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PILOTS' SPATIAL MENTAL MODELS FOR MEMORY OF HEADING AND ALTITUDE

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Abstract

A study was conducted that examined areas of a Cockpit Display of Traffic (CDTI) committed to memory during a task that required monitoring of aircraft separation. The data showed that pilots tended to recall aircraft primarily as a function of spatial range and bearing, and not as a function of temporal range.

Introduction

Researchers are currently developing design guidelines for cockpit displays of traffic information (CDTIs) to support cockpit-based separation from other aircraft. Although air-transport pilots have some experience monitoring traffic and potential conflicts on Traffic Collision Avoidance Display (TCAS), displays, self-separation is a new task. Therefore, the information needed by the pilots' in order to accomplish this task, and how they will use that information, are not well understood.

A cognitively based approach to this problem is to describe the relevant information, and how a pilot, in terms of a mental model uses it. A mental model is a cognitive construct that reflects a combination of predispositions (biases) and situation specific learning (see Tversky, 1991, for a discussion of spatial mental models). A description of this model can aid the development of good displays in two ways. First, it allows a designer to match the information and format of the display to the mental model when the mental model is appropriate. Second, it allows a designer to create a display that compensates where the mental model is incomplete or incorrect.

One method of gathering information about a mental model is to examine the contents of long-term memory (LTM). The information represented in LTM is determined (at least in part) by what a person attends to, and how permanently it is encoded. This, in turn, is determined by predispositions and situation specific factors. This study examined potential spatio-temporal determinants of the mental model that guide attention and retention of information when pilots are evaluating a self-separation task. Specifically, it focused on how the mental model was related to the x-y positions on the display.

Among the most critical elements of traffic information are distance of other aircraft to Ownship in space (spatial proximity), the absolute angular displacement of an aircraft relative to Ownship path (relative bearing), and the time it would take an aircraft to reach Ownship if that aircraft immediately turned onto a collision course (temporal proximity). These measures form the bases for three corresponding mental models that may guide a pilot's self-separation activity.

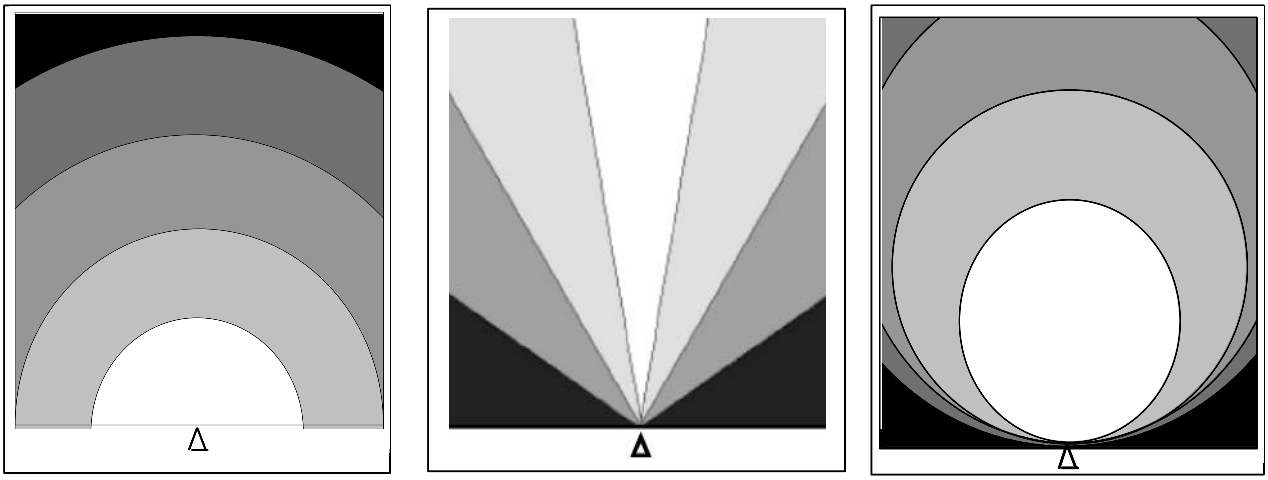


Figure 1. Recall predictions of three mental models. Left panel shows recall predictions based on spatial proximity (darker regions have poorer recall). The middle panel shows predictions based on relative bearing. The right panel shows predictions based on temporal proximity.

The predictions of these models are illustrated in Figure 1. The Spatial Proximity Model simply predicts that aircraft closer to Ownship will be better attended and encoded, and therefore better remembered. The Relative Bearing Model predicts that aircraft with smaller relative bearings will be remembered better. The Temporal Proximity Model predicts that aircraft that could reach Ownship in less time will be better remembered. For an airspace in which other aircraft are flying at approximately the same speed as Ownship, this corresponds to a set of nested centered in front of Ownship.

These three models represent different levels of sophistication with respect to traffic dynamics. The Spatial Proximity model is least sophisticated in that it only takes current separations into account. The Temporal Proximity model is more sophisticated, parsing the x-y space in terms of time needed for loss of separation. The Relative Bearing model reflects differences in closure rates (i.e., the fact that aircraft in front of Ownship tend to have higher temporal proximities than do aircraft to the side of Ownship).

In this experiment pilots were presented with a set of traffic scenarios on a CDTI and asked to evaluate their freedom to maneuver. The purpose of this evaluation task was to encourage the pilots to evaluate the display with respect to separation. After viewing and evaluating the scenario the pilots were interrupted to displace the contents of short-term memory. Following this, pilots were asked to recall as much information as possible about the traffic aircraft. These recall data were then used to determine which model or combination of models pilots likely use.

Methods

Participants

Twelve right-handed male participants with normal or corrected-to-normal vision were paid for their participation. All participants were active airline pilots experienced with glass cockpit instrumentation and with TCAS.

Apparatus

Scenarios were run on a 200MH Pentium Pro computer with an Omni Comp 300 SX OpenGL 3d accelerator graphics card. The monitor was 17 inches diagonal with 1600 horizontal by 1200 vertical resolution. Mouse and keyboard were standard. The size of the CDTI image on the monitor was 7" x 7". The display was static over the period of monitoring time given.

Design

All pilots viewed 24 scenarios, with 12 aircraft presented on the CDTI during each scenario, for a total of 288 aircraft. The locations and headings of the aircraft were randomly generated subject to the following constraints:

- The 288 aircraft located by randomly assigning six aircraft that fit within the parameters of each of the 48 predefined and approximately equally sized x-y bins that covered the surface of the display.
- Within each bin, two of the six aircraft were located at each of the three altitudes: 31,000, 33,000 and 35,000 feet.
- For each pair of aircraft at each altitude within each bin, one aircraft was randomly assigned a heading that would eventually cross the path of Ownship, and one aircraft assigned a heading that would not cross the path of Ownship.
- The locations and headings of the aircraft were selected such that their future and past trajectories never resulted in them passing within 5 NM of Ownship, or within 2.5 NM of each other.
- No aircraft populated the area in front of Ownship for a ten-mile range (to avoid focusing attention on this area).
- The locations of the twelve aircraft were selected such that the altitude tags never overlapped.

Three altitudes were used in order to place a sufficient number of aircraft in each scenario without these aircraft being on conflicting trajectories. Furthermore, all combinations of heading (toward and away from Ownship path) and altitude were included within each x-y bin to ensure that the effect of location could be evaluated with minimal confounding effects of altitude and heading.

Description of the CDTI

Figure 2 shows the CDTI used in the study. At the bottom of the CDTI there is a filled triangular symbol with a short line segment extending out from it. The point of this triangle corresponds to the position of the Ownship, and the line segment is the predicted path for the next 30 seconds. The other aircraft are depicted by similar, but unfilled, triangular symbols with short lines oriented in their direction of travel. The traffic symbols also have associated altitude tags.

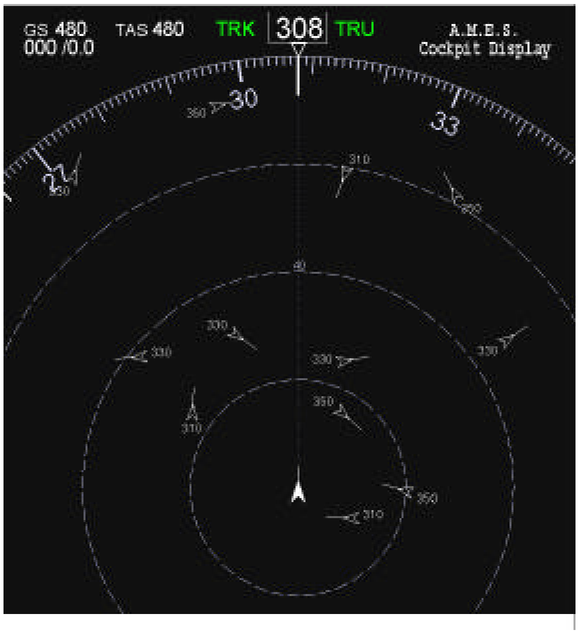


Figure 2. Example CDTI Scenario.

In addition to the aircraft, there are several other structural elements on the display. There is a compass arc at the top of the display, which shows Ownship direction. No aircraft were ever displayed beyond this compass arc. There is also a set of range rings on the display, which are circular arcs with the Ownship at the center. The range was set at 80 miles, with scale markers at 20-mile intervals. Speed was set at 480 knots for all aircraft, including Ownship and Ownship altitude was 33,000 feet. The depicted airspace extended 80 NM in front, 20NM behind, and 42.5 NM to the sides of Ownship.

Procedure and Task Description

It was explained to the pilots that each trial presented a different traffic scenario. They were told that their primary task was to evaluate how much freedom they had to safely change their heading without losing required separation from other aircraft (defined at 2.5 miles). The recall task was described as incidental to the primary task. It was emphasized that pilots should not memorize information from the display, but simply focus on the primary task as they would in a real flight situation, attending to information based on importance to the task. During each trial there were three separate stages which are described below.

CDTI Presentation and Inspection Stage:

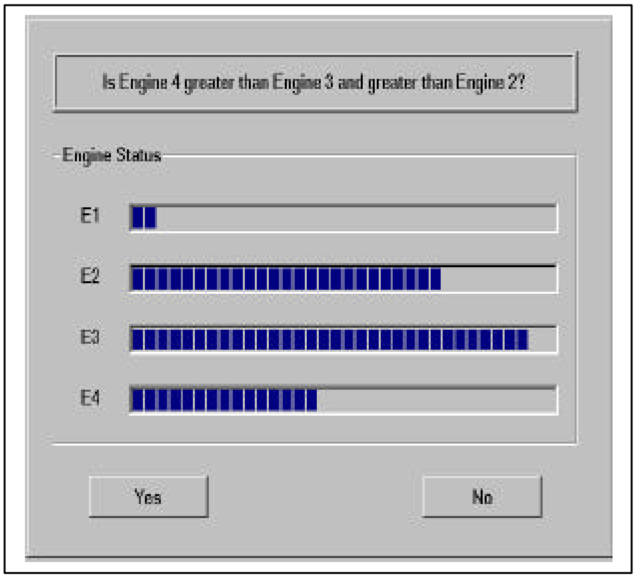
At the beginning of this stage the message "Ready to Begin Next Trial" appeared and remained on the screen until a mouse button was pressed. At this time a CDTI similar to that depicted in Figure 2 was displayed and remained on the screen for one minute. During this one-minute interval the pilots were told to evaluate how much freedom they had to safely change their heading at all three altitudes (assuming a change of altitude) and to combine their assessments into one evaluation, which they would be asked for at the end of the trial.

Interruption Task Stage:

At the end of the first stage, the CDTI was replaced by a "interruption" task display (Figure 3). The purpose of this task was to interrupt visual and verbal short-term memory for the scenario and thus to simulate the effects of the various tasks that a pilot may do between sampling from the CDTI. Performance on the memory task would then be a measure of the traffic knowledge encoded in long-term memory. The interruption task required pilots to evaluate true/false statements about magnitude readings from four graphical "Engine Gauges" (e.g. "Engine 4 is greater than Engine 3 and greater than Engine 2"). Pilots were told that it was very important to be accurate, and they were given feedback (a beep) each time they gave an incorrect answer.

CDTI Maneuver Evaluation and Recall Stage:

After pilots responded to the interruption task, the third stage of the trial was presented. During this stage pilots rated their freedom to maneuver and recalled the information they remembered from the display.



Is Engine 4 greater than Engine 3 and greater than Engine 2?

Figure 3. Engine display used for interruption task.

When rating their freedom to maneuver, pilots were asked to use a cursor to select one of five possible ratings from "Very Low" to "Very High" as a measure of their overall freedom to maneuver. After the selection was made they went on to the memory recall task.

During the memory recall task pilots were asked to recall the headings and altitudes of as many aircraft as possible. The pilots were told not to guess at random, but that they could guess if they were fairly confident of their memory. The memory task began with a display of the x-y positions of the aircraft from the previous scenario. However, in this display the triangular symbols were replaced by small circles, and all altitude tags were removed. To the left of the display several more response controls and buttons were shown and used to collect recall responses using the following techniques:

Selection: The mouse and cursor could be used to select the symbol for any aircraft. This caused an additional circle to appear around the symbol, along with a line extending from that circle. Pilots then proceeded to any of the four sub-tasks (listed below) which could be performed in any order. Recalls could be revised/modified for any aircraft as many times as the pilot wished on any trial, and pilots were never forced to make a recall response.

Heading Recall: Recalled heading for a selected aircraft was indicated by placing the cursor on the line extending from the circle and dragging the line so that it aligned with the remembered ground track for that aircraft.

Altitude Recall: Recalled altitude for an aircraft was indicated selecting 31000, 33000 or 35000 from a menu on the right of the display.

Enter/Revise Another Aircraft: After pilots had entered altitude and/or heading information for a selected aircraft they could select a new aircraft or re-select a previously chosen aircraft.

Done Entering Information: When pilots decided they had entered all of the information they could remember for a scenario, they were told to click on a button labeled "Done Entering Information". When they confirmed that they were sure they were finished, the next trial began.

Results

Two dependent measures were analyzed using analyses of variance (ANOVAs) and regression analyses. Altitude responses were scored as correct if the correct altitude was chosen from the menu. Heading was partitioned into eight equal bins and scored as correct if the chosen aircraft heading was within 22.5 degrees of the actual heading. All aircraft headings and altitudes not responded to were scored as incorrect.

Analyses of Variance:

Prior to conducting the analyses of variance the display was partitioned into16 regions (Figure 4, middle panel). Each region was 21 NM wide by 21 NM long, with the 16 regions covering an area bounded by – 9 NM and +75 NM on the vertical ('Y') display axis, and –42 NM and +42 NM on the horizontal ('X') display axis. Within this area Ownship was located at the (0,0) coordinate.

Two-way fully within-subject ANOVAs were conducted on both the altitude and the heading recall probability data. Since the focus of this analysis was not on effects of display laterality, the data were collapsed across the display midline (e.g. combining regions 1 and 13, 5 and 9, . .), thereby reducing the 16 regions to eight regions. These eight regions were then divided into two levels of an X-Location factor and four levels of a Y-Location factor.

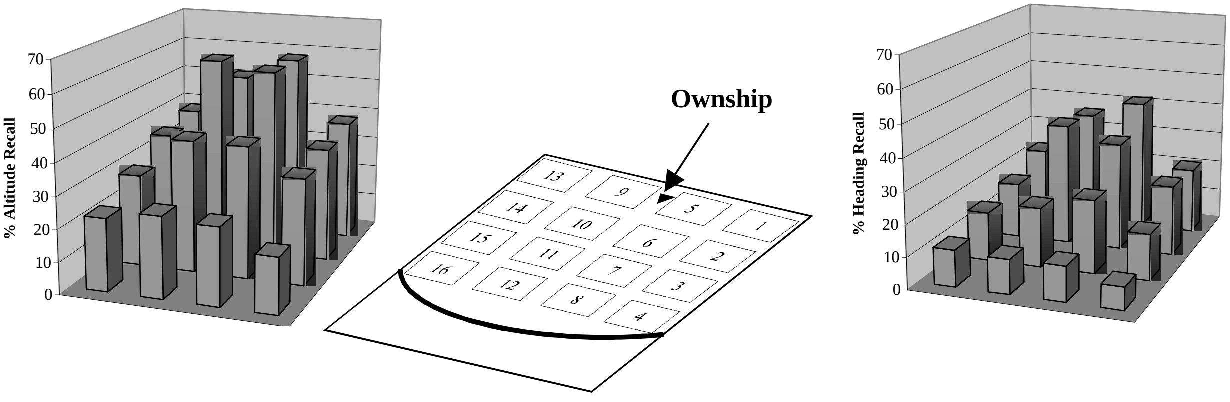


Figure 4. Percent recall for altitudes (left panel) and heading (right panel) as a function of display region. Depiction of display surface in center panel illustrates how graphs are related to display

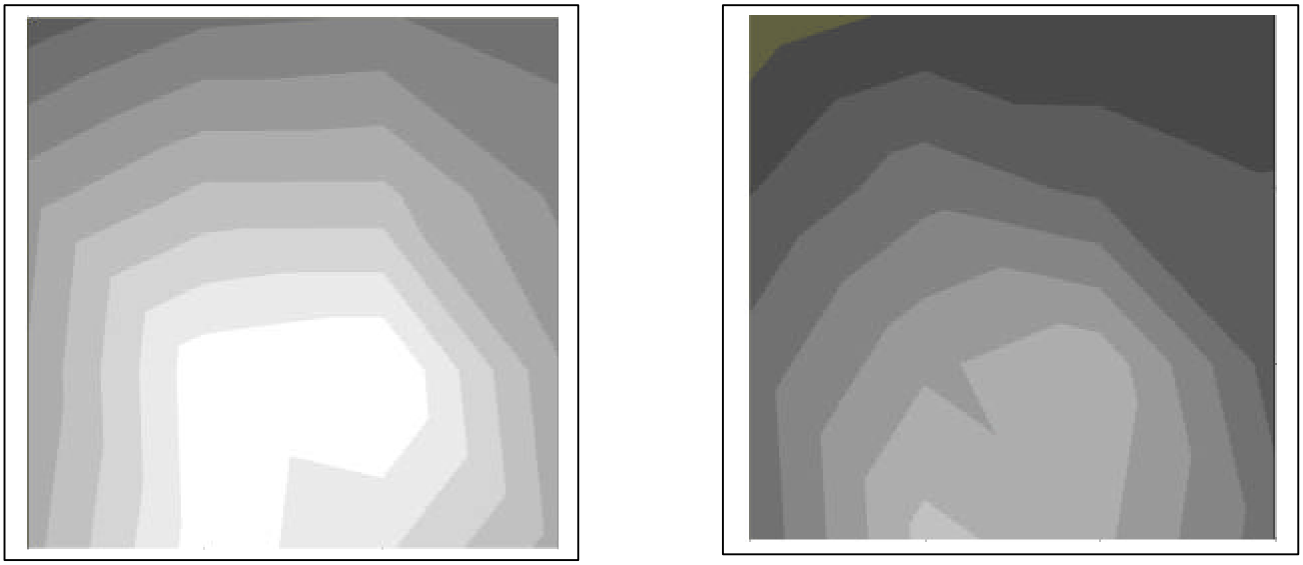


Figure 5. Probability contour plots for altitude recall (left panel) and heading recall (right panel). Ownship is located at the center bottom of graphs. Darker bands show poorer recall.

Both the altitude recall and heading recall ANOVAs yielded statistically significant ($p < .05$) main effects of X-Location, Y-Location, and a significant interaction of X-Location with Y-Location. The three-dimensional bar charts in Figure 4 show the distribution of the basic altitude and heading recall probabilities for the uncollapsed 16 regions. These charts show that best recall performance is found closest to Ownship for both variables. They also show that altitude was recalled better than heading.

Figure 5 shows best fitting contour plots for these same data. In both cases the iso-memory contours appear to be semi-circular ellipses with Ownship at the center and clearly illustrate how recall drops with increasing distance from Ownship. The elliptical form also shows that memory decreases less quickly along bearings closer to 0 (straight ahead), particularly for memory for altitude. However, memory does not appear to be especially sensitive to how quickly an aircraft could come into conflict with Ownship. Thus, data for altitude appears to reflect elements of the Spatial Proximity and the Relative Bearing Model, but not the Temporal Proximity model.

Regression Analyses:

The purpose of the regression analysis was to obtain a more quantitative test of the three models, and their corresponding measures, outlined in the Introduction. The Spatial Proximity model predicts that recall will be inversely related to the distance of an aircraft from Ownship. The Relative Bearing model predicts that recall will be inversely related to the relative bearing of an aircraft. The Temporal Proximity model predicts that recall will be inversely related to the time needed for an aircraft to reach Ownship. Prior to conducting the regression analysis, the probability of recalling each of the aircraft within each scenario was calculated by averaging across responses for all twelve participants. Furthermore, a large ($r = 0.45$) intercorrelation between the Spatial Proximity and Relative Bearing predictors (occurring because distance represented in front of ownship was greater than out to the sides) was removed by using only the data from aircraft within a 42.5 NM range. Significant intercorrelations remained between the Spatial Proximity and the Temporal Proximity predictors ($r = 0.21$), and between the Relative Bearing and the Temporal Proximity ($r = 0.50$).

For the heading variable, Relative Bearing accounted for 7% of the variability; Spatial Proximity accounted for 20% of the variability, while they jointly accounted for 25% of the variability. For the altitude variable, Relative Bearing accounted for 23% of the variability, Spatial Proximity accounted for 22% of the variability, while they jointly accounted for 40% of the variability. In all cases, and despite the intercorrelations with the other two predictors, Temporal Proximity accounted for less than 3% of the variability and was not statistically significant. The failure of Temporal Proximity as a predictor indicates that recall was not better for aircraft that were capable of quickly reaching Ownship than those that would take longer. Instead, pilots recalled aircraft better that were spatially close to Ownship and that were closer to straight-ahead.

Discussion

The mental model implied by the regression analysis of the recall data is primarily based on a combination of Spatial Proximity and Relative Bearing. The iso-memory contours are showing somewhat better memory for aircraft to the front of Ownship, than to the side. Notwithstanding this asymmetry, the near-circular form indicates that the effect of spatial proximity is dominant.

This can be contrasted with the forms that could be expected if the Temporal Proximity variable, or the Relative Bearing variable, dominated (Figure 1). The elliptical form does suggest, however, that the pilots' memories were not totally insensitive to the dynamics of the traffic situation. It shows that memories were at least somewhat better for the traffic in front of Ownship than to the sides of Ownship. The traffic in front includes the temporally most proximate aircraft, meaning, that they have the fastest potential closure rate (if they turned onto a conflicting course with Ownship). Still, a large emphasis is given in memory to aircraft that appear to be of small practical consequence (i.e. those directly to the sides and behind Ownship).

There may be several reasons for these findings. First, pilots were asked to evaluate their freedom to choose alternative headings, not just to scan for threat along their current heading. The task was meant to encourage a comprehensive encoding and evaluation of traffic. That is, the maneuver evaluation task required a pilot to compare the trajectories of a large number of other aircraft with that of Ownship. If the pilots considered a ±180-degree range of potential course changes equally, then our findings would not be surprising (i.e. memory would be as good in all directions from Ownship). However, the debriefing comments of the pilots argue against this interpretation. Eleven of the pilots stated that they only evaluated course changes of less than 30 degrees, and the twelfth pilot stated that he did not go beyond 40 degrees. Thus their statements indicated that they did not evaluate the more extreme maneuvers.

A second possibility is that the effects are task artifacts related to task demands. The memory task was designed as an incidental recall task, and not one on which the pilots should focus their attention or efforts. However, they clearly knew that it was of interest, and they would most likely have wanted to do as well as they could on this task. Therefore, they could have adopted a strategy to enhance recall, and the results could reflect that strategy and not one conducive to determining the basic memory model. However, again the debriefing comments of the pilots argue against this interpretation. All of the pilots indicated that they did not attempt to remember aircraft in order to meet the demands of the recall task. Most of them insisted that they remembered aircraft based on their performance of the primary task. This does not rule out the possibility, however, that task demands impacted their behavior at a subconscious level.

A third possibility is that the format of the display, or the nature of the task itself, may have influenced the salience of individual aircraft. In particular, since the CDTI is primarily an ego-centered display (in contrast to an air traffic controller's perspective-free display); it may have compelled attention to nearby aircraft, or to those closer to the immediate path. Research shows that memory for spatial information is affected by the observer's viewpoint, and that an ego-centered viewpoint holds a special perceptual status (Franklin, Tversky, and Coon, 1992). Thus these effects may have occurred despite a pilot's conscious intent. Comments by two of the pilots support this interpretation. These pilots said that they often "couldn't help remembering" aircraft behind them despite knowing that these aircraft could not possibly reach them.

The results of this study may be compared with studies of the memory of air traffic controllers in tasks requiring the monitoring of aircraft separation (e.g. Endsley and Rogers, 1996; Gronlund, 1997; Mogford, 1997). These studies also examined memory for aircraft information (e.g. recalled heading, altitude, and x-y location), sometimes relating it to whether aircraft were in conflict. These investigators focused upon potential relationships between memory and air traffic control performance. However, the researchers all noted that it is unclear what part of the information used to perform air traffic control is reflected in recall.

This caveat is certainly true for the present study. However, unlike the above studies, the point of the present study was to determine how spatial location affected the pilots' attention and encoding of information (although the relative sensitivity of these two processes to spatial location was not explored). Mental model structure was not related to the role of stored information in managing aircraft separation. Instead, this study used recall to uncover the spatial determinants of what is attended and encoded. This is based upon the premise, elaborated by Endsley (1995), that situational awareness, due to the degree to which it is attended and encoded should be reflected in recall.

The results indicate that pilots tend to pay undue attention to irrelevant aircraft when they are close to Ownship. This suggests that display designers need to find ways to focus pilots' attention on the most relevant aircraft.

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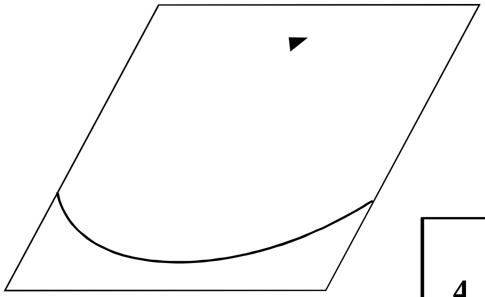

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