EXAMINING THE EFFECTS OF GUIDANCE SYMBOLOGY, DISPLAY SIZE, AND FIELD OF VIEW ON FLIGHT PERFORMANCE AND SITUATION AWARENESS

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Two experiments conducted in a high-fidelity flight simulator examined the effects of guidance symbology, display size, and field of view (FOV) on flight performance and situation awareness within a Synthetic Vision System (SVS). In Experiment 1, 18 pilots flew highlighted and lowlighted tunnel-in-the-sky displays and a less-cluttered follow-me-aircraft (FMA) through a series of curved approaches over rugged terrain. The results revealed that both tunnels supported better flightpath tracking than the FMA due to the availability of more preview information. Increasing tunnel intensity had no benefit on tracking, and in fact, traffic awareness was degraded. In Experiment 2, 24 pilots flew a lowlighted tunnel display configured according to different display sizes (small or large) and FOVs (30° or 60°). Measures of flightpath tracking and terrain awareness generally favored the smaller display and the 60° FOV.

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 (Comstock, Glaab, Prinzel, & Elliott, 2001; Scott, 2001; Stark, Comstock, Prinzel, Burdette, & Scerbo, 2001). Such systems provide an artificial, real-time presentation of terrain and other hazards to enhance situation awareness, particularly traffic and terrain awareness, combined with a depiction of the planned trajectory and augmented symbology to support guidance and control (Williams, Waller, Koelling, Burdette, Doyle, Capron, Barry, & Gifford, 2001). The Primary Flight Display (PFD) is one component of SVS, designed to provide guidance information, though important design issues exist concerning its appropriate format.

The present research, involving two high-fidelity flight simulations, examined the effects of changes to the PFD on flightpath performance and situation awareness (of traffic and terrain). In the first experiment, we consider the differences between a highlighted tunnel-in-the-sky (Williams, 2000; Fadden, Ververs, & Wickens, 2001), a lowlighted tunnel, and a follow-me-aircraft (FMA; Beringer, 2000) with a particular emphasis on traffic awareness. Two primary hypotheses underlie the manipulations in Experiment 1. First, that the FMA, by increasing the precision with which the flightpath is represented, might induce more precise tracking via a greater sense of “urgency” (Boeckman & Wickens, 2001; Doherty & Wickens, 2001; Onstott, 1976), but this added effort would cause a “keyholing” (Woods, 1984) disruption in the detection of peripheral targets, particularly relative to the lowlighted tunnel. Alternatively, the tunnel might provide valuable flightpath prediction information, inherent in its walls (future headings) and multiple segments (curvature of turns) that would be lacking in the single-point FMA (Mulder, 2003). Second, we hypothesized that imposing a highlighted tunnel would improve tracking performance (making the required guidance more salient), but do so at the expense of detection of traffic symbols on the SVS display, which would be more obscured by the higher intensity strokes when contrasted with such detection in either the lowlighted tunnel or the FMA (Wickens, Muthard, Alexander, van Offlen, & Podczerwinski, 2003).

Experiment 2 manipulated the way in which display distances represented world distances by varying the display size (small or large) and FOV (magnifying, 30° or minifying, 60°) of the world representation (Comstock et al., 2001; Stark et al., 2001), with an emphasis on terrain awareness. Both of these affect the ratio of the visual angle of the display to the visual angle represented in the world (VAD/VAW), which amounts to an expression of display gain. We hypothesized that (1) higher display gains would produce a greater sense of urgency in reducing flightpath tracking error (Stark et al., 2001); (2) the particular configuration of parameters that produced the unity gain (large/30°) would produce the smallest bias in knowing where things were, improving those aspects of SA related to position estimation, and perhaps improving tracking performance since the gain on the display was equivalent to the gain of direct viewing; and (3) the smaller FOV, presenting less depiction of the world, would contribute to a keyholing loss of SA (Beringer & Ball, 2001; Stark et al, 2001; Wickens & Prevett, 1995).

EXPERIMENT 1

Methods

Eighteen pilots (experience, M = 503 flight hours; age, M = 22 years) flew a sequence of six flight scenarios designed to compare three guidance symbology formats: highlighted and lowlighted tunnels, and the FMA. The experiment was conducted on a high-fidelity Frasca flight simulator with a 180° forward field of view.

Displays. All display formats (see Figure 1) overlaid a computer-generated terrain. A small 2D electronic map was placed in the upper right corner of the SVS display, representing the Navigation Display. Ownship was represented as a green “W”, and a white predictor portrayed the pilot’s estimated position five seconds ahead of ownship. The tunnel displays were depicted by a series of connected
green boxes 300 ft apart. Pilots maintained ownship position in the center of the path by keeping the predictor in the center of the tunnel. The FMA was a red, 3D perspective, aircraft-like symbol positioned in the center of the now-invisible tunnel, five seconds ahead of ownship. Pilots maintained ownship position in the center of the path by keeping the predictor on the FMA.

Task and Experimental Design. Pilots flew a series of six, eight-ten minute flights in simulated VMC, following curved paths over rugged terrain to an airport, with each of the three guidance symbologies. The flight paths were depicted on an electronic map display—a top-down view of the terrain in Yosemite National Park. Airborne hazards were visible against the computer-generated imagery of sky, requiring both acknowledgement and reporting of their true azimuth and elevation angle from ownship. Airspeed was fixed at 100 knots until the final approach leg. A within-subjects, counterbalanced manipulation of display type was used such that each pilot experienced each guidance symbology once, and then again in reverse order.

Results and Discussion

The goal of the present study was to examine flightpath performance and traffic awareness in the context of the three guidance symbology formats: the highlighted and lowlighted tunnels, and the FMA (see Wickens, Alexander, & Hardy, 2003).

Flight Performance. A repeated measures ANOVA on the vertical deviation data (presented in Figure 2) revealed that both the highlighted (M = 4.23 m) and lowlighted (M = 4.23 m) tunnels supported better vertical flightpath performance than did the FMA (M = 6.45 m; F(2, 34) = 6.05, p < 0.01).

Planned comparisons revealed that lateral deviations from the center of the path (see Figure 3) were smaller with the lowlighted (M = 7.18 m) than the highlighted (M = 7.74 m) tunnel (t(17) = -1.8, p < 0.09), and smaller with the highlighted tunnel than the FMA (M = 15.2 m; t(17) = -2.6, p < 0.02). For both flightpath measures note the much larger standard error (between-pilot variability) shown with the FMA.

The FMA produced a clear cost to both lateral and vertical aspects of flight performance, negating our first hypothesis that the FMA would create a greater sense of urgency through the more precise manner in which the flight path was represented. Pilots flying the tunnels presumably extracted useful preview information about the future flightpath from the multiple tunnel segments and their connections, a strategy prevented with the single element.
FMA. A second possible advantage of the tunnel displays relates to the difference between the specification of the desired flightpath, a single point for the FMA versus an area for the tunnels. Pilots, finding it difficult or impossible to precisely line-up their predictor with the FMA, may have relaxed their own internal criterion of allowable tracking error.

Traffic Awareness. Traffic detection was broken down by trials in which traffic became visible toward the middle of the forward field of view (and thus would have been more likely to be behind the tunnel) versus those trials where traffic was toward the periphery. As shown in Figure 4, aircraft located toward the middle of the display were detected much faster ($M = 7.24$ s) than those more towards the periphery ($M = 13.4$ s; $F(1, 16) = 11.2, p < .01$). There was also a nonsignificant trend such that the mean detection time was slowest with the highlighted tunnel ($M = 15.5$ s) compared to both the lowlighted tunnel ($M = 11.1$ s) and the FMA ($M = 10.7$ s; $F(2, 32) = 2.37, p = 0.11$). The interaction was not significant ($F(2, 32) = 0.35, p > 0.70$).

Mental Workload. Subjective mental workload was rated highest with the FMA ($M = 89$), intermediate with the lowlighted tunnel ($M = 76$), and lowest with the highlighted tunnel ($M = 61$). These results reveal an interesting dissociation in which the subjectively easiest (lowest workload) display, the highlighted tunnel, did not support the best performance, as reflected in the traffic awareness data.

In summary, there appeared to be little influence of guidance symbology on traffic awareness when comparing the FMA with the lowlighted tunnel. Thus, the FMA did not appear to narrow the focus of attention in a way that the detection of more peripheral traffic targets would be disrupted. Greater tunnel image intensity, however, disrupted the ability to detect traffic targets by as much as 5 seconds in the highlighted display. Overall, the lowlighted tunnel enhanced traffic awareness without sacrificing flightpath tracking, and appeared to be the best of the three configurations. These results are consistent with the findings of Wickens, Alexander, Martens, and Podczerwinski (submitted) who found that increasing the intensity of display elements does not improve performance on tasks dependent on that brightened information, but does disrupt performance on tasks that depend upon the information not highlighted.

EXPERIMENT 2

Methods

Twenty-four pilots (experience, $M = 639$ hours; age, $M = 24$ years) flew a sequence of eight flight scenarios designed to compare the four display size by FOV formats. Twelve of these pilots participated in Experiment 1, although prior experience had no effect on any of the dependent measures.

Displays. A lowlighted tunnel-in-the-sky display, similar to that used in Experiment 1, was configured according to different display sizes (small, $8''$ x $6.5''$ or large, $10''$ x $8''$) and FOVs ($30^\circ$ or $60^\circ$) as shown in Figure 5.

Task and Experimental Design. The task was similar to that used in Experiment 1, however the focus was now on terrain awareness memory probes rather than airborne hazard detection, and the simulation was flown mostly in IMC. During periodic simulation freezes (with both the PFD and outside world blanked), pilots were asked to indicate the location of certain highlighted terrain locations, that had been visible on the PFD before the blanking, by positioning a cursor.
on the 180° outside world display panel at their remembered locations. Airspeed was again fixed at 100 knots until the final approach leg. A within-subjects, counterbalanced manipulation of display size and FOV was used such that pilots experienced each display size/FOV combination once, and then again in reverse order.

**Results and Discussion**

The goal of the present study was to examine flightpath performance and SA under display size (large or small) and FOV (30° or 60°) manipulations (see Wickens et al., 2003).

**Flight Performance.** Given the nature of the particular values chosen for display size and FOV, it is possible to represent the four display formats quantitatively along a single variable defined by the degree of compression. As shown in Figure 6, the gain of the display (VAD/VAW) is inversely related to the amount of compression that the information in the world receives, as it is translated into display coordinates. For the four displays in question, these gain values ranged from 0.4 to 1.0, with the unity gain represented in the large/30° FOV format, and the 0.4 value (maximum compression) represented in the small/60° FOV format.

![Figure 6. Representation of the display size (small: 23° VAD and large: 33° VAD) and field of view (30° and 60°) conditions. The visual angle on the display depends on the viewing distance, and this was maintained relatively constant for all pilots.](image)

Vertical and lateral flightpath deviations were examined as functions of the display gain to examine the hypothesis that compressed displays might lead pilots to underestimate flight path deviations, and therefore under-estimate those deviations. The vertical tracking data (see Figure 7) revealed a monotonic trend for vertical tracking performance to actually degrade as the gain was increased (F(3, 69) = 2.70, p = 0.05; i.e., opposite the hypothesis), with the poorest performance at the highest (unity) gain (which would correspond to a conformal display if it were presented head up). In interpreting this effect, we can only offer the explanation that a unity gain provides no benefit for a head-down display.

The lateral tracking data (see Figure 8) also revealed a significant trend (F(3, 69) = 19.9, p < 0.01) for higher error at the largest gain, showing the highest lateral error in the least-compressed unity gain condition. It should be noted, however, that this high gain penalty to lateral tracking was strictly the result of the small FOV, and subsequent analysis revealed that it was only observed on curved legs. It might be the case that this penalty was a consequence of the lack of full flightpath preview, when the view ahead was through a narrow FOV and the future flightpath turned the sharpest bends (Beringer & Ball, 2001).

![Figure 7. Mean absolute vertical deviation by display gain. The gains, from smallest to largest expressed by the ratio VAD/VAW, are created by large/30° (0.4), small/30° (0.5), large/60° (0.77), and small/60° (1.0).](image)

**Terrain Awareness.** Across all displays, pilots tended to estimate terrain locations as more toward the center of the display than was the true position of the terrain element (χ²(1, N = 544) = 498, p < 0.01), as if the representation of that element in the display (smaller when compared to the measured extent of the viewing screen) led them to bias their estimate inward. However, of most interest in the terrain awareness data is the finding that the most compressed display condition (large/30°) led to the greatest error in estimating terrain element position. In interpreting this effect, we infer that reducing the amount of terrain viewable (30° FOV) produced the same sort of keyholing for terrain awareness.
Mental Workload. Although flightpath maintenance and terrain awareness measures revealed differences among the different display formats, there were no differences in the reported subjective mental workload ratings (M = 88, all p > 0.30). This mean rating of workload was higher than that found in Experiment 1 (M = 75).

GENERAL DISCUSSION
In general, the results have pointed to an overall advantage for lowlighted tunnels (Experiment 1) presented with a larger FOV with no cost for a relatively small display (Experiment 2). These data were collected in a relatively high fidelity simulation, and assessed a range of tasks and cognitive constructs beyond basic flying, including workload measures not reported here (see Wickens, Alexander, & Hardy, 2003). Several aspects of our results pointed to the possibility that keyholing contributed to undesirable aspects of performance, both in flying and in maintaining situation awareness. For example, flightpath tracking was poorest and most variable with the single-point FMA compared to two tunnel displays in Experiment 1. A tunnel display contains important perceptual properties supporting guidance (Mulder, 2003), namely, flightpath preview inherent to the multiple tunnel segments—such preview is missing from the FMA. In particular, our findings reveal that there is value in presenting the extra “strokes” of information in the tunnel display as long as it is done at a low intensity.

Furthermore, evidence for a keyholing effect on maintaining situation awareness was found in Experiment 2 in that the estimation of terrain element position was least accurate with the most compressed display (large/30°). In contrast, the data provided no clear evidence for the role of a size-mediated urgency function, in spite of similar evidence elsewhere (Boeckman & Wickens, 2001). In fact, recent studies have further suggested that pilots are able to compensate for changes in size through findings that flightpath tracking and change detection performance are rarely different across small and large displays (Wickens et al., 2003). These differences in size-mediated urgency effects are worthy of further investigation.

ACKNOWLEDGMENTS
This research was supported by grant NASA-NAG-1-02071 from the NASA Langley Research Center, for which Dr. Lance Prinzel was the technical monitor. Grant NASA-NAG-1-03014 provided funding for the development of the SVS simulation. Dr. Bettina Beard was the scientific monitor. The authors wish to acknowledge the invaluable support of Ron Carbonari, Jonathan Sivier, Roger Marsh, and Sharon Yeakel for developing the simulation used in this experiment. Robert Bernard helped in the data collection of Experiment 2. Any opinions, findings, and conclusions or recommendations in this publication are those of the authors and do not necessarily reflect the views of NASA.

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