FLIGHTPATH TRACKING, CHANGE DETECTION AND VISUAL SCANNING IN AN INTEGRATED HAZARD DISPLAY

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Twenty-four certified flight instructors were required to fly a series of curved, step-down approaches while detecting changes to surrounding traffic aircraft and weather cell icons on two integrated hazard display (IHD) formats (2D coplanar and split-screen) under varying workload levels. Generally, it appears that the 2D coplanar IHD was better in supporting flightpath tracking and change detection performance when compared to a split-screen display. Pilots exhibited superior flightpath tracking (in the vertical dimension, and under low workload) when using the 2D coplanar IHD, although this effect was mitigated by increasing workload such that tracking deteriorated faster with the 2D coplanar than the split-screen display. The spawned 3D cost of diminished size with distance from ownship played a role in change detection response time—pilots were slower (particularly in detecting traffic aircraft changes) with the split-screen compared to the 2D coplanar IHD. These effects will be discussed within the context of visual scanning measures.

INTRODUCTION

Safe and efficient navigation through mountainous terrain or low-visibility conditions can be quite challenging and such conditions have often led to tragic incidents such as controlled flight into terrain (Smith, 2001; Wiener, 1977). Synthetic vision systems (SVS) have been proposed as a possible solution to such problems (Alexander, Wickens, & Hardy, in press; Prinzel, Comstock, Glaab, Kramer, & Arthur, 2004; Schnell, Kwon, Merchant, & Etherington, 2004). SVS suites provide an artificial, real-time presentation of terrain and hazards 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). One critical component of the SVS suite is the integrated hazard display (IHD), which has primarily been used to enhance SA by portraying the relative altitude of surrounding terrain, but is currently being considered as a host for traffic and weather information. The best perspective from which to present the IHD information, however, is still under investigation.

The goal of this study was to examine flightpath tracking and stage 1 situation awareness (SA; Endsley, 1988, 1995) as measured by change detection performance as supported by two IHD formats (2D coplanar and split-screen) under varying workload levels. 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, when compared to 3D exocentric displays, due to their faithful axis representation (St. John, Cowen, Smallman, & Oonk, 2001; Wickens, 2000). However, the 2D coplanar display imposes a visual scanning cost due to the presentation of lateral and vertical information on two different display panels. The split-screen display (Figure 1b) couples a 3D exocentric view with a 2D VSD. Three-dimensional displays have the advantages of adhering to the principle of pictorial realism and allowing for integration in a single display panel. 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). In this study we are specifically concerned with the spawned 3D cost of diminished size with distance—aircraft further from ownship are typically portrayed as smaller than those closer to ownship, presumably making judgments involving the smaller aircraft icons more difficult.

The two display formats examined in the present research have also been compared in both static and dynamic simulations dealing with SA measurement in terms of traffic and terrain probes (Alexander & Wickens, 2004, 2005). In the first of those experiments, pilots viewed static images of traffic scenarios and then estimated the outside world locations of queried traffic. The 2D coplanar IHD supported better lateral traffic position estimation than the split-screen format. This finding was inferred to be due to attention allocation strategies employed within the split-screen display in which pilots presumably spent enough time looking at the precise vertical dimension representation provided in the VSD, so as to degrade lateral estimations which would only be supported by the top 3D panel. Similar attention allocation effects were found by Olmos and colleagues (2000).

A second experiment comparing the two display types used in the present research required pilots to fly a series of approaches while estimating the outside world locations of queried traffic and responding to terrain probes during simulation freezes (Alexander & Wickens, 2005). While there were no differences between the two IHD formats in terms of traffic position estimation performance, terrain awareness was better supported by the split-screen format due to its photorealistic, 3D portrayal of the surrounding environment.

In the present experiment, pilots were required to fly a series of curved, step-down approaches while detecting changes to surrounding traffic aircraft and weather cell icons under varying workload levels. We hypothesized that the costs of diminished size with distance in the split-screen display
would lead to slower change detections, especially to changes in surrounding aircraft, given that aircraft further away from ownship in the top panel took up less display space. Furthermore, the top-panel exocentric view may have been so compelling as to draw attention away from the VSD which contained a more precise depiction of vertical positioning. We expect that if pilots re-allocate attention to the top panel of the split-screen display, in an attempt to resolve the costs associated with diminished size, flightpath tracking performance will degrade. These effects are expected, however, to be mitigated by increasing workload given that previous studies have found costs to performance under high workload with a 2D coplanar but not with a 3D exocentric display (e.g., Alexander, Wickens, & Merwin, 2005), which comprises the top panel of the split-screen display in the current study. High workload will reduce the resources available to meet the demands associated with scanning the separate panels of the 2D coplanar display in order to accurately detect changes, therefore drawing resources from the flightpath tracking task. These effects will be discussed within the context of visual scanning measures collected throughout the experiment.

Figure 1. (a) 2D-Coplanar IHD; (b) Split-Screen IHD. Both screenshots show the experimental set-up consisting of the tunnel-in-the-sky in the upper left and the IHD on the right.

METHOD

Twenty-four certified flight instructors (experience, \( M = 514 \) flight hours; age, \( M = 21.6 \) years) made a series of judgments regarding traffic locations based on the representations of two different display types: a 2D coplanar and a split-screen view. 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 two ways: 2D coplanar and split-screen. The general display set-up, shown in Figure 1, 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. Ownship was always presented as a magenta icon in all display types, while other aircraft were mostly white.

2D Coplanar. As shown in Figure 1a, 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.

Split-Screen. As shown in Figure 1b, the top panel of the split-screen view consisted of a 3D exocentric view representing 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 vertical 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 bottom panel consisted of a vertical situation display as described above.

Task and Experimental Design

Pilots were asked to accurately fly a number of curved, step-down approaches containing various heading and altitude changes as represented by a tunnel-in-the-sky. Periodically, changes occurred to aircraft (altitude or heading) or weather...
cell (altitude or shape) icons. Aircraft and weather cell altitude changes were on the order of 300 ft, subtending approximately 3 degrees of visual angle at about 0.3 degrees of visual angle per second. Aircraft heading changes were on the order of 180 degrees at a rate of approximately 18 degrees per second. Weather shape changes were on the order of 30 ft in diameter at a rate of approximately 3 feet per second (in real-world terms). Upon detecting a change, pilots were required to press the right push-to-talk button and verbalize the type of change detected (i.e. “64 X-ray descending”).

Two workload levels were created. High workload was characterized by both introducing simulated turbulence and increasing the number of traffic aircraft and weather cells present in the airspace surrounding ownship relative to the low workload condition. These aircraft and weather elements served the dual purpose of increasing the amount of clutter within the IHD and the number of elements through which the pilot must successfully search in order to detect changes.

Airspeed was fixed at 100 knots until the final approach leg to ensure that all element changes were encountered at the same point in each scenario across all participants. Manual control of airspeed resumed upon crossing a final approach fix. Each scenario started in VMC but quickly degraded to IMC as if ownship flew up into the clouds. The majority of each scenario was flown in IMC to simulate actual conditions within which SVS is expected to be used. Conditions returned to VMC on the final approach leg so that the pilot could see the runway both on the SVS display and in the outside world.

A within-subjects manipulation of IHD format was used. The presentation of IHD format was counterbalanced so that each of the two IHD formats were flown with two levels of workload, for a total of four conditions presented in counterbalanced order. Visual scanning measures were collected throughout the experiment with an Applied Science Laboratories (ASL) Model 5000 monocular eye tracker and an Ascension Flock of Birds™ mid range magnetic head tracker.

RESULTS and DISCUSSION

Less than 5% of the data were removed as outliers. Log transformations were performed on the flightpath performance data (altitude and lateral deviations) in order to produce a more normally distributed data set.

Flightpath Performance. A repeated measures ANOVA on the vertical flightpath deviation data, shown in Figure 2, revealed that there was a main effect of workload such that there was less deviation under low than high workload (F(1, 23) = 32.6, p < .01). A planned comparison of display differences under low workload (n(23) = 1.9, p = .07) revealed that vertical deviations were greater with the split-screen than 2D coplanar display; a similar comparison revealed no differences under high workload (p > .15). A significant display x workload interaction revealed that increasing workload imposed a 12% greater cost on the 2D coplanar than on the split-screen (F(1, 23) = 4.48, p < .05) display. There were no significant effects on lateral flightpath deviations (all p > .15).

![Figure 2. Mean absolute vertical flightpath error by display type and workload level.](image)

Change Detection Performance. Analysis of the change detection response time data, as shown in Figure 3, revealed that pilots were faster at detecting changes with the 2D coplanar (M = 7.58 s) than the split-screen (M = 8.44 s) display (F(1, 23) = 6.39, p < .05) and that detection was faster under low (M = 7.62 s) than high (M = 8.26 s) workload (F(1, 23) = 3.20, p = .08). A display type x change type interaction (F(1, 23) = 7.22, p < .05) was primarily driven by traffic aircraft changes being detected faster with the 2D coplanar (M = 7.67 s) than the split-screen (M = 9.25 s) display, while weather changes were not.

![Figure 3. Mean change detection time by display type, workload level, and change type.](image)

It is possible that this selective effect within the traffic changes was due to the fact that, in the split-screen display, aircraft further away from ownship within the exocentric view would be seen as smaller, and therefore changes to those icons would be more difficult to detect. In order to examine this possibility, change detection performance was analyzed as a function of distance. We specifically analyzed the traffic changes as these would be most susceptible to the cost of diminished size given that distant planes would be represented by smaller icons, hence making them more difficult to see in and of themselves, as well as making their movement less apparent. Weather cell icons were of a sufficient size so as not to be subject to such costs of diminished size, although the
amount of movement would indeed be diminished with greater distance. A regression analysis on the distance of traffic changes from ownship and the time in which it took pilots to detect them revealed a marginally significant effect indicating that, within the split-screen display, changes occurring farther from ownship were detected more slowly than those changes occurring closer to ownship \((F(1, 22) = 3.27, p < .08)\). This effect appears to account for about one second of slowing in detecting traffic changes within the split-screen view. There was no effect of distance within the 2D coplanar display \((p > .15)\).

The change detection accuracy data revealed that change detection accuracy was greater under low \((M = 75\%)\) than high \((M = 49\%)\) workload conditions \((F(1, 23) = 88.3, p < .01)\). There was also an interaction of workload x change type \((F(1, 23) = 8.31, p < .01)\) revealing that weather cell changes were detected with lower accuracy \((M = 38.2\%)\) than traffic changes \((M = 59.9\%)\) under high workload, but not under low workload conditions. Display format had no influence on change detection accuracy, nor did it interact \((p > .15)\).

**Mean Percent Dwell Time.** Figure 4 shows the PDTs to the different AOIs collapsed across display type and workload level. Results revealed a dominance of scans to the PFD: about 48\% of the time across both display conditions. In analyzing the effects of the IHD formats on visual attention allocation, we found a marginally significant effect that pilots using the split-screen IHD scanned the PFD slightly more \((49\%)\) of the time than pilots using the 2D coplanar IHD \((47\%); F(1, 23) = 3.96, p = .05)\). Workload also had a marginally significant effect on PFD scans in that pilots spent somewhat less time looking at the PFD under high \((M = 47.2\%)\) than low \((M = 48.8\%)\) workload conditions \((F(1, 23) = 4.08, p = .05)\). Display type and workload did not interact in their effect on PFD scanning \((p > .15)\).

![Figure 4. Mean percent dwell time by display type, workload level, and AOI.](image)

It appears that under high workload pilots borrowed scans from the PFD in order to monitor the greater amount of objects (traffic or weather cell icons) represented within the IHD, although analyses of the IHD reveals such reallocation was only directed to the top panel of the IHD \((F(1, 23) = 12.7, p < .01)\) as opposed to the VSD panel \((p > .15)\). Overall, the top panel of the IHD was looked at about 30\% of the time while the bottom panel (VSD) was looked at about 19\% of the time. Across both workload levels, pilots using the 2D coplanar IHD spent more time scanning the top panel \((32\%)\) than pilots using the split-screen format \((28\%; F(1, 23) = 11.2, p < .01)\). Increased scanning to the top panel of the 2D coplanar IHD appeared to also account for faster detection times in noticing traffic changes.

In order to examine the pattern of attention allocation within the IHD, a second 3-way ANOVA was conducted on display format \((2D\coplanar,\text{split-screen})\), workload level \((\text{low, high})\), and IHD panel \((\text{map, VSD})\). A marginally significant effect revealed that workload and IHD format interacted in their influence on scanning the different panels of the IHD \((F(1, 23) = 3.50, p = .07)\), suggesting that increased workload shifted 3-4\% of scanning to the top panel of the IHD from the bottom panel within the split-screen view, while this was not the case in the 2D coplanar display.

**DISCUSSION**

This experiment was designed to evaluate two IHD formats \((2\text{D}\coplanar,\text{split-screen})\) under varied workload levels and within the context of a change detection task, designed to assess stage 1 SA. As discussed in the introduction, visual scanning and costs of diminished size were hypothesized to drive performance based on the different display characteristics within each IHD format.

As hypothesized, pilots exhibited superior flightpath tracking \((\text{in the vertical dimension})\) when using the 2D coplanar IHD, at least when workload was low. As workload increased, tracking error degraded to a greater extent when pilots were using the 2D coplanar than when using the split-screen format. Tracking error within the 2D coplanar display, however, was never worse than that within the split-screen display. Similar effects of workload on flightpath tracking performance within 2D coplanar and 3D exocentric (the view represented in the top panel of our split-screen format) displays have also been found in the CDTI literature \((\text{Alexander et al., 2005})\). Essentially, display suites containing a 3D panel \((\text{split-screen in the current study, 3D exocentric view in previous studies})\) were less sensitive to increasing workload costs.

We infer that increasing workload levels were more detrimental to flightpath tracking performance given a 2D coplanar IHD as opposed to a split-screen IHD because of increased scanning demands imposed by the 2D coplanar format. More specifically, each aircraft or weather cell icon consisted of two representations: one in the top panel offering lateral and longitudinal information regarding that icon, and one in the bottom VSD panel offering vertical and longitudinal information. In order to detect the types of changes imposed in this experiment \((\text{traffic: heading or altitude, weather: shape or altitude})\), pilots were required to continuously scan the two panels as changes would only be seen in one or the other. With increasing workload, this task became more difficult as there were physically more items represented within the IHD and...
there were more items changing across the course of the scenario which the pilot needed to detect. As evidenced by the visual scanning data, the demands associated with this increasing difficulty appeared to draw more resources away from the PFD and the flightpath tracking task than that demanded by detecting changes in the split-screen format. Note that in the split-screen display, all changes had at least some chance of being detected by just scanning the top 3D exocentric panel.

The spawned 3D cost of diminished size with distance from ownship played a role in change detection response time—pilots were slower (particularly in detecting traffic aircraft changes) with the split-screen compared to the 2D coplanar IHD, regardless of workload level. Given the finding that detecting changes to aircraft icons in a 3D exocentric view (as that shown in the top panel of the split-screen display) takes longer than in a 2D coplanar display, one might ask why the designer would choose to show aircraft further from ownship as smaller icons than aircraft closer to ownship. The answer to this of course deals with the depth cue of distance. In naturalistic viewing objects further from oneself appear smaller in physical size. If all icons within a 3D display were the same size, regardless of distance from ownship, this depth cue would be compromised and presumably it would be more difficult for pilots to make accurate position estimation judgments. Furthermore, a case can be made that changes farther from ownship generally are less relevant (Muthard & Wickens, 2002) and therefore can be detected slower than those close by.

Pilots apparently did not compensate for the inherent deficiency (cost of diminished size) of the 3D exocentric top panel of the split-screen view by looking at it more (and therefore looking at the PFD less). In fact, we found just the opposite—that the split-screen display induced a shift toward the PFD at the expense of the IHD. Thus, the scanning costs of the dual-panels appeared to dominate the diminished size costs of the split-screen display insofar as the demand for visual attention by the IHD (and hence, allocation of spare attention to the PFD) was concerned. Workload level, while not affecting change detection, had joint effects on vertical flightpath tracking (discussed above) and resource allocation between the two panels of the IHD. Higher workload increased scans to both panels of the IHD with the 2D coplanar display, but did not lead to increased scans to the IHD panels of the split-screen display.

CONCLUSIONS

The findings from the present study have implications for the design of an IHD in terms of display format, at least in terms of supporting flightpath tracking and change detection performance under varied workload levels. While the results from the current experiment favor the use of a 2D coplanar IHD, the collective results of a series of experiments comparing these two display formats do not necessarily point to a clear “winner”. We therefore suggest that these formats continue to be examined under the full range of flight-related tasks, and that those results be subject to a task analysis in which task frequency and the cost of performing a task inadequately are appropriately taken into account.

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REFERENCES


