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**3D Navigation and Integrated Hazard
Display in Advanced Avionics:
Workload, Performance,
and Situation Awareness**

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ABSTRACT

We examined the ability for pilots to estimate traffic location in an Integrated Hazard Display, and how such estimations should be measured. Twelve pilots viewed static images of traffic scenarios and then estimated the outside world locations of queried traffic represented in one of three display types (2D coplanar, 3D exocentric, and split-screen) and in one of four conditions (display present/blank crossed with outside world present/blank). Overall, the 2D coplanar display best supported both vertical (compared to 3D) and lateral (compared to split-screen) traffic position estimation performance. Costs of the 3D display were associated with perceptual ambiguity. Costs of the split screen display were inferred to result from inappropriate attention allocation. Furthermore, although pilots were faster in estimating traffic locations when relying on memory, accuracy was greatest when the display was available.

INTRODUCTION

Synthetic Vision Systems (SVS) are being developed for the display of information needed by the pilot in order to safely and efficiently navigate under challenging-terrain or low-visibility conditions (Wickens, Alexander, & Hardy, 2003; Prinzel, Comstock, Glaab, Kramer, & Jarvis, 2004; Schnell, Kwon, Merchant, & Etherington, 2004; Williams, 2002). While previous studies have generally examined the configuration of the Primary Flight Display (PFD), we focus here on representing terrain and traffic within an Integrated Hazard Display (IHD), and more specifically, on the measurement of traffic awareness.

IHDs are specifically being developed to assist in navigational tasks, such as global awareness and navigational checking, by representing terrain and traffic hazards through the use of high-resolution terrain databases and satellite-based navigation systems, and will be used in conjunction with the PFD (Kroft & Wickens, 2001; Muthard & Wickens, 2002; Ververs, Dorneich, Good, & Downs, 2002). The IHD must of necessity be presented from a different frame of reference than is typically used with the Ego-referenced or “immersed” SVS primary flight display, because this frame of reference does not readily present information beside and behind the aircraft, critical for traffic awareness. However, the best perspective from which to present the IHD information is still under investigation as research has generally offered conflicting results as to which of many display options are most optimal for the various tasks involved with navigation.

Frames of Reference

We examine the viability of three display formats (2D coplanar, 3D exocentric, split-screen; Wickens, 2003) to support traffic awareness in the current study. The 2D coplanar display (Figure 1a) couples a top-down view with a side-view Vertical Situation Display (VSD). In general, 2D coplanar displays allow for more precise spatial judgments due to their faithful axis representation (St. John, Cowen, Smallman, & Onk, 2001; Olmos, Wickens, & Chudy, 2000; Wickens, 2000, 2003; Wickens & Prevett, 1995). However, the 2D coplanar display imposes a visual scanning cost due to the presentation of lateral and vertical information on two different display panels.

Another option for an IHD is a 3D exocentric display (Figure 1b). Three-dimensional displays have the advantages of adhering to the principle of pictorial realism and allowing for integration in a single display panel (Wickens, 2003). However, 3D displays tend to invite ambiguities due to the compression effect—a spawned cost of portraying a 3D world on a 2D screen (McGreevey & Ellis, 1986). At least two of the three axes visible in a 3D display must be compressed in order for the 3D world to be viewed on a 2D screen, and these ambiguities must be resolved in order to form an accurate representation of the 3D world (in our current experiment, the lateral dimension is the least compressed).

While some studies reveal dimensionality tradeoffs (e.g., Alexander & Wickens, 2002), most comparisons of 2D coplanar and 3D exocentric displays tend to favor the 2D coplanar format across a variety of tasks, requiring precise estimation of location and trajectory, such as would be required for traffic awareness in a CDTI. Coplanar displays support superior performance on flightpath tracking tasks (Rate & Wickens, 1993) and on a number of judgment tasks (e.g., Wickens & Prevett, 1995; Wickens Liang, Prevett, & Olmos, 1996) when compared with 3D exocentric displays.

One possible solution to the tradeoffs between 2D and 3D displays is the “split-screen display” (Figure 1c), consisting of a 3D exocentric view in the top panel to support global awareness and a side-view vertical situation display (VSD) in the bottom panel to support precise hazard localization and avoidance. Importantly, information needed at any given time will be spread across panels (as is also the case with the 2D coplanar display) and the lateral dimension still remains somewhat ambiguous. Only one study involving a split-screen display has been conducted. Olmos et al. (2000) examined navigational performance using a split-screen (3D egocentric display coupled with a small-scale global display), 2D coplanar, and 3D exocentric display. Guidance and navigation were most efficiently supported by the split-screen display, at a cost of responding to some hazards, when compared to both the 2D coplanar and 3D exocentric displays. Essentially, the split-screen display suffered in its support of traffic awareness due to the inappropriate allocation of visual attention to the more compelling and information-rich source of navigation guidance within the egocentric panel, to the exclusion of attention to the global panel. Hence traffic events that were visible only on the global panel were less readily detected.

Situation Awareness Measures

We now turn to the challenge of measuring “traffic awareness”, one of a general class of situation awareness (SA) measures which assesses the pilot’s accurate and timely understanding of the representation of traffic in 3D space (Endsley, 1995; Endsley & Garland, 2000). Endsley (1995, 2000) has proposed a memory-based Situation Awareness Global Assessment Technique (SAGAT). In which a scenario is temporarily frozen, and hidden from view, while the pilot is asked a question concerning the location of entities within the display. These questions must be answered by consulting working memory. In contrast, Durso and Gronlund (1999, 2004) have argued for a perception-based Situation Present Assessment Technique (SPAM). Analysis of these techniques suggests two important differences. First, SA measures of memory are ideally assessed through accuracy of report, whereas those of perception (e.g., SPAM), in which the original data are available for inspection, may be better assessed through measures of response

time since, given enough time, people may be able to reach perfect accuracy by retrieving all necessary perceptual information. Hence accuracy could not discriminate the viability of different displays. Second, measures of memory are often more challenging to cognition than measures of perception, and may therefore be more likely to reveal differences between different display conditions. That is, they may be less likely to encounter a “ceiling effect”.

Durso and colleagues (Durso, Hackworth, Truitt, Crutchfield, Nikolic, & Manning, 1998) compared both SAGAT and SPAM techniques in an air traffic control context and found that both techniques were able to predict various measures of performance of air traffic controllers. Jones and Endsley (in press) have also conducted several studies comparing these two SA techniques, and concluded that while weak (but significant) correlations exist between the two measures, SAGAT still seems to provide a more robust and validated approach to SA measurement. This conclusion, however, was based on comparing SAGAT probes with a SPAM-variant in which the simulation was **not** frozen (i.e., measurement with SPAM was in real time). That is, the authors stipulated that repeated measures of probes were key to the robustness of an SA measure. Such repeated measures are possible in SAGAT as well as in the SPAM-variant in which the simulation is frozen, a case which was not included in those studies.

Experimental Objectives

The current experiment is the first in a series of three comparing the three frames of reference for IHDs presented in Figure 1, and also comparing memory-based versus perception-based measures of SA, to be more fully described below. The research goals for the current experiment may be defined in terms of design-driven and methodology-driven hypotheses. Our primary design-driven goal is to determine which IHD is best for supporting traffic awareness. We hypothesize that the ambiguity costs in the 3D display will hurt traffic position estimation performance within the vertical dimension. 3D costs to lateral estimation are not predicted because there is neither 3D axis compression nor ambiguity along the lateral axis. We also hypothesized that attention allocation demands within the split-screen view may hurt lateral estimation. Therefore, we expect to find that the 2D coplanar display will better support traffic awareness overall compared to the 3D and split-screen displays.

Our primary methodology-driven goal is to evaluate measures of traffic awareness and how specific types of measures will modulate the effects of our IHDs. We hypothesize that the costs associated with 3D and split-screen displays, discussed previously, will be amplified in the memory-based (display blank) SA condition. Resolving 3D ambiguity and determining the appropriate way in which to allocate attention are both resource-intensive processes involving working memory, which would also be required to retain the display imagery in the memory-based condition. Finally, in terms of the SA measures themselves, we expect to see a speed-accuracy tradeoff between the memory and perception-based conditions such that traffic position estimations will be more accurate when relying on perception, but more rapid when relying on memory.

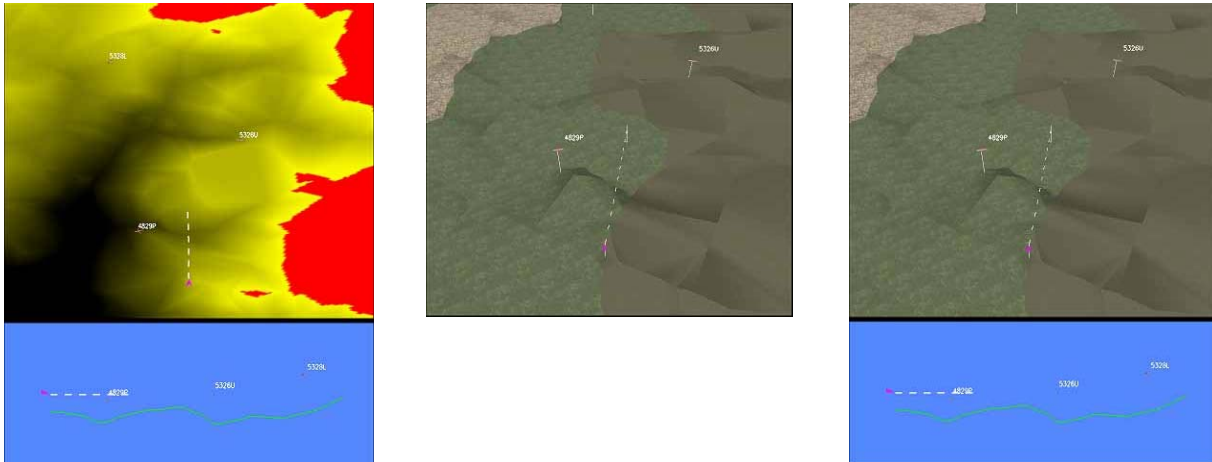


Figure 1. Display types: (a) 2D coplanar, (b) 3D exocentric, (c) split-screen format. In both formats with the vertical situation display, note the profile of terrain extending before ownship.

METHOD

Participants

Twelve pilots (experience, \bar{M} = 203 flight hours; age, \bar{M} = 20 years) made a series of judgments regarding traffic locations based on the representations of three different display type: 2D coplanar, 3D exocentric, and a split-screen display. The experiment was conducted on a high-fidelity Frasca flight simulator with a 180° outside-world view spread across three display screens.

Displays

The integrated hazard display was configured in three ways: (1) 2D coplanar, (2) 3D exocentric, and (3) split-screen. The general display set-up consisted of one of the aforementioned integrated hazard displays taking up most of the right side of the display screen, while a tunnel-in-the-sky and instrumentation were provided in the upper left corner (the latter were not used in the current experiment given that no flight control was involved). Ownship was always presented as a magenta icon in all display types, while other aircraft were mostly white.

2D Coplanar. The top panel of the 2D coplanar display represented terrain, ownship, and other traffic in a traditional map format. The terrain in this top-down panel was color-coded relative to ownship according to TAWS specifications: red represented terrain that was above ownship, yellow represented terrain that was up to 1000 ft below ownship, and black represented terrain that was more than 1000 ft below ownship. The bottom panel of the 2D coplanar display showed the same airspace information from the side with ownship presented 1/3 of the distance from the left. Altitudes of the terrain directly below ownship, ownship itself, and other aircraft were presented on this side-view panel.

3D Exocentric. The 3D exocentric display represented a three-dimensional view of the airspace around ownship and other traffic overlaid on a computer-generated, photorealistic terrain. Vertical posts connected to each aircraft provided information about their horizontal positions as well as their altitudes. This view presented a “tethered” view of the world from an elevation angle of 45° and an azimuth offset of approximately 10° in the clockwise direction. The viewpoint was positioned approximately 4900 feet behind and 8500 feet above ownship. The geometric field of view of the display was 60°.

Split-Screen. The split-screen view consisted of both the 3D exocentric view and the side-view panels described above. The top panel was exactly the same as the 3D exocentric display while the bottom panel was exactly the same as the side view.

Task and Experimental Design

Pilots made traffic location judgments on a total of 60 aircraft targets across the three integrated hazard display types. Pilots viewed static images of traffic scenarios containing between 1 and 4 aircraft for 5 seconds before being asked to estimate the location of the nearest aircraft by reference to its azimuth and elevation as expressed in reference to the outside world (OW). Visibility was adjusted so that these aircraft were not visible in the OW. However, the OW did present the corresponding mountainous terrain that was visible on the display, so that correspondence between locations in the OW and the display could be easily established. After the 5-second viewing time expired, one of four things would happen as defined by the presence or absence (blinking) of either the OW or the display. That is:

1. both the display and OW would remain visible,
2. the display would blank out and the OW would remain visible,
3. the display would remain visible and the OW would blank out,
4. both the display and OW would blank out.

In other words, our SA measures were defined orthogonally by whether the display was present (perception based: SPAM) or blank (memory based: SAGAT), and whether the outside world did or did not remain visible to establish a spatial context in which the response could be given.

Upon one of these four events occurring, the pilot was first asked to use a knob on the left-hand of the yoke to move a white ball in the OW to the position where they estimated the location of the closest aircraft to be. Once the pilot placed the white ball in the desired location, s/he pressed a button on the yoke to continue to the next trial. Pilots were instructed to perform the location estimation task as quickly and accurately as possible. No feedback was provided.

After completing ten practice trials, pilots viewed 10 static images on each of the three display types in one order, and then 10 more static images on each display type in reverse order, for a total of 60 experimental trials. Display presentation was counterbalanced across pilots. The four display/outside-world conditions described previously were quasi-randomized within each block of 10 trials. Thus, each pilot encountered 5 trials with each combination of display x SA assessment method.

RESULTS

To evaluate the accuracy of traffic estimation, the difference between the pilots positioning of the symbol, and the true location of the closest traffic aircraft was recorded. In one set of analyses, this difference was partitioned into vertical and lateral estimation errors, and these in turn were examined in both their absolute value, and their signed value. The latter was used to examine if there were systematic biases associated with estimation.

Vertical Estimation Absolute Error

Figure 2 presents the mean vertical traffic location estimation error as a function of display type (2D, split, 3D) and display condition (present/blank). A significant main effect of Display Condition ($F(1, 11) = 27.3, p < .01$) revealed that vertical estimation performance suffered when pilots were forced to rely on traffic location memory (display blank) rather than perception (display present). A marginally significant Display Type x Display Condition interaction ($F(2, 22) = 3.19, p = .06$) further revealed that in the memory-based (display blank) condition, the 3D display, the only display **without** a vertical profile view, suffered a cost relative to the two displays that did have a profile view ($F(2, 22) = 3.80, p < .04$). The form of this main effect and interaction was identical whether the OW was present or absent, hence the data plotted are collapsed across OW conditions.

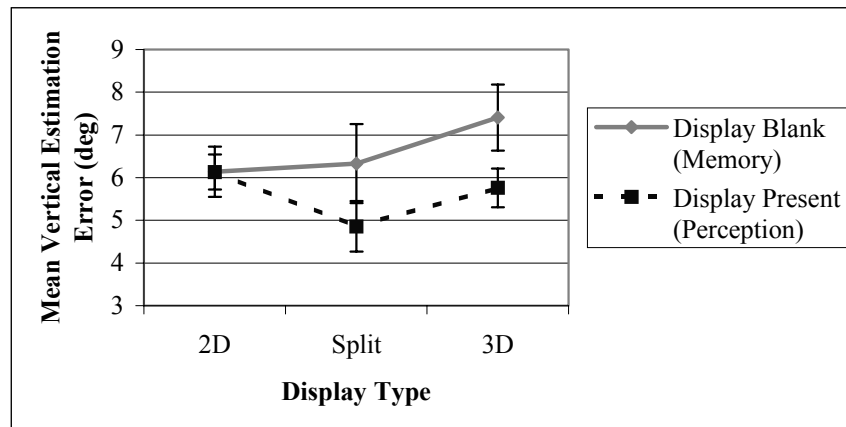


Figure 2. Mean vertical traffic location estimation error in degrees of visual angle as a function of display type and display condition collapsed across OW condition.

Lateral Estimation Absolute Error

The mean lateral traffic location estimation error data, within the OW present condition, are plotted in Figure 3 as a function of display type and display blanking condition. A Display Type x Display Condition x OW Condition interaction ($F(2, 22) = 4.32, p < .03$) led us to examine the data first when the OW was blank, and then when the OW was present. When the OW was blank, the data revealed no effects. Examining the OW present data, as shown in figure 3, the 2D coplanar display supported better lateral estimation performance than the split-screen display in the memory-based (display blank) condition ($t(11) = -2.65, p < .03$). Given that lateral estimation performance did not suffer with the 3D display, we inferred that the greater lateral error with the split-screen view was not due to any inherent property of the 3D panel in conveying lateral

information, such as field of view compression. . Rather, we infer that attention within the split-screen view was inappropriately allocated to the vertical profile view more so than necessary. While resolving ambiguity within the 3D panel is certainly resource-intensive in and of itself, adding an additional panel, in particular one which shows a precise vertical representation, may have drawn attention away from the task of determining lateral position accurately.

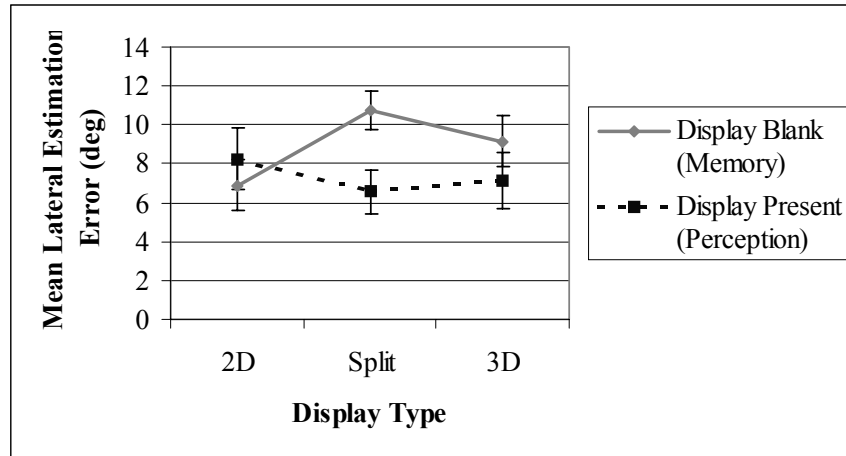


Figure 3. Mean lateral traffic location estimation error in degrees of visual angle as a function of display type and display condition for the OW present condition.

Signed Error

In order to determine the source of the larger absolute vertical estimation error found with the 3D display, a signed error analysis was conducted, as shown in Figure 4. This analysis specifically tests the hypothesis that the increased vertical error may have been a result of a systematic bias to estimate altitude as higher than it actually was due to the contamination of height in the visual field in judging true altitude (Wickens, 2002). Such a bias has been observed in previous studies (e.g., Alexander & Wickens, 2002), and can be related to the perceptual bias in 3D displays known as “slant underestimation” (Perrone, 1982). The analysis revealed that pilots did indeed exhibit a bias in overestimating altitude when using the 3D display, and this was not the case with either the 2D coplanar or split-screen displays, both of which portray a linear representation of the vertical dimension.

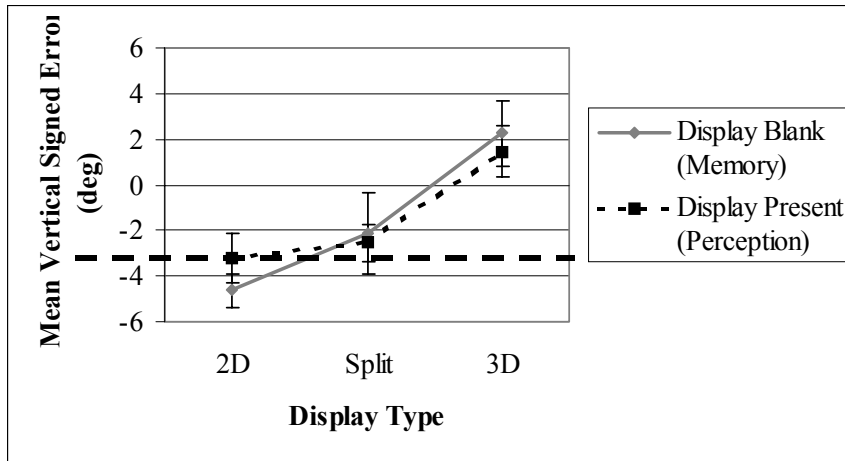


Figure 4. Mean vertical signed error in degrees of visual angle as a function of display type and display condition, collapsed across OW conditions. The black dashed line at the -2.68° position marks the ownship-bias correction described below.

Importantly, analyzing the signed error data as a function of the relative altitude of aircraft compared to ownship, as shown in Figure 5, revealed an overall tendency to underestimate the altitude of those aircraft that were at the same altitude of ownship by about 2.68° . This finding is interpreted as showing an overall bias to underestimate the actual position of **ownship** within the outside world when that altitude is translated from the exocentric display to the egocentric representation of the outside world. Inferring that pilots estimated ownship's position as being about 2.68° lower than its actual position would corroborate the signed error findings with those of the absolute error findings, in which the 3D display was shown to suffer in terms of vertical estimation compared to the 2D coplanar and split-screen displays. Taking such a correction into account reveals an even larger bias in overestimating altitude within the 3D display, a finding to be expected given its vulnerability to spatial awareness biases. (Wickens, 2002). At this time, we cannot fully explain the cause of the "ownship low altitude bias" that was observed.

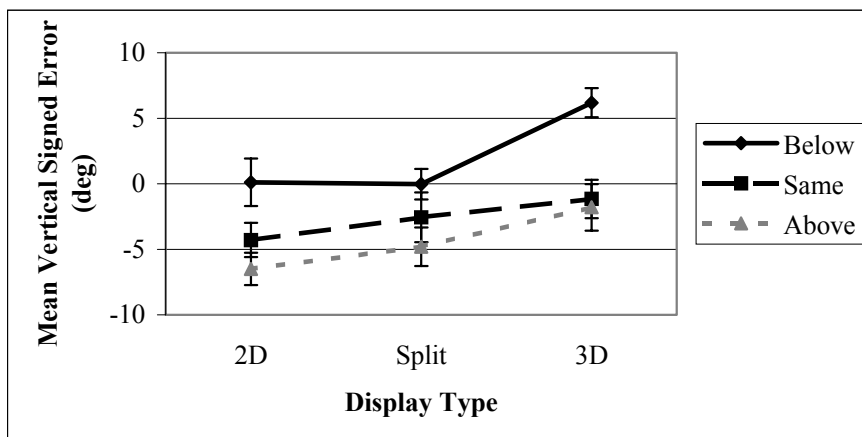


Figure 5. Mean vertical signed error in degrees of visual angle as a function of display type and relative altitude of traffic compared to ownship.

Memory vs. Perception in SA assessment

We now turn to the methodological examination of the specific traffic awareness measures used in this study, and therefore have collapsed the data across display type. Figure 6 shows the mean traffic location estimation response time by OW condition (present/blank) and display condition (present/blank). A main effect of Display Condition ($F(1, 11) = 38.7, p < .01$) revealed that estimations when the display was present were as much as three seconds slower than estimations when the display was blank. As might be expected, pilots took longer to make their judgments when the display was available for double-checking (e.g., time-consuming glances back to the display while positioning the ball). A main effect of OW Condition ($F(1, 11) = 6.49, p < .03$) revealed that pilots were about one second slower in estimating traffic location when the OW was present than when it was blank, again reflecting the needed scan to cross check a visible area. A Display Condition x OW Condition interaction ($F(1, 11) = 6.20, p < .04$) stipulated that the difference in response time between the display conditions was greatest when the OW was present. When all information was available, pilots presumably used the OW as a visual context in which the aircraft could be placed, thus demanding more time for matching up features within the display to those in the OW so that the spatial coordinates of the two spaces, represented in different (egocentric versus exocentric) frames of reference, could be aligned.

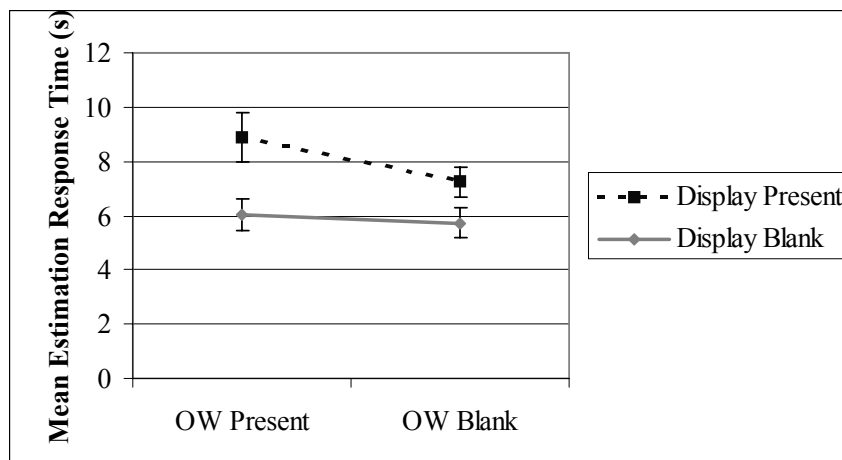


Figure 6. Mean traffic location estimation response time in seconds as a function of display condition and OW condition, collapsed across display type.

Figure 7 presents the vector estimation error data (e.g., combined lateral and vertical) and reveals that there were main effects of both Display blanking conditions ($F(1, 11) = 13.5, p < .01$) and OW blanking conditions ($F(1, 11) = 12.2, p < .01$). Greater accuracy in estimating traffic location was achieved when the display was present compared to when it was blank, and when the OW was present compared to when it was blank. While the interaction was not significant ($p > .23$), it is noteworthy that the form of the interaction is precisely the opposite of the significant interaction that was shown in Figure 6, reflecting a speed-accuracy tradeoff. That is, the condition with the most perceptual information (both OW and display present) requiring the longest time (Figure 6) also produced the greatest accuracy (lowest error) in Figure 7.

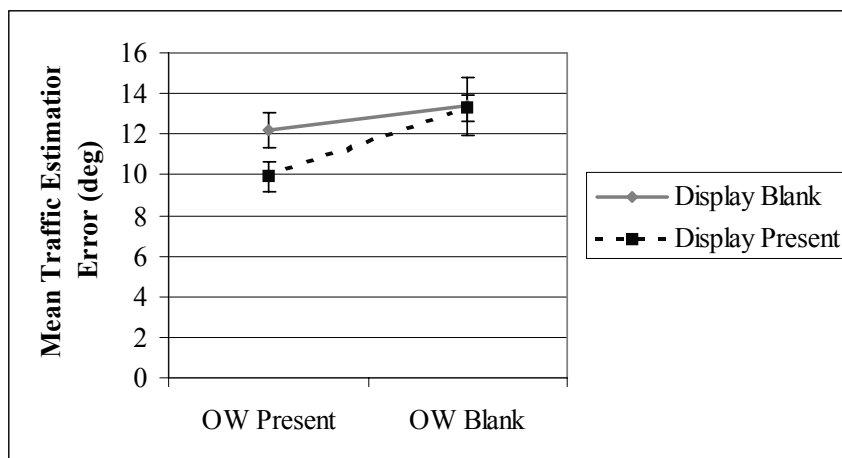


Figure 7. Mean traffic vector estimation error in degrees of visual angle as a function of display condition and OW condition, collapsed across display type.

DISCUSSION and CONCLUSIONS

In determining which integrated hazard display (2D coplanar, split-screen, or 3D) is best for supporting traffic awareness, we note that the traffic estimation error data revealed that ambiguity costs within the 3D display hurt vertical estimation, and that lateral estimation suffered with the split-screen view, perhaps due to an inappropriate allocation of attention to the VSD at a cost to estimating lateral position within the 3D panel. The latter attention-allocation costs had been previously observed with a different form of the split-screen display by Olmos et al. (2000) who found that guidance and navigation were most efficiently supported by the split-screen display, at a cost of responding to hazards that appeared on only one panel of the split screen display. The costs to performance within the 3D and split-screen displays in the current experiment were certainly amplified within the memory-based measurement condition, where pilots could not look back to their display while estimating the aircraft location. Therefore, the 2D coplanar display appears to be best at supporting traffic awareness within both the vertical (compared to 3D) and lateral (compared to split-screen) dimensions. This makes sense given that both dimensions are presented in a precise manner within the 2D coplanar display.

The differences in estimation performance within the vertical and lateral dimensions across the 3D and split-screen views can be explained by the differing demands imposed by the display characteristics. The vertical dimension was more compressed within the 3D display than was the lateral dimension, therefore it was expected that vertical estimation performance would suffer within that display (especially in the more-challenging, memory-based condition), and this was what we found. In the split-screen view, however, a precise representation of the vertical dimension was provided in the side-view VSD. To the extent that this faithful vertical representation drew attention away from the 3D panel, we would expect lateral estimation to suffer given that visual resources necessary to carry out lateral estimation were removed from that panel. Alternatively, this finding may have been due to the fact that resolving 3D ambiguity is a resource-intensive process involving working memory, and working memory was also required in integrating traffic location information across the two display panels. We currently do

not have eye movement data to support either hypothesis, though another experiment has recently been run which addresses this issue.

In terms of the specific traffic awareness measures used in this study, there was an apparent speed-accuracy tradeoff between the memory-based (display blank) and perception-based (display present) conditions. While pilots took longer to make their traffic positions estimation when the display was present, those judgments were made with greater accuracy. This tradeoff was amplified in the OW present condition presumably due to the fact that the OW provided a visual context that could be compared to the traffic location within the display, or the pilot's memory thereof (decreasing error), but taking time to do so (increasing response time).

This study not only examines dimensionality within a new context (an SVS IHD), it also addresses a new design concept which was intended to bring the "best of both worlds" (i.e., 2D coplanar and 3D displays) together in a split-screen format. Importantly, the 2D coplanar display appeared to best support traffic awareness. Equally important is the comparison of SA methodologies within a traffic awareness framework. Overall, the memory-based measurement technique appeared to be the most sensitive to display differences in supporting traffic awareness. These findings have implications for both the design of an IHD and the evaluations which lead to the recommendations therein.

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