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Superimposed Symbology: Attentional Problems and Design Solutions

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ABSTRACT

This paper reviews recent human factors research studies conducted in the Aerospace Human Factors Research Division at NASA Ames Research Center on superimposed symbology and head-up displays (HUDs). We first identify various performance problems that have been associated with HUD use. Results of experiments that suggest an attentional account of these problems are described. A design solution involving the concept of "scene-linked" HUDs is developed, and an experiment testing the design solution is discussed.

INTRODUCTION

HUDs are devices that superimpose instrument symbology directly on the pilot's forward field of view. They have been used by the military for decades, and are beginning to penetrate the commercial and general aviation aircraft sectors as well. A number of factors are fueling the expansion. HUD symbology typically presents flight path information (the actual direction of flight, as opposed to just the orientation of the aircraft). Without a direct presentation of flight path, the pilot is required to do visual scanning and mental transformations to determine the path of the aircraft. A display featuring flight path information allows for a more natural, intuitive method of control. Numerous studies have shown that HUDs equipped with flight path symbology produce superior flight path maintenance and landing precision relative to traditional flight director instrumentation (Boucek, Pfaff, & Smith, 1983; Bray, 1980; Lauber, Bray, Harrison, Hemingway & Scott, 1982).

In addition to these performance advantages, it is widely assumed that HUDs increase the pilot's ability to monitor instrument information and the far visual scene in parallel (Naish, 1964; Lauber, Bray, Harrison, Hemingway, and Scott, 1982). Among other advantages, the presumed increase in parallel processing ability implies that under low visibility conditions, pilots ought to be able to acquire the runway following breakout more rapidly with a HUD than with a conventional head-down display.

PERFORMANCE PROBLEMS - Over the years, however, human factors researchers have identified a number of performance problems with HUDs. Fischer, Haines, and Price (1980) found that pilots flying simulated approaches using a HUD often failed to notice an unexpected runway incursion; no such failures were observed among pilots flying with conventional head-down instrumentation (see also Weintraub, Haines, & Randle, 1984, for similar results with static displays). Unfortunately, the Fischer, Haines, and Price (1980) study confounded location of the instrumentation (head up versus head down) with type of instrumentation: The HUD included contact analog symbology, whereas the head down instrumentation did not. It is not clear, then, whether the failure to notice incursions was due to the change in the location of the symbology or the change in the symbology itself. Wickens and Long (1994) recently rectified this by presenting the identical symbol set either head down or head up. Pilots flying simulated instrument approaches took, on average, 2.5 seconds longer to respond to an unexpected runway incursion when the symbology was head-up compared to head-down. Together with the Fischer, Haines, and Price (1980) result, the Wickens and Long data suggest that, instead of supporting concurrent processing of instrument information and world-referenced information, HUDs may actually interfere with this ability.

A further performance problem has emerged from part-task simulations of helicopter flight conducted at NASA-Ames. Brickner (1989) had subjects fly a simulated helicopter through a slalom course demarcated by virtual pylons. The pilots were instructed to fly around the pylons while maintaining an altitude of 100 feet. Altitude information was available either on a superimposed digital symbol (hereafter, a HUD) or on the basis of naturally occurring environmental cues (e.g., pylon size). Not surprisingly, the presence of digital altitude information improved altitude maintenance performance, relative to the no-HUD condition. However, this performance benefit was obtained at the cost of an increase in the number of collisions with the pylons. Superimposing digital symbology on the scene yielded a performance tradeoff: the presence of the symbology supported more precise altitude maintenance performance at the cost of less precise navigation performance.

Foyle, McCann, Sanford, & Schwirzke (1993) reported a similar performance tradeoff using a different flight task. Subjects were instructed to fly a curving path demarcated by small pyramids on the ground, while maintaining an altitude of

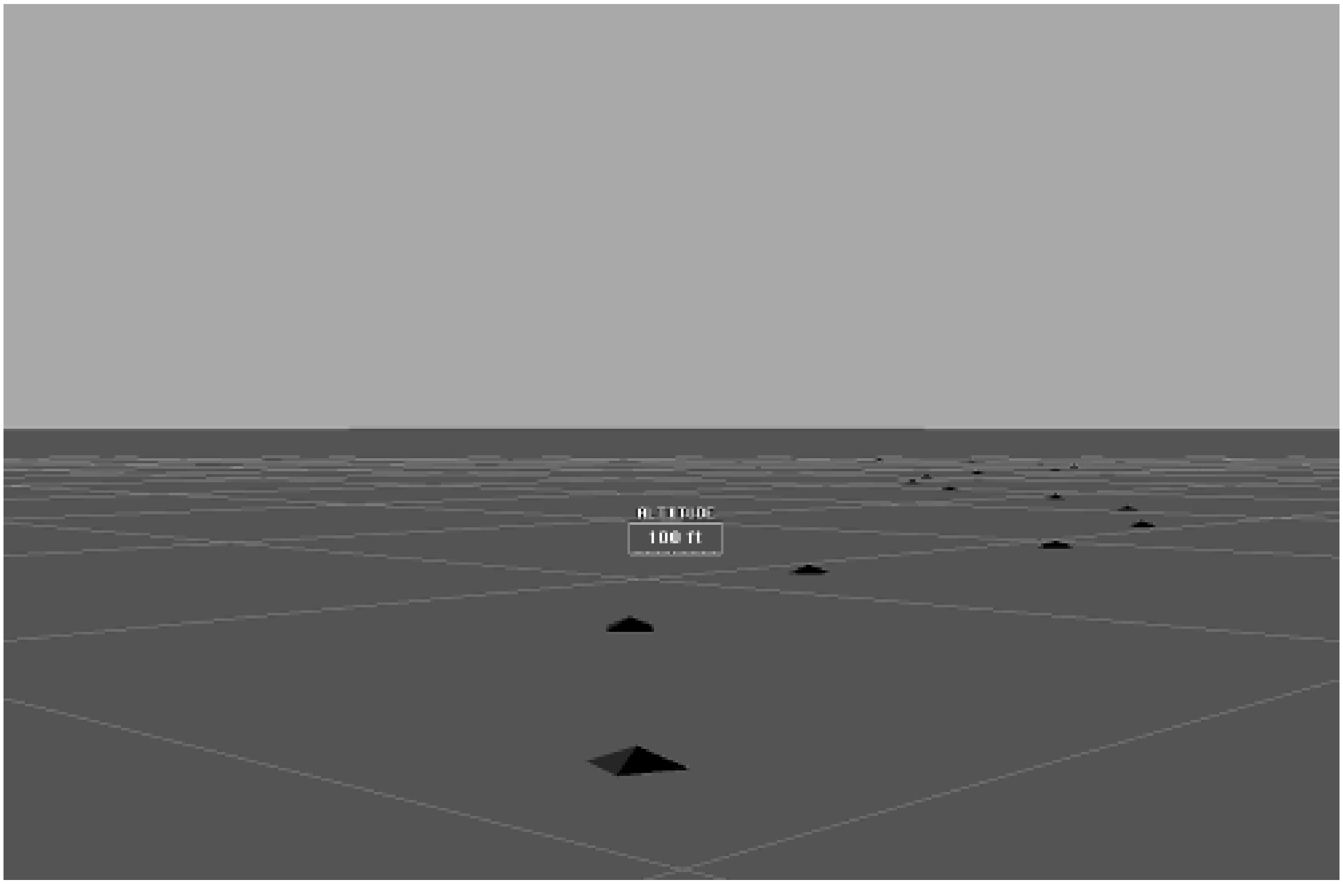

Figure 1. Part-task simulation environment showing ground track to be followed (pyramids) and digital superimposed symbology (currently showing 100 ft). (After Foyle, McCann, Sanford & Schwirzke, 1993.)

100 feet (illustrated in Figure 1). The stimuli were presented on a color monitor slaved to an IRIS computer. Random buffeting was introduced along both the vertical and horizontal dimensions throughout each 2-minute flight; the dependent measures were flight path accuracy (measured by root mean square deviations from the designated path) and altitude error (measured by root mean square deviations from 100 feet). Following Brickner (1989), altitude information was available either in the form of a digital symbol, superimposed on the world, or altitude had to be inferred from environmental cues. Once again, a performance tradeoff was observed: The presence of altitude information on a digital superimposed symbol reduced altitude error, but increased path following error.

SOURCE OF THE PERFORMANCE PROBLEMS

These performance problems have a number of possible sources. One possibility, discussed by Roscoe and his colleagues (Iavecchia, Iavecchia, & Roscoe, 1988; Roscoe, 1987), is that even though HUDs are collimated to appear at visual infinity, there are still a variety of perceptual cues that the HUD is closer to the pilot than the world (such as scratches or dirt on the combiner glass or the frame). When processing the HUD, the eye accommodates inward, which blurs the out-the-window scene to the point where concurrent processing of the HUD and the world is not possible. However, this account cannot explain the performance problems reported by Foyle, McCann, Sanford, & Schwirzke (1993) and Wickens and Long (1994). Both studies used computer-generated images, where the superimposed symbology and the out-the-window scene were part of the same synthetic display; thus, both the superimposed symbology and the image of the world were at the same optical distance from the eye.

A second possibility is that the problems reflect limitations on the ability of the cognitive/visual system to attend to superimposed symbology and the world in parallel (Fischer, 1979; Fischer, Haines, & Price, 1980; Foyle, Sanford, & McCann, 1991). This hypothesis follows naturally from "object-based" models of visual attention (Kahneman & Henik, 1981; Duncan, 1984). These models hold that attention can be "captured" and held by collections of visual elements if the elements form a well-defined perceptual group. Perceptual grouping is generally associated with such physical attributes as coherent motion, common color, or common texture (Kahneman & Henik, 1981; McLeod, Driver, Dienes, & Crisp, 1991; Yantis, 1992). HUDs are typically distinguished from the outside world by a number of these characteristics, making them a prime candidate for attentional capture. On the further assumption that attention is allocated to a perceptual group as a unit (Duncan, 1984; Kahneman and Henik, 1981; Treisman, Kahneman, & Burkell, 1983), elements within a perceptual group should be processed concurrently, while elements in different perceptual groups should be processed serially.

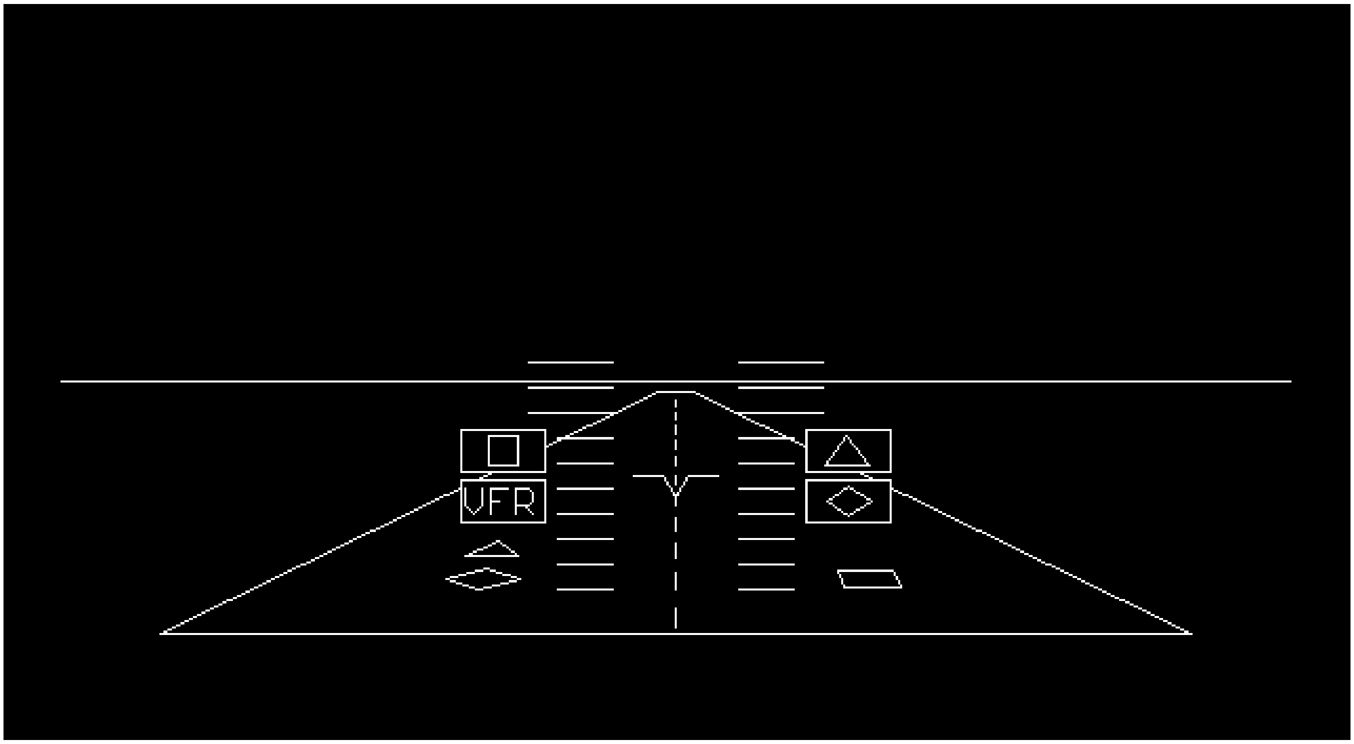

Figure 2. HUD symbology overlaid on runway scene. Subjects' task shown was to identify "VFR" prime (on HUD), then visually acquire diamond (lower left on runway). (After McCann, Foyle & Johnston, 1993.)

Attentional capture by superimposed symbology provides a natural account of the performance problems described earlier. The increased latency to notice incursions when using HUDs (Wickens & Long, 1994) follows from the fact that attention must be switched from the HUD to the outside scene, and attention switching takes time (Baylis & Driver, 1992). The performance tradeoffs documented by Brickner (1989) and Foyle, McCann, Sanford, & Schwirzke (1993) follow from the assumption that when pilots are attending to the HUD, processing visual scene information is impaired, so departures from the flight path take longer to be noticed and corrected.

In the rest of this article, we discuss the results of two lines of research. One line verifies a key empirical prediction of the attentional capture account, and identifies the perceptual characteristic most responsible for capture. The second line of research incorporates this information into candidate HUD displays, which are then tested to see whether they alleviate the concurrent processing problem.

ATTENTION SWITCHING

Consider the task of actively processing a display consisting of a pilot's eye view of a runway overlaid by superimposed symbology. If attention is captured by the symbology, then processing two display elements should proceed in parallel when the elements are both superimposed symbols; however, if one element is a superimposed symbol and the other is on the runway, processing should be serial, requiring a shift of attention. The presence of an attention shift should be revealed in the form of slower responses in the "between-group" processing condition than in the "within-group" processing condition.

We recently completed a series of studies testing this prediction (McCann, Foyle, & Johnston, 1993; McCann, Johnston, Foyle, & Lynch, 1993; McCann, Lynch, Foyle, & Johnston, 1993). Following Weintraub, Haines, & Randle (1984), subjects viewed computer-generated displays containing of a set of symbols (hereafter referred to as a HUD) superimposed on a night view of a runway (Figure 2). The world was dynamic, consistent with the appearance of a runway during final approach, whereas the HUD was stationary. Participants in these studies first identified a three-letter "priming" stimulus that appeared either on the HUD or on the surface of the runway. Depending on the identity of the prime, they then searched either the HUD or the runway surface for one of two prespecified targets - a stop sign or a diamond. The instructions stressed responding as rapidly as possible to the identity of the target (i.e., press one button if the target is a stop sign, another button if the target is a diamond).

The results were straightforward. Responses were approximately 100 msec slower when the prime and the target belonged to different perceptual groups (i.e., prime on the HUD and target on the runway) compared to when both stimuli belonged to the same group. Since the displays carefully controlled for the physical distance between prime and target across the two conditions, attention switching provided the most straightforward account of the increased latencies in the "between-groups" condition.

REDUCING PERCEPTUAL SEGREGATION - According to object-based models, attentional capture is a consequence of the fact that the visual system parses HUDs as a distinct perceptual group, separate from the world. In the course of pursuing a design solution to attentional capture, our first step was to identify the perceptual characteristic, or combination of characteristics, most responsible for perceptual grouping. As with most actual HUDs, the superimposed symbology in our studies was distinguished from the world by a number of highly salient characteristics, including differential motion, differential color, and viewing perspective (the HUD symbology was vertical with respect to the eye, whereas the world-referenced objects appeared as they would when viewed from above and behind). Which of these characteristics was the most important cause of perceptual segregation between the HUD and the world?

McCann, Lynch, Foyle, & Johnston (1993) addressed this question by systematically removing the color and differential motion characteristics from the display, and measuring the impact on the between-group processing penalty (i.e., the switching cost). The experiment jointly manipulated whether the HUD and the world were shown in the same or different colors, and whether the point of regard with respect to the runway was dynamic, consistent with final approach, or held constant, so that the world appeared as it would about 5 seconds prior to touchdown. Since the HUD and the elements of the out-the-window scene were both "frozen" in this condition, there were no differential motion cues to distinguish HUD symbology from the world.

The results of the experiment were informative. In the control condition, where the HUD and the world continued to be distinguished by both color and motion cues, responses were longer when the prime was in one group and the target in the other, compared to when both stimuli belonged to the same group. This "between-group" processing penalty replicated McCann, Foyle, & Johnston (1993), and was taken as evidence for attention switching. The presence/absence of color as a distinguishing feature had no effect on the size of the between-group penalty, suggesting that differential color is not an important cause of HUD/world segregation. However, when differential motion cues were removed, the switching cost was reduced by 50 percent. Thus, the differential motion between the fixed-location symbology and the movement of the world scene was revealed as a potentially important source of attentional capture by HUDs.

A CANDIDATE DESIGN

If differential motion between superimposed symbology and the out-the-window scene is the primary driver behind attentional capture, then removing the differential motion cues between the HUD symbology and the world ought to minimize the capture problem. One design option that achieves this goal is to replace conventional HUD symbols with virtual symbols that appear to be physically part of the world (Foyle, Ahumada, Larimer, & Sweet, 1992). As the aircraft moves through the world, these "scene-linked" symbols undergo the same visual transformations as real objects. There are no differential motion cues to cause the visual system to interpret the virtual symbols as part of a perceptual group distinct from the world. In the absence of such parsing, attentional capture should be prevented, enhancing the ability of operators to process scene-linked HUD symbology in parallel with real-world information.

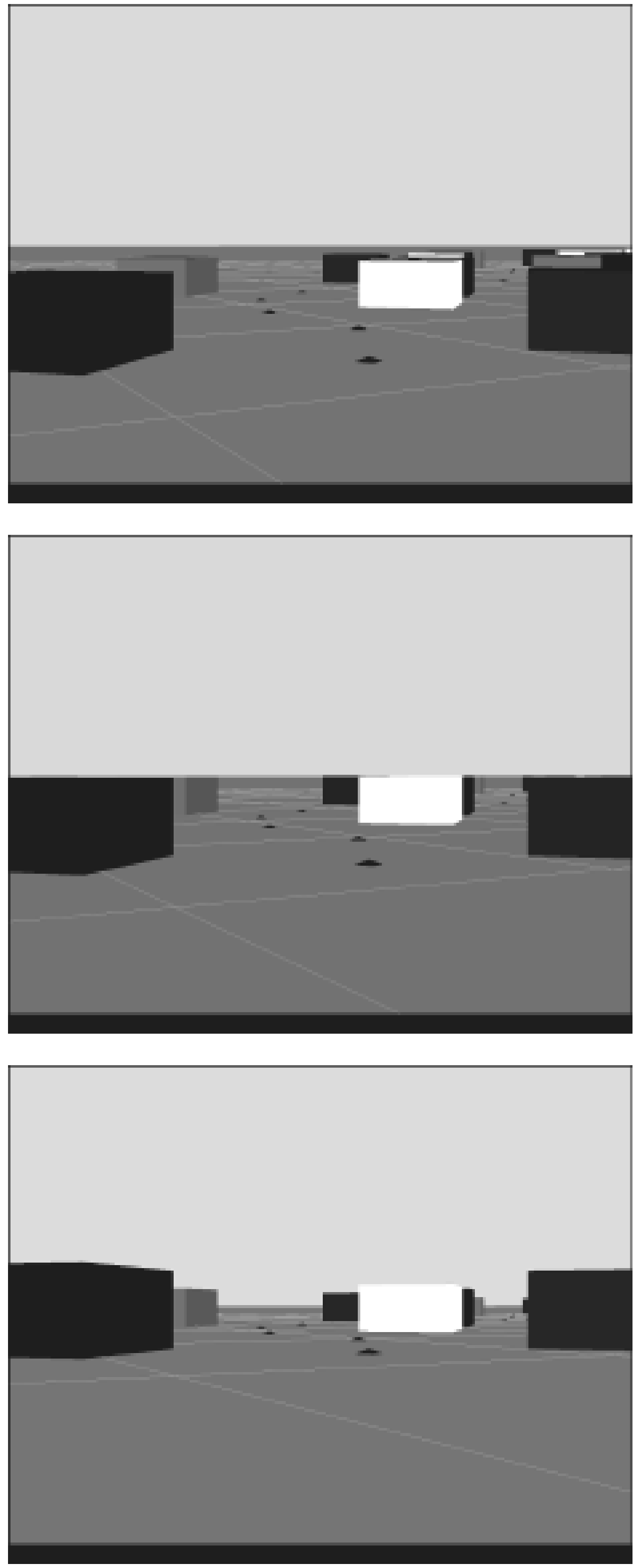

Figure 3. Flight simulation environment with virtual buildings showing current altitude above 100 feet (top panel), at 100 ft (middle) and below 100 ft (bottom).

EXPERIMENTAL TEST - If this analysis is correct, scene-linked HUDs should alleviate performance problems associated with conventional HUD symbology. Recall that in our part-task simulations of controlled flight over terrain,

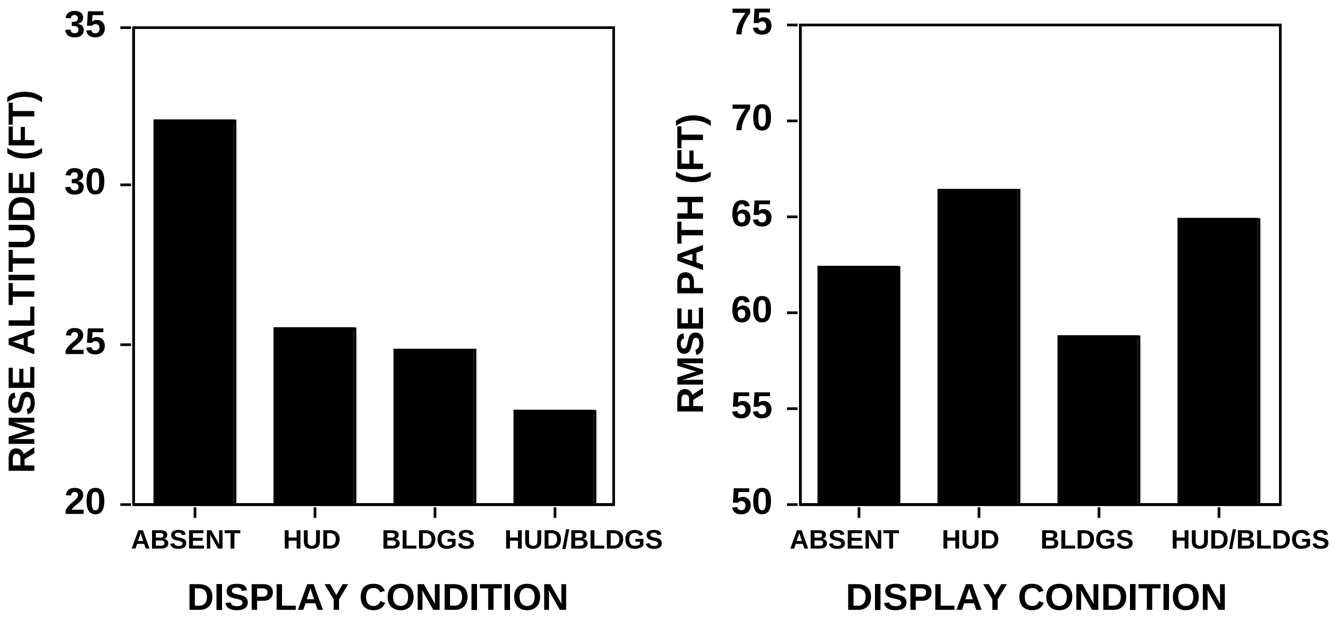

Figure 4. Results of experimental test: Effects of HUD altitude symbology absence, presence, virtual buildings and virtual buildings with altitude symbology on RMS Error Altitude (left) and RMS Error Path (right).

adding a digital HUD to the display improved altitude maintenance performance, but impaired path following performance. In a recent study, we examined the effect of a scene-linked HUD on the performance tradeoff. In addition to the standard condition, where altitude information was available in the form of a superimposed digital symbol, we added a condition in which "virtual" buildings were added to both sides of the path at regular intervals. The buildings were exactly 100 feet in height. The three panels in Figure 3 illustrate the various cues to altitude supplied by the virtual buildings. In the top panel, the aircraft is higher than 100 feet, so the black tops of the buildings are visible. In the middle panel, the aircraft is at exactly 100 feet, and is exactly flush with the tops of the buildings. Additionally, as determined by the visual geometry, the tops of the buildings are coincident with the horizon line. Finally, in the bottom panel the aircraft has fallen below 100 feet, so the buildings now "loom" above the horizon. Thus the buildings provide a number of high quality visual cues with which to compare current altitude against the 100 feet target altitude.

PREDICTION - Assuming subjects make use of the altitude cues supplied by the buildings, altitude maintenance should improve relative to the control condition where the only cues to altitude are those naturally available in the world. Assuming the building are interpreted perceptually as part of the world, altitude cues and path information should be processed in parallel; consequently, the improvement in altitude maintenance should be achieved without the associated cost in path performance found with digital HUDs.

METHOD AND RESULTS - The experiment included four conditions, defined by the type of altitude information available: A control or no-HUD condition, a digital HUD condition, a scene-linked HUD condition (i.e., buildings present), and a "both" condition where the digital HUD and the virtual buildings were present. Fourteen subjects flew 12 flights in each condition, for a total of 48 experimental flights each (plus practice).

The results are presented in Figure 4. Turning first to the left panel we see that, as expected, the presence of digital altitude information improved altitude performance, relative to the control condition. The virtual buildings also improved altitude performance, by an amount equal to the digital HUD. The right panel shows that the digital HUD again produced a decrement in path performance relative to the control condition, replicating the performance tradeoff found in earlier studies (Foyle, McCann, Sanford, & Schwirzke, 1992). However, there was no decrement in path performance with the virtual buildings; on the contrary, this condition produced a small benefit to path performance, although the benefit was not statistically significant. In summary, the digital HUD yielded a performance tradeoff, but the scene-linked HUD did not.

DISCUSSION - These results provide strong evidence that scene-linked imagery can provide information that is just as useful as instrument information presented on a HUD. This follows from the fact that the improvement in altitude maintenance provided by the virtual buildings was equal to the improvement provided by the digital HUD. Unlike the HUD, however, the virtual buildings did not produce a decrement in path following. This result suggests that subjects were able to process virtual imagery and other world-referenced visual elements concurrently, supporting our contention that scene-linked HUDs provide a solution to the concurrent processing problems found with traditional HUD symbology.

The results of this experiment also speak to a possible alternative account of the performance tradeoff found with digital HUDs. One might argue that when the digital HUD was present, subjects simply deemed the altitude component of the task to be more salient than when the symbology was absent, so they expended more effort on maintaining altitude, and less effort on flying the path. On this model, the

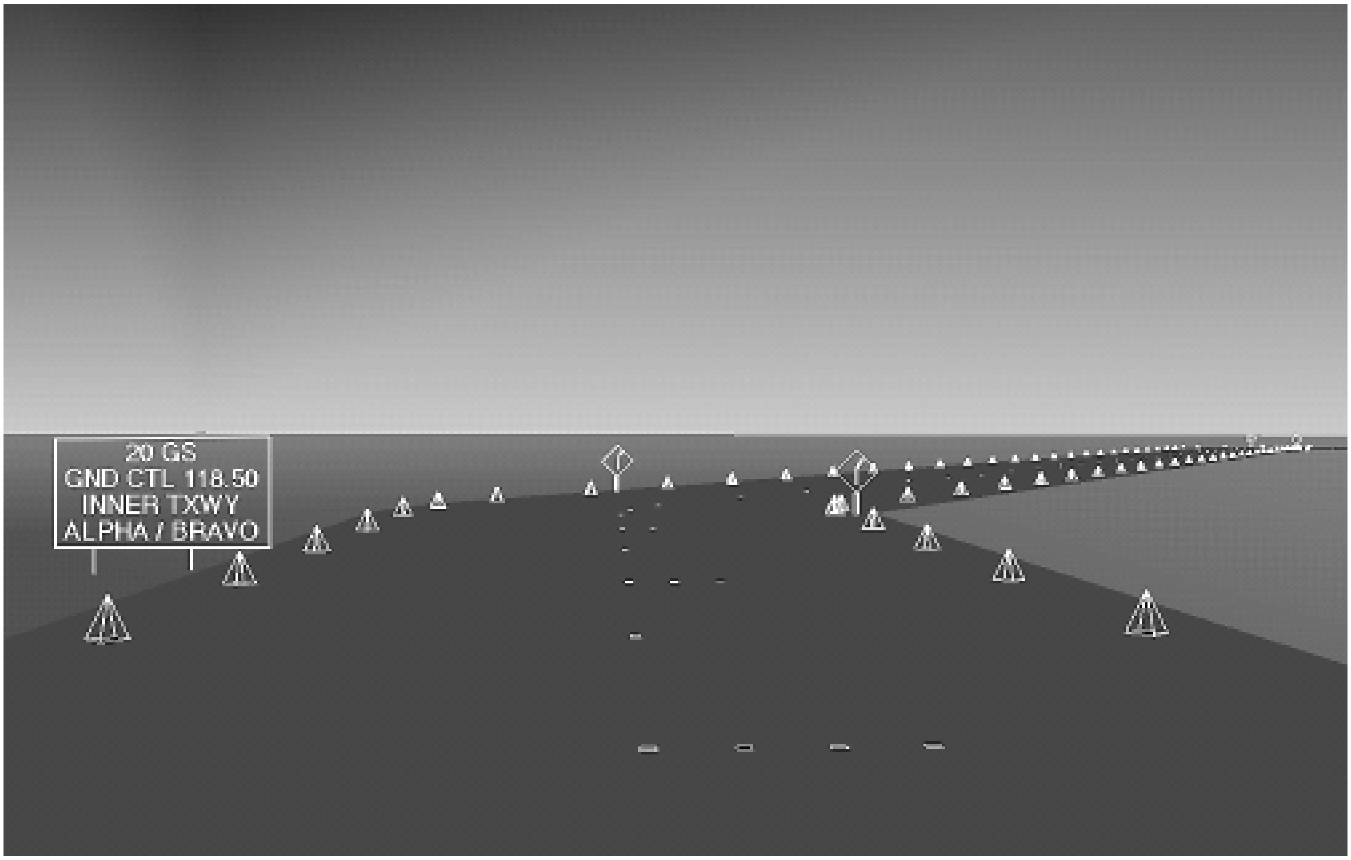

Figure 5. Candidate scene-linked HUD symbology for taxi and surface operations. Symbology (shown in white) includes virtual billboard aircraft instrumentation and location information, as well as virtual scene enhancements (edge cones, turn signs and "countdown" warnings).

performance tradeoff was the product of a strategic change in the relative priority given to the navigation and altitude components of the flying task, instead of an inability to visually process the digital symbology and the world. However, the relative emphasis account predicts that performance tradeoffs should occur any time there is a systematic improvement in one task component relative to the other. The fact that the virtual buildings yielded as much improvement in altitude maintenance as the digital HUD, but not at the expense of an increase in path error, is evidence against the relative emphasis account.

The remaining conditions of the experiment also deserve comment. Providing both digital altitude information and the virtual buildings improved altitude maintenance marginally over either information source alone; however, the reappearance of the performance tradeoff in this condition suggests that subjects were inclined to rely on the digital HUD when it was present, despite the fact that a more efficient scene-linked cue was available.

FUTURE DIRECTIONS

Design solutions are only useful insofar as the technology is available to implement them. We should note that certain components of a scene-linked HUD, such as fully conformal runway edge lines, are currently undergoing testing (Wickens & Long, 1994). The ability to generate this and other scene-linked symbology requires an advanced display medium, such as a holographic HUD, and a highly accurate positioning system. Today, these systems are only available at airports equipped with precision radar facilities. In the near future, however, it is expected that differential GPS systems will be installed on virtually all active aircraft. As GPS systems saturate the marketplace, there is no technical reason why scene-linked HUDs cannot proliferate along with them.

Our research suggests that linking HUD symbology to the outside scene abolishes performance problems associated with attentional capture. Scene-linked HUDs are likely to be particularly beneficial in two operational scenarios. First, scene-linking ought to assist nap-of-the-earth helicopter flying, where rapid switching between the instruments and the out-the-window scene is a constant requirement. Second, scene-linked symbology should be beneficial in conditions where pilots are focusing on primary flight display symbology, as in a low visibility approach, but must at the same time be sensitive to runway incursions, other air traffic, and ground traffic.

SURFACE OPERATIONS - Taxi and other surface operations are a particularly attractive environment for scene-linked HUDs. Currently, surface operations are one of the most inefficient components of the air transport system. Pilots are given little or no explicit information about their current position, and routing information is limited to ATC communications and airport charts. Under low visibility conditions, pilots can easily become spatially disoriented, leading to time-consuming interactions with ATC and reductions in taxi speed. In Figure 5, we present a candidate scene-linked HUD display to alleviate these problems. The candidate HUD contains aircraft instrumentation information and current location displayed on a virtual "billboard", as well as pictorial augmentations to the scene.

The virtual billboard to the left of the taxiway includes aircraft status information and ground location. The top line contains the aircraft's current ground speed (20 kts, "20 GS"). This is a dynamic readout and would change as appropriate. Similarly, the ground control radio frequency that is currently set is shown ("GND CTL 118.50"). The other two lines on the virtual billboard represent the aircraft's current airport location. The "Current, Last/Next" format represents current runway or taxiway segment ("Inner Taxiway"), the last intersection passed ("Alpha"), and the next intersection upcoming ("Bravo"). The example shows that this aircraft is on the Inner Taxiway, past Alpha and before Bravo taxiways.

The pictorial scene augmentations shown include visual enhancements that would aid the pilot in following the taxiway clearance and completing turns. Vertical side cones on the side of the commanded taxiway path depict the ATC cleared route on the HUD in superimposed symbology (as in "Pink 5" at Chicago O'Hare). These are conformal and represent a virtual representation of the cleared taxi route on the HUD. The side cones and the centerline markings are shown repeated every 50 feet down the taxiway. The vertical development and constant spacing should yield increased capability for estimating ground speed, drift, and look-ahead capability for turns. Turn "countdown" warnings are shown in which each turn has countdown (4, 3, and 2) centerline lights that are (300, 200, and 100 feet, respectively) before each turn. This gives added distance cues for the turn. The virtual turn signs (with the arrows) give an added cue that there is a turn necessary. In addition, the angle of the arrow on sign represents the true angle of the turn (i.e., 30 deg right for a 30 deg right turn). All of the HUD symbology is scene-linked, allowing the pilot to process the symbology in parallel with other traffic, including possible incursions. In the near future, we plan to test this and other candidate scene-linked HUDs in a high fidelity part task simulator being developed at Ames.

SUMMARY

This paper has reviewed recent superimposed symbology display research in the Aerospace Human Factors Research Division at NASA Ames Research Center. We discussed how human information processing abilities are severely constrained by attentional limitations. These limitations must be taken into consideration when evaluating the costs or benefits of a particular display device. In the present case, we have seen that placing HUD symbology in the pilot's forward field of view is necessary but not sufficient to allow the pilot to process instrument information and world-referenced information concurrently. Concurrent processing can be achieved, however, with scene-linked HUD designs, which project HUD symbology virtually into the world.

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