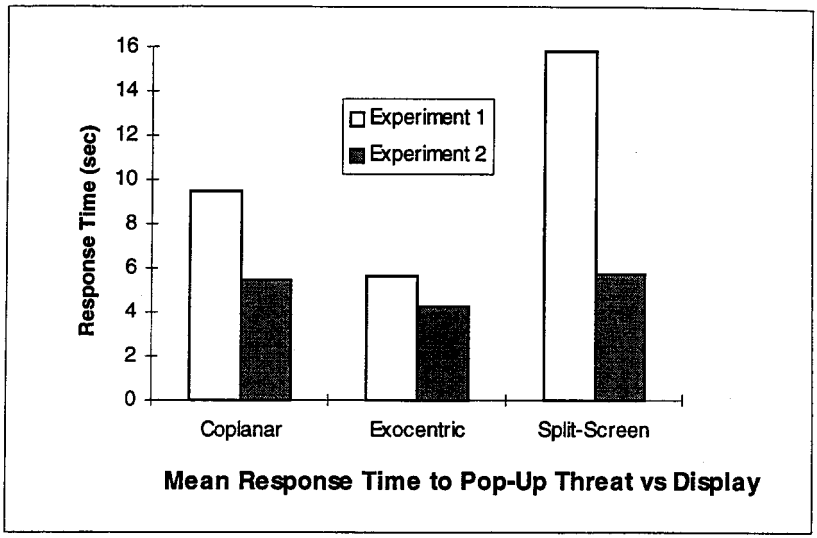

FIGURE 8 Mean response time to aircraft threat.

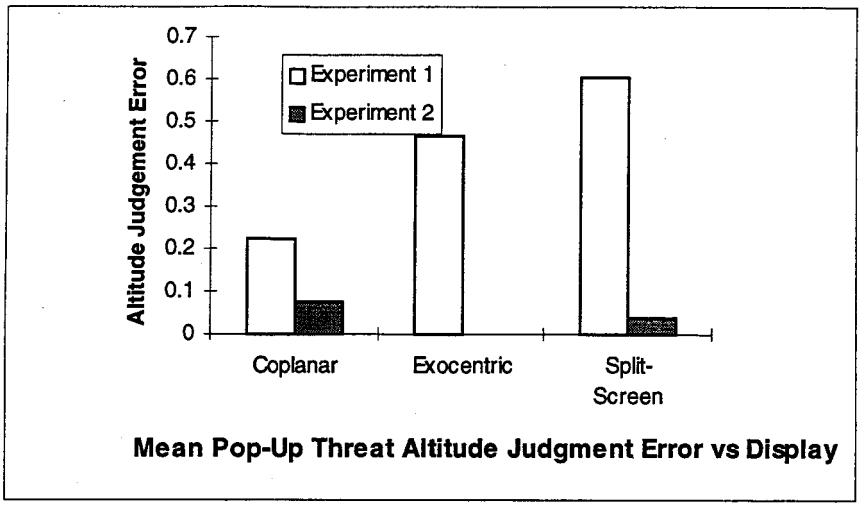

FIGURE 9 Mean error in altitude judgment of aircraft threat.

scribed subsequently.) Figure 6 shows the mean time to traverse all waypoints within a mission as a function of display type. The significant effect of display, $F(2, 40) = 20.7$, $p < .01$, revealed the clear (and predicted) advantage of the immersed split screen display for this local guidance task, relative to the costs shown by the coplanar format (reflecting the costs of lateral and vertical cross panel integration) and the costs shown by the 3-D exocentric format (reflecting ambiguity in estimating ownship position and heading). Subsequent analysis revealed that the major deficiency of the exocentric format was in the fine maneuvering required to capture the 3-D spatial envelope surrounding each waypoint, replicating effects also observed by Andre, Wickens, Moorman, and Boschelli (1991) and by McCormick et al. (1998).

Further analyses revealed differential costs for the coplanar and exocentric displays on vertical (climbing or descending) versus lateral (turning) legs. Performance with the coplanar display suffered the greatest costs on legs involving only vertical maneuvers, $F(1, 20) = 10.35$, $p < .01$, whereas the exocentric display showed the greatest costs on lateral maneuvering legs whether these were level, $F(1, 20) = 31.9$, $p < .01$, or also involved vertical maneuvering, $F(1, 20) = 13.93$, $p < .01$.

Figure 7 presents the amount of time spent within a hazard volume (e.g., ownship has temporarily penetrated a radar coverage zone). These times are relatively short (around 1 sec in a several minute flight). Again, they reflect the marginally significant advantage of the split screen display and its ego-referenced guidance panel in supporting this aspect of navigation, $F(2, 40) = 2.93$, $p < .01$, perceived in the forward view. This cost was greatest for the coplanar display and on those legs requiring lateral maneuvers.

Figure 8 presents the time required for pilots to respond to a traffic threat, as inferred by the time to initiate the first component of their identification response. In this case, the significant effect, $F(2, 40) = 19.85$, $p < .01$, reverses the pattern shown in the guidance measures plotted in Figures 6 and 7 and indicates a substantial cost imposed by the split screen display. A subsequent debriefing of the participants revealed that the cost was attributable to the compelling nature of the immersed screen (on top), which appeared to inhibit participants from allocating much of their visual attention to monitoring the global hazard awareness screen below. Note in contrast that on the coplanar display, information necessary for the primary guidance task was distributed across both panels; on the exocentric display there was only one unified panel. A comparison between the coplanar and exocentric format revealed the latter, with its single integrated panel, to have a marginally significant benefit for response time, $F(1, 19) = 3.66$, $p < .08$.

Our assessments of the accuracy of estimating azimuth and closure of the intruder traffic revealed no differences between the three display formats. However, Figure 9 suggests a marked influence on the estimation of intruder altitude, $F(2, 40) = 7.54$, $p < .01$. The coplanar display, with its linear depiction of altitude, sup-

ported best performance. We infer that both 3-D displays suffered the cost of ambiguity in estimating the vertical dimension. We also inferred that the split screen cost was greater than the exocentric cost, because the dimensions of the perspective display at the bottom of the split screen on which all targets were viewable were considerably smaller than those of the exocentric display, with a resulting loss in resolution. This resolution reduction resulted because the global 3-D view in the split screen display had to share the limited physical display space with the immersed view.

Discussion: Experiment 1

The results of Experiment 1 revealed some of the predictable shortcomings of each prototype display format: The coplanar and exocentric display supported less efficient guidance and navigation, although each, we assume, for different reasons (vertical and lateral integration demands for the coplanar display and ambiguity in estimating ownship for the exocentric display). Replicating earlier findings of Merwin et al. (1997), it is interesting to note that the cost of the exocentric display was much greater on legs that required combined vertical and lateral maneuvering than on straight and level legs in which top-down constraints could be applied by the pilot. It is not entirely clear why the cost of scanning and integration for the coplanar display was greatest on vertical maneuvering legs.

With regard to hazard awareness, both of the 3-D displays suffered ambiguity in estimating the altitude of traffic. Furthermore, hazard awareness with the immersed display suffered from inappropriate allocation of visual attention, as we assume that visual scanning to the hazard display was drawn away to the more compelling and information-rich source of navigational guidance. Efforts to address these various display deficiencies were undertaken in Experiment 2.

EXPERIMENT 2: COGNITIVE ENGINEERING ENHANCEMENTS

Cognitive engineering is a discipline in which its goals, in part, are directed toward engineering human–system performance improvements, based on a clear understanding of the cognitive strengths and limitations of the human user (Rasmussen et al., 1995; Vicente & Rasmussen, 1990), although the characteristics of cognitive engineering also embody the interactions between multiple agents (other humans and computers), as well as between the human (pilot) and the work domain (aircraft). In this application, we first carried out a cognitive task analysis on the pilot-display interactions observed in Experiment 1. This analysis was based on participant debriefing, performance records, and our own expertise in cognitive psychology. We identified cognitive limitations in each display suite related to two

critical aspects of cognition: perception and attention. We then developed enhancements based on different aspects of perception, attention theory, and the concept of visual momentum (Aretz, 1991; Olmos et al., 1997; Woods, 1984), which is a concept used by film editors (Hochberg & Brooks, 1978) to better link two different renderings of the same (or overlapping) spatial environments. Finally, we applied these selectively to each display format, to be evaluated in its enhanced form in Experiment 2. We describe the cognitive limitations of and the enhancement to each format as follows.

Displays

Split screen display. The deficiencies of the split screen display in supporting traffic awareness resulted from the inappropriate allocation of selective attention to the immersed display panel (Gopher, 1993; Kahneman, 1973; Wickens, 1989). Pilots' eyes were drawn upward, more than they should have been, into the compelling and very effective immersed display at the expense of the global situation display that depicted a greater proportion of the enemy contacts. To address this limitation in Experiment 2, we provided an auditory annunciation for the appearance of each target on the radar display. This feature, a brief tone, was incorporated with all three displays, but we reasoned that its benefits would be greatest for the split screen. The elevation angle of the bottom global display was now set at 30°, equivalent to that in the exocentric display.

Coplanar display. The expected difficulties of navigating with this display were attributed to difficulties in integrating the lateral maneuvering aspects with the vertical. Hence, two corrective techniques were applied in Experiment 2, both based on the concept of visual momentum (Aretz, 1991; Woods, 1984), to provide pilots with a better understanding of how overlapping entities depicted in the top (lateral map) panel were depicted in the bottom (vertical profile) panel. First, the vertical depiction was rotated 90° to present a view from behind, rather than from the side. This orientation has the advantage of providing vertical alignment or correspondence between different representations of the same geographical features in the two displays. That is, the "God's eye" representation of a given entity in the upper display will be directly above its corresponding profile representation in the bottom display. This alignment was expected to help to cognitively link the two panels, whereas visual scanning could directly reorient fixation between the two panels, with no time-consuming visual search for uncertain locations (Liu & Wickens, 1992). Second, greater heterogeneity of color coding of the features was employed. Therefore, by making each feature relatively more distinct and unique (in relation to its neighbors), such coding enables the pilot to gain greater certainty

as to the match between the two panels. For example, if a (red) terrain feature were attended in the upper display, and the pilot wished to assess its altitude by scanning to its rendering on the lower display, the scan could proceed without search by directly visiting the only common color (red) feature directly below. The elevation angle of the vertical display was also shifted slightly upward from 0° to 5°. Finally, because of the ambiguity with which altitude information of the traffic threats was encoded in Experiment 1, in this experiment, intruder altitude was provided with color coding: red if below ownship, black if level, and white if above.

Exocentric display. The deficiencies of this display were those that had been observed previously and concerned ambiguities in estimating the position of ownship when nearing a waypoint and when navigating close to the 3-D hazards. To address these limitations, command vertical guidance information was presented at each waypoint in the form of an arrow that pointed up or down, depending on the required vertical correction. Capitalizing on the cognitive benefits offered by 3-D predictor displays in general (Wickens, 1986), and by 3-D or depth predictors in particular (Wickens, Haskell, & Harte, 1989), ownship was also provided with an inverted triangle predictor symbol. This predictor, extending approximately 10 sec ahead with its apex attached to ownship's nose, was designed to change coloration any time it penetrated a volume hazard or terrain, thereby providing 3-D spatial prediction of clearances. As with the split screen display, color coding of altitude of the threat display was also included. The azimuth angle offset was reduced from 15° to 8°. Finally, as with the split screen display, intruder altitude was provided with color coding: red if below ownship, black if level, and white if above.

Thus, across all three displays, two features characterized the augmentations. They were based on cognitive principles of perception and attention, and they were designed to engineer performance improvements targeted at specific display deficiencies. In all cases, the visual augmentations were applied selectively only to the format or formats that had shown the deficiencies. Only in the case of the auditory cueing was it applied to all displays, rather than exclusively to the one that we felt would yield the greatest benefits (the split screen). This is because we reasoned that such a cue might provide a general alerting function in addition to the selective cueing function (desired for the split screen display), and we did not wish to deprive the coplanar and perspective formats of the former benefit.

It could be argued that perfect experimental control of the effects of all independent variables (manipulated changes between Experiments 1 and 2 or differences between the displays in Experiment 2) was lacking; such control is neither possible nor always desirable within the domain of cognitive engineering in which a goal is to enhance human–system performance by application of relevant design principles based on cognitive task analysis.

Design and Procedures

In contrast to Experiment 1, a between-subjects design was employed for Experiment 2 because of our desire to avoid possible asymmetric transfer effects (although these had not been observed in Experiment 1). Nine pilots were assigned to each of the three display conditions. Each pilot then flew a total of three missions, with each mission, as in Experiment 1, consisting of a series of waypoints, hazards, and traffic threats. All other procedures were identical to those employed in Experiment 1.

Results: Experiment 2

The time required to navigate a mission (and hence, also a measure of the efficiency of flight path) is shown by the dark bars in Figure 6. The most striking property of Figure 6 is that the differences across displays, evident in the light bars (Experiment 1), are now eliminated as a result of differential improvement by the two displays that had been deficient in Experiment 1—the coplanar and exocentric display. Hence, the consequence of these improvements is that there was no significant difference across displays in navigation time observed in Experiment 2 ($F < 1$). We assume that the predictive tools assisted with disambiguating the navigational paths in the exocentric display (center bar), and that the visual momentum links between the two panels of the coplanar display facilitated the pilots' navigational awareness in estimating 3-D trajectories (left bar).

Figure 7 depicts the total amount of time spent flying within a hazard volume. The display augmentations served to improve performance, once again achieving greater equivalence of the performance across the three displays by showing the greatest improvement on the coplanar display that had supported the poorest performance in Experiment 1. Once again, we assume that the visual momentum augmentation to the coplanar display proved quite helpful. Analysis of the Experiment 2 data revealed a significant effect of display on contact time, $F(2, 24) = 6.46$, $p < .01$, with the exocentric display now showing the greatest cost.

Figure 8 depicts the response time to detect (and begin identifying) the pop-up threat. As with the previous two measures, an overall performance improvement was observed, which may have reflected the general alerting properties of the auditory cue. However, this improvement was greatest for the split screen display for which the attention allocation deficiencies had been greatest in Experiment 1. The data for Experiment 2 revealed a still significant effect of display format, $F(2, 159) = 8.16$, $p < .01$, still favoring the most integrated exocentric display.

Figure 9 shows the error in altitude judgment of the pop-up threat across the three displays and reveals the manner in which the color coding of relative altitude almost entirely eliminated any errors in this task. In a sense, this improvement for the two 3-D formats is easily predictable because it would have been

possible for pilots to make the required altitude judgments strictly by attending to the symbolic color coding of the threat symbol and ignoring vertical position altogether (whether they did so or not cannot be established). The modest (but nonsignificant) improvement for the coplanar display cannot be attributed to color coding because this was not applied in this case.

DISCUSSION AND CONCLUSIONS

It is clear that the enhancements applied to the displays, based on cognitive task analyses of display deficiencies in Experiment 1, were successful. In all cases, performance on the various tasks improved or remained constant without encountering compensatory costs in other performance aspects. One caution, however, should be exercised in interpreting these results. Because of the limited availability of participants, some of the pilots had also participated in Experiment 1, and for these individuals, the differences between displays in Experiment 2 was confounded with practice. However, this was only a small percentage of our participant population, and these individuals were equally balanced across the three display conditions in Experiment 2. Furthermore, a subsequent analysis revealed that the benefits that these repeating participants realized were not substantially greater than the benefits of the nonrepeaters.

The most important point to note, in any case, is that generally the "fixes" offered to the displays served to equalize performance across them, thus alleviating the problem that often occurs in engineering design; namely that a fix applied to address one aspect of performance succeeds only in creating another problem elsewhere. We believe that a careful application of engineering principles that address the perceptual cognitive mechanisms underlying performance, rather than just addressing performance deficiencies themselves, can alleviate some of the trade-offs that are often observed. Cognitive engineering can accomplish this, as we believe we have demonstrated here.

In Experiment 1, two important cognitive deficiencies were identified that demanded attention in the redesign of the displays used in Experiment 2: perceptual ambiguity and inappropriate attention allocation. Both of these trace their importance to human factors lessons learned in some of the earliest days of aviation psychology: the role of visual depth and distance illusions in aircraft landing (e.g., Kraft, 1962) and the importance of visual scanning in the cockpit (Fitts, Jones, & Milton, 1950).

Display integration, such as that incorporated in the exocentric display format, can reduce the problems of attention allocation (because the eyes do not have to move to separate panels to get lateral and vertical information, or to access forward and global information). Although the 3-D exocentric format invited the potential costs of depth and distance ambiguity, this was remediated by the 3-D predictor, as

well as the redundant color coding of critical altitude variables. Solutions applied to both (exocentric and immersive split screen) 3-D formats.

Correspondingly, problems of inappropriate distribution of attention to separate display panels (the split screen and coplanar formats) were addressed by a combination of attention cueing (to redirect attention to the less salient global panel of the split screen display) and visual momentum (to make it easier for pilots to shift attention between the two coplanar display panels).

Which of the three displays ultimately produced the best performance remains difficult to judge. In the unaugmented form (Experiment 1), it is apparent that the split screen format provided the greatest benefits and fewest costs across all dependent variables. However, with the application of the cognitive engineering redesign, most differences vanished, although a designer's choice could be based on the extent to which guidance (avoiding threat contacts in the forward path; see Figure 7) versus global awareness (responding rapidly to enemy threats; see Figure 8) should be weighted more highly. The data showed that the coplanar format slightly favored the former (bypassing the residual effects of 3-D ambiguity), whereas the exocentric 3-D format slightly favored the latter (bypassing the residual effects of attention allocation).

It should be noted, however, that these experiments only partially addressed the range of possible flight conditions relevant to combat maneuvering; in particular, the low level of fidelity, and the relatively sluggish maneuvering characteristics (e.g., compared to the dynamic response of an F16 fighter aircraft), prevents generalization to the fighter cockpit environment from being offered with high confidence. As another example, careful consideration would need to be given in operational environments as to the nature of the auditory cue and its discriminability from a host of other acoustic stimuli. An additional feature of that environment, missing from our paradigm, was the existence of a visual world, which could make a difference of potentially favoring the 3-D formats (Olmos et al., 1997).

Nevertheless, what is important in these data is the ability to associate the three relatively generic, or *canonical*, viewpoints with specific strengths and weaknesses, inherent in the nature of pilot information processing, and then to successfully implement remediations based directly on the analysis of those weaknesses, following the spirit of cognitive engineering. Thus, there is reason to be optimistic that a corresponding approach can be applied in more realistic flight settings.

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