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ATTENTIONAL EFFECTS WITH SUPERIMPOSED SYMBOLOGY: IMPLICATIONS FOR HEAD-UP DISPLAYS (HUD)

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Previous research has shown that the presence of head-up display (HUD) symbology containing altitude information improves altitude performance at the cost of terrain path performance, implying that these information sources may not be available for concurrent cognitive processing. In two flight simulation experiments, the influence of attentive field size on this concurrent processing limitation was evaluated. In Experiment 1, a superimposed digital altitude (i.e., HUD) indicator was presented at three distances from a flight-relevant ground track. A control condition eliminated the digital altitude indicator. Altitude symbology improved performance on the altitude maintenance task, but impaired performance on the ground track task only when directly superimposed. Experiment 2 tested a visual masking explanation of the performance tradeoff. Irrelevant HUD information yielded identical results to the HUD absent condition, ruling out effects of visual masking. An explanation in which visual/spatial attention cannot be directed to both HUD information and terrain information simultaneously is proposed. The absence of a performance tradeoff when the HUD and the terrain information are not directly superimposed is attributed to a breaking of attentional tunneling on the HUD, possibly due to eye movements.

INTRODUCTION

Superimposed symbology was developed to allow the pilot to spend more time "eyes out", retaining both aircraft and world awareness. The symbology may be superimposed on a direct view of the world (via transparent electronics as in a head-up display, HUD), on sensor information (AH-64 Apache Helicopter), or on a graphics version of the world (e.g., a synthetic vision system). The HUD uses the technique of placing symbology collimated at optical infinity in the pilot's field-of-view. This allows pilots to access both the out-the-window view of the world and onboard aircraft displays in the same region of fixation and accommodation. Without a HUD, pilots must scan their eyes and refocus to view the outside world and the instruments. Various advantages of HUD over non-HUD designs have been demonstrated (e.g., Weintraub, Haines & Randle, 1985).

In the early stages of HUD design, however, a human factors concern surfaced: Fischer, Haines and Price (1980) noted occasions when pilots failed to attend simultaneously to both the HUD symbology information and the outside world information. In their experiment, after many trials of practice using the HUD for landings, an aircraft unexpectedly moved onto the runway from the taxiway. Pilots continued their landing as if the runway incursion was not there, suggesting that they were not monitoring the visual scene upon which the HUD was superimposed.

Roscoe (1987) has suggested that these failures occur because HUDs cause pilot's accommodation to move inwards toward the resting dark focus level away from the optimal infinity focus. Roscoe's argument, however, does not explain the findings by Brickner (1989) or Foyle, Sanford and McCann (1991) who demonstrated the failure to process simultaneously outside world information and HUD symbology information with a noncollimated graphics display. Both studies found a performance tradeoff between ground track (path) and altitude maintenance performance: Digital HUD altitude information yielded better altitude maintenance, but with decreased ground track performance. Without digital altitude information, altitude maintenance was poor, but terrain path-following was improved.

Brickner (1989) and Foyle, Sanford and McCann (1991) proposed an attentional account of this performance trade-off: Limitations on visual/spatial attention prevented concurrent processing of the HUD symbology and the "out-the-window" terrain path information. Two models of visual/spatial attention could explain the altitude/path performance trade-off: Object-based and location-based.

Models of Attention

Object-based models assume that complex scenes are visually parsed into groups of objects. These perceptual groups control the distribution of spatial attention across the visual field, with attention focused only on one group at a time (Kahneman & Treisman, 1984). Concurrent processing of two sources of information is only possible if they are part of the same object (see Neisser & Becklen, 1975; Becklen & Cervone, 1983). Relative motion and display format are two salient cues that may cause the visual system to parse the HUD symbology and terrain into two separate objects. Since HUD symbology occurs in a fixed screen location as the vehicle moves through the terrain, the HUD symbology and terrain information have differential motion. Additionally, these two sources of information also differ in their display format (pictorial terrain information and digital HUD information). Therefore, the HUD information and terrain information may segregate into separate objects, thereby preventing concurrent processing.

Location-based models of attention hold that concurrent processing of two sources of information is only possible if they are located near one another. Eriksen and Yeh (1985) proposed the analogy of an attention spotlight for this model. The location of the HUD symbology may have affected the ability to use both path and altitude information in the Brickner (1989) and Foyle, Sanford and McCann (1991) studies. In the simulated flight tasks, the altitude information was located slightly above and to the left of the center of the display while the path information (determined by the terrain) moved across the display as the aircraft moved through the simulated world. In each task, the altitude information was displaced from the path information. The spatial displacement of the two information sources may have affected the ability to use both pieces of information.

Purpose and Predictions

The purpose of the experiments being reported is to distinguish between the object-based and location-based attentional accounts of the altitude/path performance trade-off (Brickner, 1989; Foyle, Sanford & McCann, 1991). The location-based attentional hypothesis suggests that efficient processing of two separate information sources is only possible when both sources are near the center of an attentive field (within the attentional spotlight). Placing terrain path and altitude information closer together would put them within the same attentive field and allow concurrent processing of both information sources. The location-based attentional hypothesis predicts that the altitude/path performance trade-off should decrease as the distance between path and altitude information decreases.

The object-based attentional hypothesis suggests that efficient processing of two information sources is only possible when they are part of the same perceptual object. Therefore, since the same perceptual cues distinguish the HUD symbology from the terrain regardless of HUD symbology location, moving path and altitude information closer together should not improve processing of both information sources. The object-based attentional hypothesis predicts that the altitude/path performance trade-off should be unaffected by a decrease in the distance between altitude and path information.

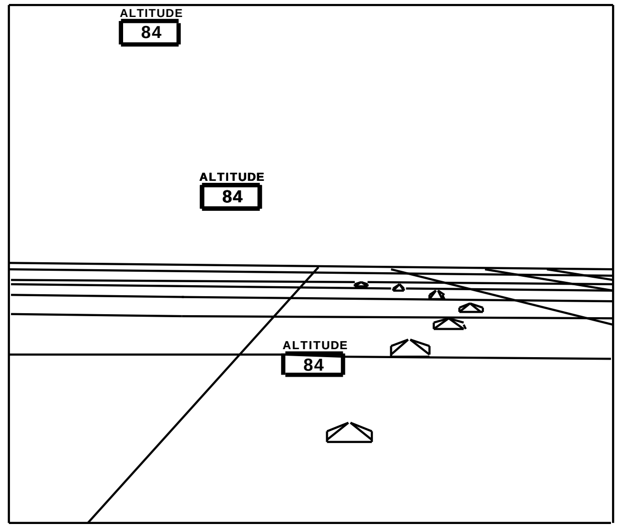

Figure 1. Schematic of the three HUD locations (only one per trial) in Experiment 1. The three locations are Lower (bottom), Center, and Upper (top).

EXPERIMENT 1

Method

A flight simulation task was used to evaluate the effect of information location on the concurrent processing of superimposed symbology and "out-the-window" information. HUD digital altitude symbology was presented in the lower portion of the screen near the path/terrain information ("lower" condition), at an intermediate distance from the path information ("center"), or in the upper left corner of the screen, far from the path information ("upper"), (see Figure 1). The three HUD locations were 8.14 deg visual angle apart at the 65-cm viewing distance. A control condition in which the HUD information was absent was also tested. Pictorial path information was present in the virtual flight environment during every trial as shown in Figure 1. Subjects flew through the virtual environment while performing the ground track path task and an altitude maintenance task.

The simulation was implemented on an SGI IRIS 3130 with a right-hand spring-centered joystick and a 19-inch high-resolution monitor. Fourteen right-handed male subjects, with normal- or corrected-to-normal eyesight were required to maintain altitude at 100 ft, and to follow the ground path as closely as possible. Simulated horizontal and vertical wind disturbances were presented. Root mean squared error (RMSE) altitude and RMSE path were measured representing departures from the assigned altitude and paths. The design was a within-subjects design, with each subject tested in all four conditions. The 4 conditions were tested in random order within 20 blocks of 4 trials each (80 total trials). The first 16 trials were designated practice and not analyzed.

Results and Discussion

Separate analyses of variance (ANOVAs) were conducted on the RMSE altitude and RMSE path measures. HUD condition had a reliable main effect on altitude performance F(3,13) = 10.61, $p < .0001$, (see Figure 2, top panel). This was attributable to better altitude performance when altitude information was present than when it was absent, F(1,13) = 13.09, $p < .005$. Altitude performance for the three HUD locations were equally good, and did not differ significantly, F(1,13) < 1.

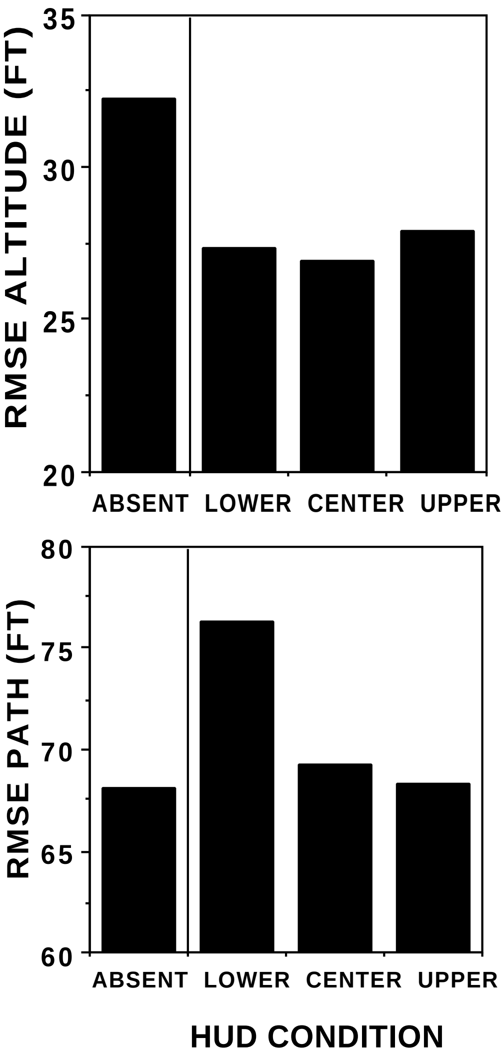

Figure 2. Experiment 1 results: Effect of symbology condition on Altitude (top) and Path RMSE (bottom).

As seen in Figure 2 (bottom), HUD condition also produced a reliable main effect on path performance, F(3,13) = 12.27, $p < .0001$. This was attributable to better path performance when the HUD symbology was absent than when it was present in the lower superimposed screen location, F(1,13) = 16.51, $p < .001$. Path performance in the lower superimposed screen location was worse (larger RMSE) than the average of the HUD absent, center, and upper locations, F(1,13) = 36.34, $p < .0001$.

The superimposed HUD symbology demonstrated both an advantage and a disadvantage: With digital altitude information available, altitude maintenance performance is improved due to the accurate and immediate information available. When directly superimposed ("lower" condition) on the ground path, however, the improvement in altitude maintenance, is accompanied by poorer performance in terrain path following. For symbology that is not directly superimposed ("center" and "upper" conditions), subjects can effectively process both the HUD symbology and the out-the-window flight path information.

The location-based attentional model predicted that performance on both the altitude maintenance and path tasks would be best when the HUD symbology and terrain information were located near each other (the "lower" condition). The present results do not support the location-based attentional model. In fact, the results were opposite of those predicted. Performance did not improve when the HUD symbology and terrain information were located near one another. Instead, the "lower" condition was the only condition to yield an altitude/path performance trade-off. Furthermore, when the two sources of information were farther from one another ("center" and "upper" conditions) altitude performance improved without an associated decrement in path performance. The location-based attentional model cannot explain these results.

The object-based attentional model predicted that performance should not be influenced by the distance between the HUD symbology and terrain information. The presence of an altitude/path performance trade-off in the "lower" location supports the contention that the HUD symbology and the terrain are parsed into separate perceptual objects. However, the absence of the altitude/path performance trade-off in the "center" and "upper" conditions does not support the strongest form of the object-based attentional model.

EXPERIMENT 2

The findings in Experiment 1 could possibly be due to visual interference or visual masking. If the directly superimposed ("lower") HUD symbology visually obscured the flight path information, the observed results could obtain. Experiment 2 tested for visual masking by evaluating whether directly superimposed HUD symbology would interfere with path performance when it was present, but was irrelevant to the task. Evidence for visual masking would be found if irrelevant, to-be-ignored symbology produced poorer path performance than with no symbology present.

Method

The same flight simulation and flight tasks were used as in Experiment 1. Three HUD information conditions were tested using only the directly superimposed location of Experiment 1 ("lower" position in Figure 1): Relevant altitude (replicating the "lower" condition in Experiment 1), irrelevant dynamic, and irrelevant static. For the irrelevant dynamic condition, dynamic digital compass values were presented. For the irrelevant static condition, a constant two-digit value was presented. A factorial design was used, with the three HUD information conditions (between), and HUD presence/absence (within). Ten male, right-handed, normal-vision subjects were tested in each HUD information condition. HUD presence/absence was tested in blocks of 8 trials and alternated. A total of 88 trials were tested, with the first 40 trials discarded as practice (leaving 24 trials each for the HUD presence and absence conditions). Subjects in the two irrelevant HUD information conditions were instructed to ignore the (irrelevant) superimposed information.

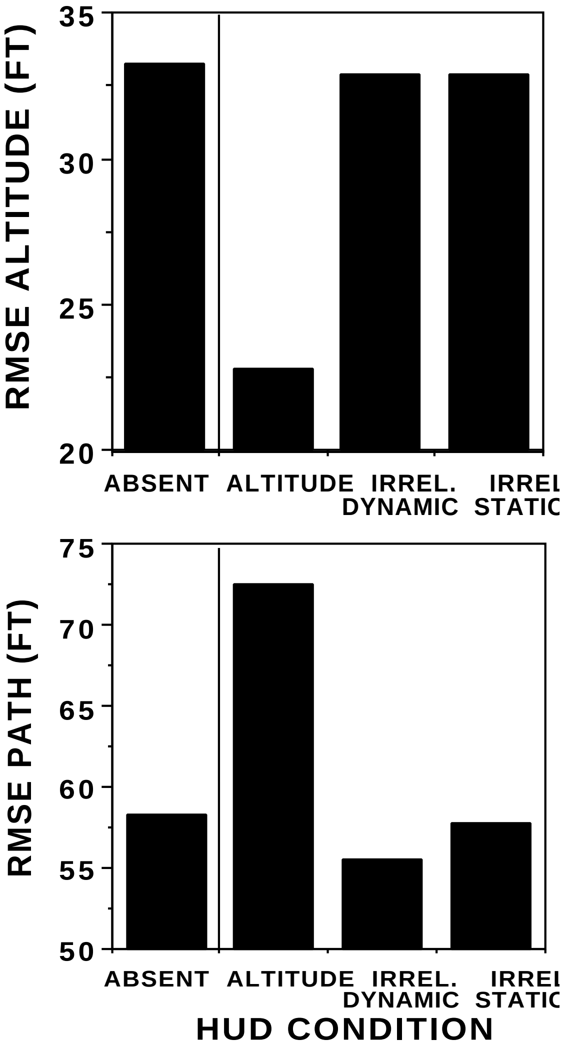

Figure 3. Experiment 2 results: Effect of HUD condition on Altitude (top) and Path RMSE (bottom). HUD absent is the mean for the three (n=30) HUD condition groups.

Results and Discussion

Separate ANOVAs were conducted on the RMSE altitude and RMSE path measures. The following variables had reliable effects on altitude performance: HUD presence $F(1,27) = 7.09$, $p < .025$, HUD information (altitude, irrelevant static and dynamic), $F(2,27) = 3.74$, $p < .05$, and the HUD information by presence interaction $F(2,27) = 3.96$, $p < .05$. Figure 3 (top, note that the HUD absent condition represents the mean of all 30 subjects, across HUD information) shows that the altitude HUD information improved altitude maintenance performance compared to when it was absent, replicating the effect seen in Experiment 1. It also can be seen that the irrelevant HUD information resulted in equal RMSE altitude as when HUD symbology was absent.

For path RMSE, HUD presence $F(1,27) = 6.51$, $p < .025$, and HUD information by presence interaction were significant $F(2,27) = 5.19$, $p < .025$. As seen in Figure 3 (bottom), path performance was reliably better when the HUD symbology was absent than when it was present. Additionally, irrelevant superimposed symbology yielded equal performance to that of the HUD absent condition.

Performance with the irrelevant, to-be-ignored HUD symbology was identical to that of the HUD absent condition. No evidence is found that the HUD/ out-the-window performance tradeoff for directly superimposed information is due to visual masking effects.

GENERAL DISCUSSION

The results of both experiments demonstrate that subject pilots were not able to attend simultaneously to both the HUD and the outside world information when superimposed altitude and path information were directly overlaid. This effect appears to be due to attentional factors rather than simple visual masking or interference effects. Experiment 2 further demonstrates that the superimposed information must be actively processed to yield the HUD/out-the-window performance tradeoff.

Improved altitude performance was only associated with a decrement in path performance in the directly superimposed ("lower") condition. This may be attributable to attentional tunneling. Attentional tunneling describes a failure to switch attention between two separate objects. In this case, attention was focused on the object providing altitude information (the superimposed altitude indicator) resulting in inefficient processing of the terrain path information. Proximity of information sources seems to encourage the use of inefficient attentional switching strategies, resulting in attentional tunneling. Therefore, a performance trade-off was observed in the directly superimposed (lower) condition, but not in the other conditions.

The somewhat counter-intuitive finding that efficient processing of HUD symbology occurs only when not directly superimposed on "out-the-window" information is supported by the work of Weintraub, Haines and Randle (1985). Comparing HUD and panel-mounted displays, they proposed that visual scanning of conventional panel-mounted displays could lead to efficient processing. Visual scanning to known locations may be efficient due to its active, volitional nature. That is, visual/attentional scans only occur when one is prepared to process that information. This may explain the results of the Experiment 1, in which efficient altitude (HUD) and path (out-the-window) processing occurred only when visual/ attentional scanning was required. Simultaneous processing of both the HUD and the outside world information occurred only in those conditions that encouraged visual/attentional scanning. When scanning is required, attentional tunneling is broken, and the altitude/path performance trade-off is not observed.

CONCLUSIONS

Concurrent processing of HUD symbology and "out-the-window" information was found to occur only in conditions which require visual scanning. The result that symbology directly superimposed on terrain information leads to inefficient processing provides evidence against the location-based attentional model of HUD symbology/"out-the-window" concurrent processing deficits. The object-based attentional model was partially supported, indicating that the HUD symbology and terrain information were parsed into separate perceptual objects. However, efficient processing of information even from separate perceptual objects occurred when visual/attentional scanning was required.

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