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Synthetic Vision Systems: Flightpath Tracking, Situation Awareness, and Visual Scanning in an Integrated Hazard Display

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SYNTHETIC VISION SYSTEMS: FLIGHTPATH TRACKING, SITUATION AWARENESS, AND VISUAL SCANNING IN AN INTEGRATED HAZARD DISPLAY

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Twenty-four certified flight instructors participated in an experiment designed to examine the viability of three Integrated Hazard Display (IHD) formats representative of Synthetic Vision System (SVS) technology (2D coplanar, 3D exocentric, split-screen; Wickens, 2003) in supporting flightpath tracking and situation awareness (SA). SA was probed through the use of two techniques, a memory-based technique called SAGAT and a variant of a perception-based technique called SPAM. Overall, the 3D exocentric display appeared to be the worst display format in terms of supporting SA and utilizing visual attention for the betterment of performance. There was an apparent speed-accuracy tradeoff between the memory-based (display blank) and perception-based (display present) conditions such that pilots took longer to make their traffic position estimations when the display was present, but those judgments were made with greater accuracy compared to when the display was removed. The perception-based measurement technique appeared to be the most sensitive to display differences in supporting SA.

Introduction

Synthetic vision systems (SVS) have been proposed as a possible solution to such problems in aviation as controlled flight into terrain and low-visibility conditions (Alexander, Wickens, & Hardy, accepted; Prinzel, Comstock, Glaab, Kramer, & Arthur, 2004; Schnell, Kwon, Merchant, & Etherington, 2004). SVS provides an artificial, real-time presentation of terrain and traffic to enhance situation awareness (SA), combined with a depiction of the planned trajectory from a 3D perspective to support guidance and control (Williams, Waller, Koelling, Burdette, Doyle, Capron, Barry, & Gifford, 2001).

While a primary flight display (PFD) has been developed to provide tunnel flightpath guidance, it may or may not also be used to represent other hazards such as terrain or traffic aircraft. In the absence of such information within the PFD itself, a critical component of the SVS suite becomes the Integrated Hazard Display (IHD). IHDs are specifically being developed to assist in navigational tasks by representing terrain and traffic hazards through the use of high-resolution terrain databases and satellite-based navigation systems. However, the best perspective from which to present 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. The goal of the current study is to examine flight performance, situation awareness (SA), and visual scanning in the context of three IHD frame of reference formats: the 2D coplanar, 3D exocentric, and split-screen displays.

A 2D coplanar display contains a top-down view of the flight environment in the top panel, as well as a side-view depiction in the bottom panel, also called a vertical situation display (VSD; Fadden, Braune, & Wiedemann, 1993; Thearle, 2002). More precise spatial and relative position judgments are best made using a 2D coplanar display due to its unambiguous depiction of the three dimensional airspace (St. John, Smallman, Bank, & Cowen, 2001; Wickens, 2000). Despite its faithful axis representation, the 2D coplanar display imposes a visual scanning cost due to the presentation of lateral and vertical information on two different display panels. This spatial separation of information will produce information access costs (IACs) to the extent that cognitive and/or physical effort must be exerted in sampling the two views (Wickens, 1992).

While 3D displays have been supported due to their "natural", integrated representation of the 3D world, costs in terms of biases and distortions are inherent. Namely, the "2D-3D effect" leads pilots to subjectively rotate vectors in depth more parallel to the viewing plane (McGreevy & Ellis, 1986). This effect may be manifest as the compression effect which describes how at least two of three axes must be compressed to display a 3D world on a 2D screen. Increased compression is associated with a reduction in resolution which will lead to a bias in estimating distances along the compressed axis as shorter than they really are (Boeckman & Wickens, 2001).

One possible solution to the tradeoffs between 2D and 3D displays is the "split-screen display", consisting of a 3D exocentric view to support global awareness and the side-view VSD of the 2D coplanar format to support precise hazard localization and avoidance. Although split-screen displays resolve issues of bias and distortion associated with 3D displays by also providing a VSD which inherently maintains faithful axis representations, inappropriate allocation of visual attention to the more compelling and information-rich 3D exocentric panel may deter performance overall, as found in previous work involving a split-screen display (Olmos, Wickens, & Chudy, 2000; note that this study used 3D exocentric and 3D egocentric panels, without a VSD).

Given the importance of SA maintenance in preventing incidents from occurring under low-visibility or terrain-challenging conditions, we now turn to the issue of measuring SA. SA can be defined as “the perception of the elements within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future” (Endsley, 1995, p. 36). Endsley (1988) 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 series of questions concerning the location of entities within the display. These questions must be answered by consulting working memory or long-term working memory.

It has been argued that having high situation awareness does not necessarily require **memory** of relevant information. Durso and colleagues (1998) proposed that knowing where to find information could be indicative of good situation awareness even if that information was not available in memory. In light of this, a Situation Present Assessment Methodology (SPAM) was developed which would rely on perception of the situation at hand in answering real-time probes.

Analysis of these techniques suggests the likelihood of a speed-accuracy tradeoff. SA measures of perception (e.g., SPAM) may lead to greater accuracy, given that the original data are available for inspection, but this would be at the cost of a longer response time since it will take time to process that information. These results, of course, would be relative to lower accuracy and faster response times with SA measures of memory (e.g., SAGAT) given that without the original data available pilots will be forced to rely upon a degrading memory trace. Such a tradeoff was indeed found in a previous study examining traffic awareness within an IHD context (Alexander & Wickens, 2004).

The current paper describes results from a study which examined flightpath tracking, SA, and visual scanning to assess attention allocation within an IHD context. A PFD containing a tunnel-in-the-sky was presented in the upper-left corner of the screen, while the IHD was presented to the right of it. Given that the PFD provided tunnel guidance, the format of which was consistent across IHD presentations, we do not expect to see differences in flightpath tracking across display types. Any differences therein, however, would presumably be governed by the extent to which the IHD demanded attention from the pilot, a quantity inferred in the present experiment from the measure of visual scanning.

SA, or more specifically, traffic awareness, was probed through SAGAT and SPAM. Our SAGAT probes consisted of freezing the simulation and blanking the IHD at unexpected times and asking pilots to estimate the position of a queried aircraft in the outside world based on its representation within the IHD (note that aircraft were not visible in the outside world). Our SPAM-variant also consisted of freezing the simulation, although the IHD and queried traffic remained visible. SA as measured by traffic probes will presumably be better supported by a 2D coplanar or split-screen display than a 3D exocentric display due to the faithful axis representation within the former formats (both panels of the 2D coplanar, bottom panel of the split-screen).

The display modulation of flightpath tracking and SA traffic position estimation performance will also be examined in terms of visual scanning measures of pilot attention allocation. Such measures are hypothesized to reveal (dis)associations with performance to the extent that relations of changing performance and/or scanning behavior across conditions can speak to the nature of the underlying processes. For example, in terms of flightpath tracking performance, equivalent performance is predicted across display types. Scanning measures might reveal, however, that less visual attention is demanded in a specific display, therefore allowing more visual attention to be freed for other tasks. The freeing of visual resources may be seen as an advantage to that display despite equivalent flightpath tracking performance, given that the flight environment is often composed of multiple task demand at any given time.

Method

Twenty-four certified flight instructors (age, M = 21.6; experience, M = 514 total flight hours, M = 83 instrument flight hours) from the University of Illinois Institute of Aviation flew a series of flightpaths and made judgments regarding traffic locations based on the representations of three IHD formats. The experiment was conducted on a highfidelity Frasca flight simulator with a 180° outside-world view spread across three display screens. Pilots were paid $9/hour for their participation.

Displays

2D Coplanar. The coplanar display shown in Figure 1a consisted of two windows offering a horizontal, top-down (X-Z axes) view and a vertical, side-looking (Y-Z axes) VSD projected orthogonally (without perspective information) depicting 4 miles ahead of ownship and 1 mile behind. The terrain in the top-down panel is color-coded relative to ownship: red represents terrain that is higher than ownship, yellow represents terrain that is up to 1000ft lower than ownship, black represents terrain that is more than 1000ft lower than ownship. A predictor vector based on current state information was displayed.

3D Excocentric. The 3D exocentric display presented a "tethered" view (see Figure 1b). An elevation angle of 45° was imposed to optimize judgments within the longitudinal and vertical dimensions (Boeckman & Wickens, 2001) with an azimuth offset of approximately 10° in the clockwise direction (Ellis, McGreevy, & Hitchcock, 1987). The ambiguity of judgments in the vertical direction was further reduced by attaching a "drop line" from ownship and other aircraft to the terrain below (St. John, Cowan, Smallman, & Oonck, 2001: Wickens, 2003). A predictor vector based on current state information was displayed.

Split-Screen. The split-screen view was comprised of a 3D exocentric view in the top panel and a side-view VSD in the bottom panel (see Figure 1c). A predictor vector based on current state information was displayed.

(a) (b) (c)

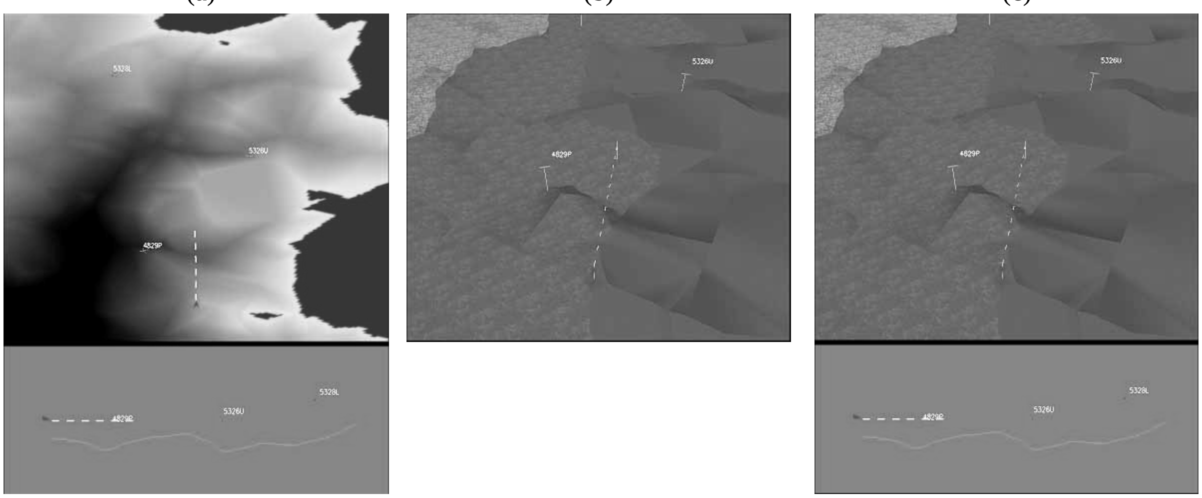

Figure 1. *Display formats: (a) 2D coplanar display, (b) 3D exocentric display, and (c) split-screen view.*

Task & Design

Pilots made traffic location judgments on a total of 60 aircraft targets across the three IHD types. Pilots flew scenarios containing multiple aircraft, between one and four of which were within the display view at any given time. Pilots were periodically asked, during simulation freezes, to estimate the location of the nearest aircraft within the outside world. Visibility was adjusted so that these aircraft were <u>not</u> visible in the outside world. However, the outside world did present the corresponding mountainous terrain that was visible on the display, so that correspondence between locations in the outside world and the display could be easily established. During simulation freezes on some trials the display would remain visible (SPAM-variant), whereas on others, it would blank (SAGAT).

Upon one of these two 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 outside world 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 the scenario. Pilots were instructed to perform the location estimation task as quickly and accurately as possible.

A within-subjects manipulation of IHD format was used. The presentation of IHD format was counterbalanced so that every possible combinatory order of the formats was used, and then repeated in reverse order. Display presentation was counterbalanced across pilots. The two display present/blank conditions described previously were quasi-randomized within each scenario.

Eye movements were recorded by an Applied Systems Laboratory (ASL) Model 5000 eye-tracker throughout the experiment. Those data collected during the simulation freezes were removed from analysis.

Results

Flightpath Tracking Performance. Given that flightpath information was presented identically across display types (that is, shown in the egocentric PFD in the upper-left corner of the display), it is not surprising that there were no main effects of display type in either vertical or lateral deviations ($F(2, 46) = 0.87$, $p > .42$; $F(2, 46) = 1.12$, p > .33, respectively).

SA Response Time. Results revealed a significant main effect of SA measurement condition ($F(1, 23) = 43.2$, $p < .001$) such that response time to the traffic awareness probes was two seconds faster in the memory (display blank; $M = 6.44$ s) than perception (display present; $M = 8.44$ s) condition. There was no effect of display nor an interaction of display type and condition (both $p > .24$).

*Vertical Position Estimation Error***.** As shown in Figure 2, vertical estimation error results revealed a significant main effect of SA measurement condition ($F(1, 23) = 33.6$, $p < .001$) such that estimation error was about two degrees of visual angle greater in the memory (display blank; $M = 6.64$ degrees) than perception (display present; $M = 5.15$ degrees) condition.

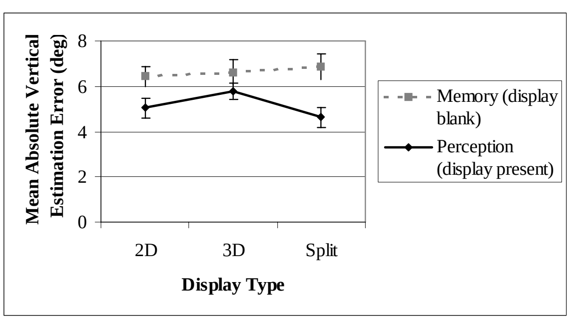

Figure 2. *Mean absolute vertical estimation error by display type and condition.*

Although there was no effect of display nor an interaction of display type and condition (both $p > .22$), there was a significant difference within the perception (display blank) limb such that vertical estimation error was about 1.5 degrees greater with the 3D ($M = 5.78$ degrees) than split-screen ($M = 4.63$ degrees) display ($t(23) = 2.53$, $p < .02$).

Lateral Position Estimation Error. There was a significant main effect of condition ($F(1, 23) = 25.4$, $p < .001$) such that lateral estimation error was about four degrees of visual angle greater in the memory (display blank; $M = 11.9$ degrees) than perception (display present; $M = 7.93$ degrees) condition. There was no effect of display nor an interaction of display type and condition (both $p > .26$).

Mean Percent Dwell Time. The allocation of attention, as measured by percent dwell time (PDT) within the different areas of interest (AOI), is shown in Figure 3. Again, these measures do not reflect scanning during simulation freezes. Results reveal an obvious dominance of scans to the PFD about 66% of the time in all display conditions. Visual attention was captured roughly 19% of the time by the top panel of the IHD, regardless of whether that panel presented a 2D or 3D view. Scanning to the VSD and outside world was equivalent between the 2D coplanar and split-screen formats, accounting for about 8% of the time, within the 2D coplanar and split-screen displays. Given that the 3D exocentric display format did not have a VSD representation, the extra visual attention which had been directed to the VSD in the other two displays was instead split among the PFD and top panel of the IHD (i.e., the 3D view).

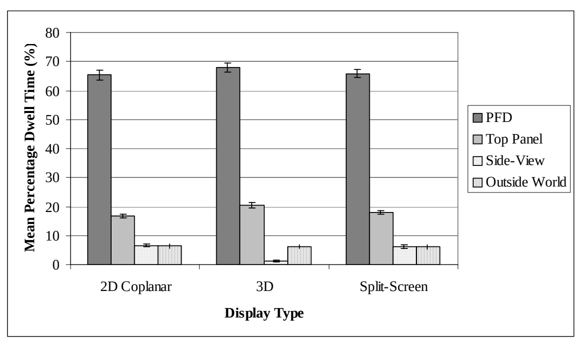

Figure 3. *Mean percentage dwell time by display type and area of interest.*

In terms of effects driven by the attentional demands of the IHD formats, a few differences within the individual AOIs are of interest. First, visual attention was directed to the PFD about 2% of the time more with the 3D exocentric display than either the 2D coplanar or split-screen views ($F(2, 46) = 3.27$, $p < .05$). Pilots also spent about 3% more time looking at the IHD with the 3D exocentric display compared to visual scans to the 3D panel of the IHD in the 2D coplanar and split-screen views ($F(2, 46) = 16.7$, $p < .001$). However, pilots spent less time looking at the IHD in the 3D display than they spent looking at both panels of the IHD in the other two formats.

Discussion

In examining the null effects of display type within the flightpath tracking data, it is apparent that pilots were protecting the primary flight task of aviating and navigating. In other words, attentional demands of the different IHD formats did not affect tracking performance as pilots were appropriately treating that task as top priority.

Added visual attention to the PFD in the 3D exocentric condition did not improve flightpath tracking performance relative to that obtained with the 2D coplanar and split-screen displays. Increased scans to the IHD with the 3D exocentric compared to the 2D coplanar and split-screen displays also showed no improvement in terms of estimating traffic position during the SA probes, and indeed, position estimation error within the vertical dimension, in fact, was worst with the 3D display (in the display present condition). SA within the 3D exocentric display was expected to be more poorly supported due to the lack of a faithful presentation of the vertical dimension. Hence, the added visual attention to the IHD was not enough to resolve the ambiguities inherent to a 3D exocentric viewpoint.

Interestingly, the only display difference found in the SA data was revealed within the perception-based (display present) SPAM condition. As already discussed, traffic position estimation was found to be better supported by the split-screen than 3D display when examining judgments specifically within the vertical dimension. This finding of the SPAM condition being most sensitive to display differences requires further exploration.

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 compared to when the display was removed. As described in the introduction, such a tradeoff was expected given that more perceptual data was available during display-present SPAM simulation freezes, and it therefore took pilots longer to process the available information. The consequence of this longer processing, however, is for improved accuracy relative to the degraded memory trace available in the display-blank SAGAT freezes.

Conclusions

This study not only examines dimensionality within an important context for aviation safety (an SVS IHD), it also addresses a relatively new design concept which brings the “best (or worst) of both worlds” (i.e., 2D coplanar and 3D displays) together in a split-screen format. Importantly, the 3D exocentric display appeared to be the worst display format in terms of supporting SA and utilizing visual attention for the betterment of performance. Thus highlighting the critical importance of a VSD for hazard awareness (Fadden et al., 1993; Thearle, 2002). Importantly, while such a VSD “consumes” slightly more attentional resources to process, the withdrawal of these resources from the PFD led to no decline in performance.

Equally important is the comparison of SA methodologies within a traffic awareness framework. A speed-accuracy tradeoff is noted between the perception-based (SPAM) and memory-based (SAGAT) conditions such that pilots took longer to make their traffic position estimations when the display was present, but those judgments were made with greater accuracy compared to when the display was removed. The perception-based measurement technique appeared to be the most sensitive to display differences in supporting SA task, although display differences were only found within the vertical dimension position estimations.

These flightpath tracking, SA, and visual scanning findings have implications for both the design of an IHD in terms of display format, and the evaluations which lead to the recommendations therein. Given the overall lack of display differences found, specifically between the 2D coplanar and split-screen views, more experimentation is recommended in resolving what types of tasks one format might be better than the other in supporting. We have only examined one task in the current study, traffic awareness, one of a general class of SA measures. More comprehensive conclusions with regard to global awareness, hazard localization, and hazard avoidance measures are desired in recommending a single IHD format.

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