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EFFECTS OF SCENE-LINKED SYMBOLOGY ON FLIGHT PERFORMANCE

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Previous research has shown that the presence of aircraft head-up display (HUD) symbology indicating altitude improves maintenance of altitude, but at a cost to (ground) path-following ability. We term this the *altitude/path performance trade-off*. Differential motion between HUD symbology and the world has been posited as leading to attentional tunneling on the symbology at the expense of flight information in the world. In the first of two flight simulation studies, scene-linked symbology was tested to see if the absence of differential motion cues between the symbology and the world would negate attentional tunneling and the resulting performance trade-off. This not only proved to be the case, but relative to a control condition with no explicit altitude display, scene-linked symbology yielded improved altitude *and* path performance. In the second study, an attempt was made to discern the source of improvement in path performance found with the use of scene-linked symbology. The result suggests that flight task integration and fusion of the symbology with the world permits object-based parallel processing benefits that are evidenced by improved path-following performance.

INTRODUCTION

Aircraft flight instrument symbology has traditionally been made available to the pilot on a panel located forward of the pilot and beneath the flight deck windshield. Head-up display (HUD) technology permits projection of a wide array of graphical flight information and symbology onto a collimated, transparent medium located between the pilot and the windshield. With the HUD both transparent and head-up, the pilot is afforded the opportunity to monitor the external environment in tandem with the aircraft's flight status information. The efficacy of HUDs over traditional head-down flight data presentation has been clearly demonstrated (Weintraub, Haines, & Randle, 1984; Boucek, Pfaff, & Smith, 1983).

Several different studies have, however, illustrated performance problems associated with HUD use. Both Fischer, Haines, and Price (1980) and Wickens and Long (1994) found that, rather than facilitating joint awareness of both the symbology and external world, HUD use can prove detrimental during simulated precision landing approaches. Participants in both studies took longer to respond to unexpected runway incursions when flight symbology was presented head-up than when head-down. This finding was taken as evidence for attentional tunneling -- a failure to switch between objects (in this case from the HUD symbology to the out-the-window scene) -- causing inefficient processing of the two domains.

HUD-related performance problems have also been demonstrated in continuous flight simulation tasks (Foyle, McCann, Sanford, & Schwirzke, 1993; McCann & Foyle, 1994). In these studies, participants were asked to maintain a 100 ft altitude while simultaneously following a ground path of small pyramids, all in the presence of lateral and vertical turbulence. In one condition, a superimposed digital readout of altitude was presented in a fixed location. Altitude and path (i.e. ground path) maintenance performance were measured by root mean square error (RMSE) deviations from the target altitude, and lateral offset from the ground path, respectively. The superimposed altitude display improved altitude maintenance as compared to a control condition where only environmental cues were available (horizon line, pyramid and surface grid size). Path-following performance, however, was negatively affected by the presence of the superimposed altitude display, as compared to the control condition. Attentional tunneling on the HUD symbology was suggested by this performance trade-off.

As the symbology of an operational HUD is most often superimposed in a fixed location, it may be that the proximal cause of attentional tunneling is the differential motion between the HUD symbology and the visual flow of the world. McCann, Lynch, Foyle, and Johnston (1993) measured the time it took to switch between fixed-location superimposed symbology and a moving world scene. They found that differential motion led to increased attentional switching times.

One design option to obviate differential motion is to replace the more traditional fixed-location, superimposed HUD symbology with virtual, scene-linked symbology that appears to be physically part of the world (Foyle, Ahumada, Larimer, & Sweet, 1992). In contrast to traditional fixed-location, superimposed HUD symbology, scene-linked symbology can take multiple forms (Foyle, McCann, & Shelden, 1995). *Scene Enhancements* are the graphic outlines of existing objects in the external world, such as a graphic runway that overlays an actual runway, or a virtual horizon. *Scene Augmentations* are the addition of virtual, three-dimensional objects that are otherwise non-existent in the real world, such as "virtual traffic lights" that may operate on taxiways to separate aircraft. *Virtual Instruments* are the depiction of ownship flight instrumentation and data such as a glideslope readout on "virtual billboards" that appear to the side of the aimpoint of a cleared runway at landing. In each case the symbology appears to the pilot as part of the external world, moving in unison with the out-the-window scene.

EXPERIMENT 1

If differential motion between HUD symbology and the world is indeed the proximal cause of attentional tunneling, scene-linking the symbology ought to prevent such attentional tunneling, and the performance problems associated with it. Experiment 1 tested this hypothesis using the continuous flight simulation developed by Foyle et al. (1993). As in previous studies, participants flew the simulation with or without explicit real-time altitude symbology. Two forms of symbology were compared: the standard superimposed symbology which occupies a fixed location on the screen, and scene-linked symbology spread at equal intervals along the ground path (see Figure 1). In the case of the fixed, superimposed symbology, we would expect to replicate earlier studies in finding an altitude/path performance trade-off. In contrast, the scene-linked altitude symbology should also improve altitude maintenance, but *without* the associated cost to path maintenance.

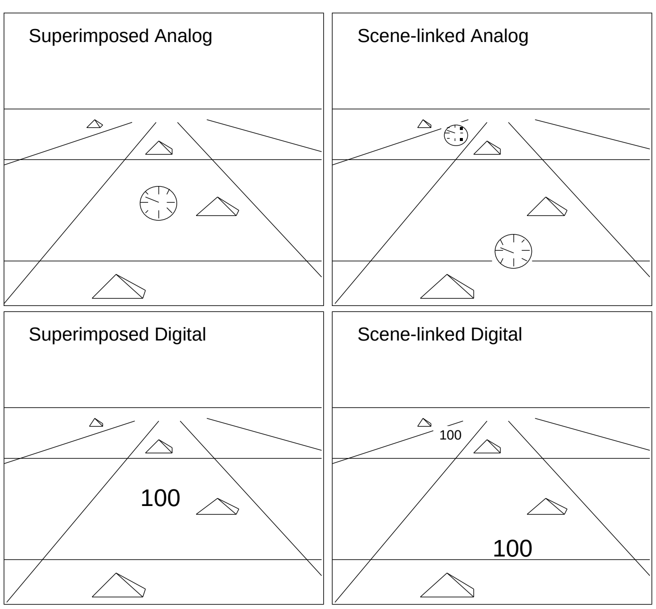

Figure 1. Schematic drawings (not to scale) of the symbology conditions. HUD symbology absent condition not shown.

Method

A within-participants design testing five symbology formats was utilized. Altitude information was presented as either superimposed digital, superimposed analog (both in a fixed screen location), scene-linked digital, scene-linked analog, or no explicit altitude symbology was present (see Figure 1).

The flight simulation was a simple kinematic model that maintained pitch during climbs and descents to ensure that the altitude and heading information was visible at all times. Roll was accurately depicted. The environment contained a blue sky and a white grid superimposed on a green ground surface. One of eight different paths was presented on every trial, each marked by a series of 37 brown pyramids scaled to be 24 ft square at the base, 6 ft high, and 330 ft apart on the ground. Forward speed was a constant 160 knots, with each course taking approximately 55 seconds to complete. Random vertical and lateral turbulence (a sum of sines) was present during each trial. This was intended to replicate previous simulation conditions and to create a high workload environment. The graphics and data were updated and collected at a rate of 12 Hz.

The analog altitude display had a yellow face, black tick marks indicating 25 ft intervals, and a single black bar that indicated an altitude of 100 ft at the 9 o'clock position, 50 ft at the 6 o'clock position, and 150 ft at the 12 o'clock position (after Weinstein, Ercoline, Evans, & Britton, 1992). The digital altitude display indicated real-time altitude in black numerals. In the scene-linked conditions, the analog and digital altitude displays were positioned equi-distant between each second pair of pyramids, directly on the ground path. In the fixed/superimposed conditions, the analog and digital displays were centered laterally on the screen, approximately two-thirds of the way from the bottom of the screen to the horizon line.

Each of fourteen male participants "flew" 90 trials (18 replications of the 5 HUD conditions) viewed on a 19-inch color monitor using a spring-centered joystick built into the participant's chair. The first 8 replications served as practice, with analyses being conducted on the remaining 10 replications. Participants were asked to simultaneously maintain an altitude of 100 ft and follow the ground path as closely as possible. Each trial began with 9 sec of flight without turbulence, at exactly 100 ft altitude, directly toward the first pyramid, during which participants were to "calibrate" themselves to the environment. Only after crossing the first pyramid did turbulence and data collection begin. The dependent measures were RMSE in altitude and path.

Results and Discussion

Separate analyses of variance (ANOVAs) were conducted on the RMSE altitude and path data. For altitude maintenance (Figure 2, top), display condition had a reliable main effect on performance [$F(4,52) = 22.29$, $p < .0001$]. This was attributable to improved altitude performance in the four conditions when HUD altitude information was present than when absent [$F(1,13) = 47.57$, $p < .0001$]. Altitude maintenance was equally good across type of altitude display present (all planned comparisons $F<1$).

For path maintenance (Figure 2, bottom), display condition also had a reliable main effect [$F(4,52) = 6.57$, $p < .0002$]. Path performance in the two superimposed symbology conditions was marginally worse than when no altitude display information was available [$F(1,13) = 4.43$, $p = .055$]. In contrast, the two scene-linked display conditions yielded *improved* performance relative to the control condition with no explicit altitude information [$F(1,13) = 5.58$, $p < .035$].

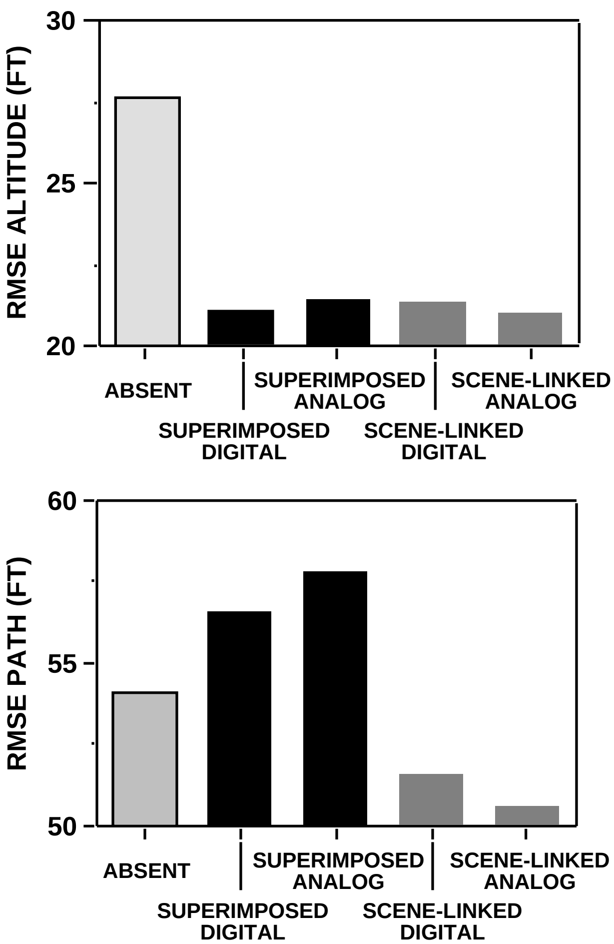

Figure 2. Effect of display symbology type on altitude and path maintenance.

In summary, fixed-screen location, superimposed symbology led to inefficient simultaneous processing of the symbology and path, resulting in a performance trade-off. In contrast, the scene-linked symbology led to more efficient simultaneous processing of the symbology and path, as evidenced by the lack of any performance trade-off. Unexpectedly, in addition to the lack of a path-following *deficit* with scene-linked symbology, a significant improvement in path-following performance emerged.

EXPERIMENT 2

The goal of Experiment 2 was to discern the source of the improvement in path-following performance found in Experiment 1 with the use of scene-linked symbology. To that end, three possible hypotheses were proposed and tested.

1) *Increased Path Definition*. From the perspective of a change in the perceptual configuration of the simulation environment, the insertion of the scene-linked symbology in Experiment 1 had the effect of increasing the number of items delineating the path. This increased definition of the path may have allowed participants to better determine the magnitude of their deviations from the path, and make appropriate corrections.

To test this possibility, scene-linked gauges that were static and irrelevant to altitude maintenance were incorporated into the path. If increased path definition drives better path-following performance through the simple processing of the additional path cues, then the addition of static/irrelevant symbology to the flight environment should improve path-following maintenance beyond that obtained in the baseline (no symbology) condition.

2) *Dynamic Symbology*. Alternatively, the scene-linked symbols may have changed the nature of the participant's attentional processing of the simulation environment. Specifically, the fact that the scene-linked symbology was dynamic may have locked participants' visual/spatial attention onto the path, to a greater extent than in the baseline condition. To test this possibility, scene-linked gauges that were dynamic but *irrelevant to altitude maintenance* were incorporated into the path. These gauges were otherwise identical to the earlier analog scene-linked symbology tested, except that they imparted real-time compass heading. Given the twisting layout of the paths, compass heading information was unlikely to be useful in following the path.

If the dynamic nature of the scene-linked symbology engages visual/spatial attention, thereby facilitating the processing of the additional path cues, then the addition of such dynamic/irrelevant symbology should improve path-following performance beyond that obtained in the baseline (no symbology) condition.

3) *Task Relevance*. The third hypothesis for the improved path-following performance in Experiment 1 is that active processing of the scene-linked symbology for purposes of extracting relevant altitude information encouraged the “incidental” processing of the additional path cues. To test this possibility, symbology identical to the scene-linked analog symbology used in Experiment 1 was incorporated into the path.

This hypothesis would be supported if the results of Experiment 1 were replicated, i.e., the addition of dynamic/ relevant symbology to the flight environment improves path-following performance beyond that obtained in the baseline condition, concurrent with a failure on the part of either the static/irrelevant or dynamic/irrelevant symbology to evidence any similar improvement over their paired control (no symbology) conditions.

Method

A mixed-participant design was utilized. Each participant saw only one of the three symbology display conditions, and the control condition in which no explicit altitude information was available. The flight simulation was similar to that described in Experiment 1 for the scene-linked analog condition with the following exceptions: in the static/irrelevant display condition, the indicator bar on each scene-linked gauge remained fixed at the 9 o'clock position; in the dynamic/irrelevant display condition, the indicator bar depicted real-time compass heading, with 0 degrees at the 12 o'clock position; and in the dynamic/relevant display condition the indicator bar imparted real-time altitude similar to that in Experiment 1, with 50, 100, and 150 ft mapping to the 6, 9 and 12 o'clock positions on the clock face of the gauge.

Thirty male participants "flew" a total of 84 trials each. The trials were blocked, each consisting of 6 trials with no altitude display, and 6 with an altitude display. The first 4 blocks served as practice, with analyses being conducted on the remaining 3. In all other respects the simulation was identical to that used in Experiment 1. Participants were asked to maintain a target altitude of 100 ft while simultaneously following the ground path as closely as possible. Verbal feedback was given at the conclusion of each trial. The dependent measures were RMSE in altitude and path.

Results and Discussion

Separate ANOVAs were conducted on the RMSE altitude and path data. Display type had no main effect on altitude performance (Figure 3, top). Display presence, however, had a reliable main effect on altitude performance [$F(1,27) = 12.21$, $p < .01$], and was found to interact with display type [$F(2,27) = 27.47$, $p < .01$]. Simple comparisons between the three display types indicated a reliable difference for only the dynamic/relevant display condition versus its paired no HUD display, control condition [$F(1,9) = 50.29$, $p < .001$]. This indicated that RMSE altitude was lower when the display type was dynamic/relevant (Figure 3, top right panel).

Display type was also found to have no main effect on path performance (Figure 3, bottom). Display presence, however, had a reliable main effect on path-following performance [$F(1,27) = 15.78$, $p < .01$], and was found to interact with display type [$F(2,27) = 4.12$, $p < .05$]. Simple comparisons undertaken on the three display types indicated a reliable difference for only the dynamic/relevant display condition versus its paired no HUD display, control condition [$F(1,9) = 44.44$, $p < .001$]. This indicated that RMSE path was lower only when the display type was dynamic/relevant (Figure 3, bottom right panel). This replicated our finding in Experiment 1: scene-linking the altitude symbology produced an improvement in path-following performance.

In summary, the static/irrelevant symbology failed to yield an improvement in either altitude or path maintenance, as compared to its paired control where no altitude display was available. The hypothesis that increased perceptual definition of the path might lead to increased processing of the additional path cues and improved path-following performance (the Increased Path Definition hypothesis) can therefore be rejected. Similarly, the dynamic/irrelevant symbology failed to yield any path -following improvement over its paired control where no altitude display was available. The hypothesis that the dynamic nature of the scene-linked altitude symbology increased visual attention onto the additional path cues, with resultant improved path performance (the Dynamic Symbology hypothesis), can likewise be rejected. This symbology format also failed to improve either altitude or path maintenance over the no-HUD control condition.

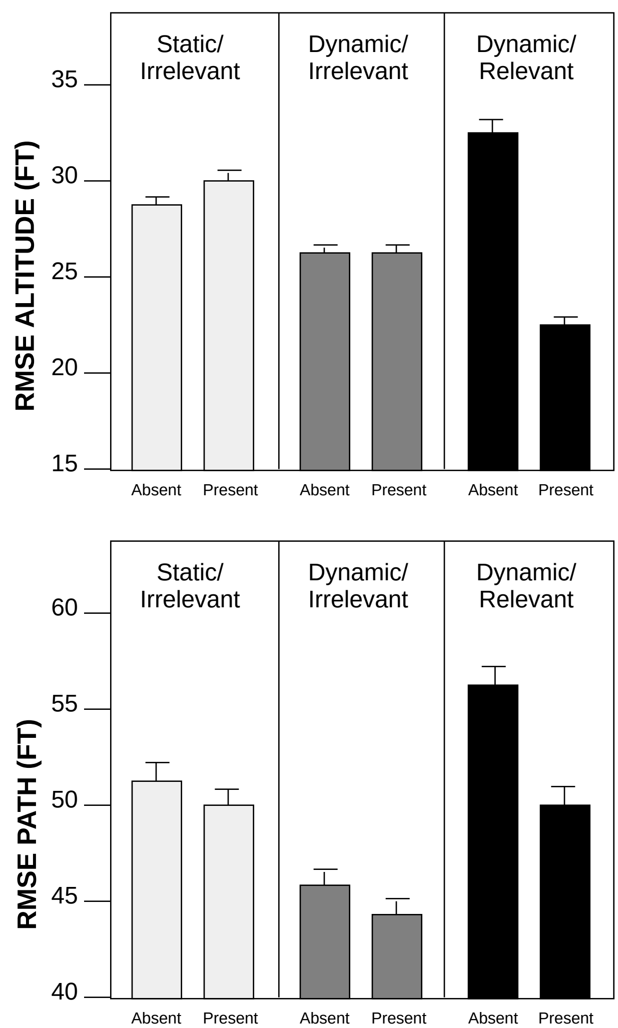

Figure 3. Effect of display symbology type on altitude and path maintenance.

The dynamic/relevant altitude display did, however, produce an altitude and path-following performance improvement which mirrored that found in the Experiment 1. Compared to its control condition where no explicit altitude information was available, this scene-linked altitude display produced an improvement in both altitude *and* path maintenance. It therefore appears that the active processing of task relevant, scene-linked altitude symbology is the necessary ingredient to improved path-following.

Wickens and Long (1994) suggested that an object-based theory of attention would predict "an added benefit" for presentation of conformal (vs. non-conformal) HUD flight data symbology. The scene-linked symbology employed here may derive its benefits from the fusion of the "HUD" symbology with the external environment to form a single perceptual object, with object-based parallel processing benefits taking the form of an improvement in path maintenance performance.

CONCLUSIONS

In the simulation environment studied here, scene-linked symbology yielded two performance advantages. First, the altitude/path performance trade-off was eliminated by scene-linking the appropriate altitude display symbology, as described in Experiment 1.

Second, not only did scene-linking the altitude symbology eliminate the performance trade-off, but a significant *improvement* in path-following performance (relative to baseline) was found. The results of Experiment 2 suggest that neither increased path definition nor the dynamic nature of the symbology were sufficient to account for the improvement. The necessary component appears to be object and task fusion, where task relevant processing of the symbology "in the world" is required.

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