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HEAD-UP DISPLAYS: EFFECT OF INFORMATION LOCATION ON THE PROCESSING OF SUPERIMPOSED SYMBOLOGY

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ABSTRACT

Head-up display (HUD) symbology superimposes vehicle status information onto the external terrain, providing simultaneous visual access to both sources of information. Previous research (Brickner, 1989; Foyle, Sanford & McCann, 1991) found that the presence of HUD symbology representing altitude information was associated with improved altitude maintenance performance but with a corresponding reduced ability to follow a designated path through the environment (heading maintenance component). By varying the location of the altitude information relative to the path information, the present study was able to discriminate two accounts of this concurrent processing limitation. Relative to a baseline condition in which the superimposed altitude indicator was omitted, altitude maintenance was improved by the presence of the altitude indicator, and this improvement was the same magnitude regardless of the position of the altitude indicator on the screen. However, a concurrent deficit in heading maintenance was observed only when the altitude indicator was proximal to the path information. These results did not support a model of the concurrent processing deficit based on an inability to attend to multiple locations in parallel. They are consistent with previous claims (Foyle et al., 1991) that the deficit is the product of attentional limits on subjects' ability to process two separate objects (HUD symbology and terrain information) concurrently. The absence of a performance tradeoff when the HUD and the path information were less proximal is attributed to a breaking of attentional tunneling on the HUD, possibly due to eye movements.

INTRODUCTION

Head-up display (HUD) symbology visually superimposes vehicle status information onto the external terrain providing simultaneous visual access to both sources of information. The HUD symbology is collimated and projected onto a combining glass located between the pilot and the windshield. Therefore, the terrain and vehicle status information should be available for concurrent use, and the need for reaccommodation should be eliminated. However, there has been debate about whether the superimposed symbology format has successfully accomplished these design goals.

Difficulties with the use of HUD symbology

Fischer, Haines, and Price (1980) reported that during a simulated landing, pilots took longer to respond to an unexpected airplane on the runway when using HUD symbology as compared to a panel-mounted display. In fact, two out of eight pilots failed to see the runway obstruction in the superimposed symbology condition and flew into it. Weintraub, Haines, and Randle (1985) presented a similar runway obstruction and reported that six out of eight pilots failed to see the jet on the runway when using HUD symbology. Failure to detect unexpected events in the external scene with the use of superimposed symbology suggests that processing superimposed symbology reduces the availability of information in the terrain.

Further examples of performance problems with HUDs were reported by Brickner (1989) and Foyle, Sanford and McCann (1991). Both studies used a computer graphics flight simulation with overlaid graphics HUD symbology presenting altitude information. Heading information was presented in the virtual terrain. Subjects flew through a virtual environment while performing two tasks: a ground track (heading) task and an altitude maintenance task. Both Brickner (1989) and Foyle et al. (1991) found that the presence of superimposed digital altitude information improved altitude maintenance compared to the condition where the HUD symbology was absent. However, the improvement in altitude performance was accompanied by an impairment on the ground track (heading) task.

Sources of the concurrent processing deficit

Accommodation. Roscoe (1984) reported that it is difficult to accommodate simultaneously to the HUD information and the terrain. He suggests that misaccommodation is implicated in the performance problems with superimposed symbology. However, Sheehy and Gish (1991) found that there is no shift in accommodation when HUD symbology is used. Furthermore, the presence of an altitude/heading performance trade-off in the Brickner (1989) and Foyle et al. (1991) studies also illustrate that misaccommodation cannot fully account for the difficulties with HUD use. In these studies the HUD symbology and the terrain were both presented graphically on a computer monitor where the optical distance was equal. Consequently, accommodation cannot be the source of the altitude/ heading performance trade-offs found in these studies.

Attentional Limitations

Since accommodation was controlled in these studies, Brickner (1989) and Foyle et al. (1991) proposed an account based on attentional limitations. That is, the limitations on visual/spatial attention prevented concurrent processing of HUD and terrain information. Two models of visual/spatial attention could explain the altitude/heading performance trade-off: object-based and location-based.

Object-based models. 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, and attention can only be focused on one group at a time (Kahneman & Treisman, 1984). Therefore, concurrent processing of two sources of information is only possible if they are part of the same object (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 the HUD symbology moves with the vehicle as the vehicle moves through the terrain, the HUD symbology and terrain information have differential motion. Since the terrain information is generally pictorial in nature while the HUD information is primarily digital, these two sources of information also differ in their display format. Therefore, the HUD information and terrain information may segregate into separate objects, thereby preventing concurrent processing.

Location-based models. The location-based model of attention contends that concurrent processing of two sources of information is only possible if they are located near one another in space. Eriksen and Yeh (1985) proposed the analogy of an attention spotlight for this model. It is possible that the location of the HUD symbology may have affected the ability to use both heading and altitude information in the Brickner (1989) and Foyle et al. (1991) studies. Symbology location may have contributed to the heading/altitude performance trade-off. In the simulated flight tasks, the altitude information was located slightly above and to the left of the center of the display. Brickner (1989) used a slalom flight task. Therefore, the heading information, which was determined by the terrain, moved across the display as the simulated aircraft moved through the slalom course. Conversely, the heading information was located along the vertical center of the display in the task used by Foyle et al. (1991). In each task, the altitude information was displaced from the heading information; thus, the spatial displacement of the two information sources may have affected the ability to use both pieces of information.

Hypotheses

The purpose of the experiment being reported is to distinguish between the object-based and location-based accounts of the altitude/heading performance trade-off (Brickner, 1989; Foyle et al., 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). Moving heading and altitude information closer together may place them within the same attentive field and improve the ability to process both pieces of information more effectively. The location-based attentional hypothesis predicts that the altitude/heading performance trade-off should decrease as the distance between heading 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 heading and altitude information closer together should not improve the ability to process both sources of information. The object-based attentional hypothesis predicts that the altitude/heading performance trade-off should be unaffected by a decrease in the distance between altitude and heading information.

A flight simulation task was used to evaluate the effect of information location on the processing of superimposed symbology. HUD symbology presenting digital altitude information was presented in the lower portion of the screen near the heading information (the proximal condition), near the center of the screen at an intermediate distance from the heading information (the intermediate condition), or in the upper left corner of the screen far from the heading information (the distal condition). Figure 1 illustrates these locations. There was also a control condition in which the HUD information was absent. Pictorial heading 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 (heading) task and an altitude maintenance task. Root mean squared error (RMSE) heading and RMSE altitude were dependent variables.

METHOD

Subjects. Fourteen right-handed adult male subjects with unaided normal or corrected to normal vision were paid to participate in this experiment.

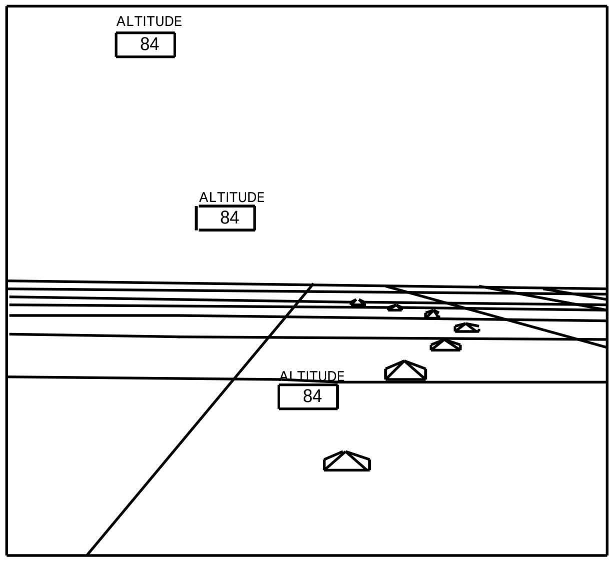

Figure 1: Schematic representation of flight simulation with HUD symbology displaying the three altitude locations (proximal, intermediate and distal, from bottom to top).

Apparatus. An IRIS 3130 Silicon Graphics computer was used to present the flight simulation program and to collect data. The program was viewed on a 19-inch Silicon Graphics color monitor from a distance of 65 cm. The flight simulation was controlled with a spring-centered joystick built into the right arm of the subjects' chair. The flight simulation display did not pitch up or down when climbing or descending to ensure that the heading information in the virtual environment would be visually available at all times. The virtual environment contained a blue sky that met a green ground at the horizon. A white grid was superimposed on the ground. The eight paths which subjects followed were each marked by brown pyramid-shaped objects that were 12 ft x 12 ft at the base and 6 ft high (scaled in the virtual environment). The pyramids were located 33 ft apart on the ground. Each path consisted of nine segments four pyramids in length. The segments were joined at 60˚, 90˚ or 120˚ angles that turned either right or left. The turn directions alternated between right and left, forming a zig-zag pattern. The order of angle placement was randomly assigned with the restriction that each angle was used three times in each path.

A digital altitude indicator (e.g., a HUD) was presented in one of three locations relative to the path-defining pyramids: proximal, intermediate, or distal. The altitude indicator was a rectangle 0.8 cm x 0.4 cm on the display. The boundary of the rectangle was white, while the interior was translucent blue. The digital information was presented in white 12-point Chicago font. Directly above the box, the word "altitude" was presented in white capital 12-point Chicago font. In the proximal condition, the altitude indicator was centered along the width of the screen. The upper left corner of the indicator was located 18.5 cm from the left edge of the screen and 17.5 cm from the top of the screen. The upper left corner of the intermediate altitude indicator was located 13.0 cm from the left edge of the screen and 10.0 cm from the top of the screen. In the distal condition the upper left corner of the altitude indicator was 7.5 cm from the left edge of the screen and 2.5 cm from the top of the screen. As shown in Figure 1, these locations were equidistant (8.14° visual angle) from one another. Random vertical and horizontal turbulence were introduced in all trials. The joystick sampling, data collection and graphics were updated at 12 Hz.

Design. A two-way within-subjects design with repeated measures was used. The variables of interest were HUD location and replication. There were three levels of HUD symbology distance relative to the path-defining pyramids: proximal, intermediate and distal. There was also a control condition in which the HUD symbology was absent. There were 20 replications of the four conditions. The first four replications served as practice trials. The remaining sixteen replications served as experimental trials. The replications were blocked. Each location was presented once in each replication. However, the order of presentation within each block was randomly assigned. There was a total of 80 trials. One of eight paths was randomly assigned to each trial, with the restriction that each path was used ten times for each subject. The dependent measures were RMSE altitude and RMSE heading. Altitude errors were determined by measuring subjects' distance from the assigned altitude (100 ft) as they flew through the virtual environment. Heading errors were determined by measuring subjects' distance from the closest straight line segment in the path as they flew through the virtual environment.

Procedure. Each subject participated in one 2.5 hr session. Subjects were verbally instructed to fly directly over the path and simultaneously maintain an altitude of 100 ft. Instructions emphasized the need for accuracy. The experimenter demonstrated the flight task, and the subjects were familiarized with each of the four experimental conditions and both components of the task during the sixteen practice trials. Once the experimental trials began, each subject completed sixteen replications of the four conditions.

RESULTS

To maintain a familywise error rate of $p < .05$, a Scheffe test was used to establish a modified critical F value of 2.84. This criterion was applied to the two-way 4 (locations of altitude information: lower, center, upper and absent) x 16 (replications) x 14 (subjects) within-subjects analyses of variance with repeated measures and the planned comparisons that were performed in both the RMSE altitude and RMSE heading performance data.

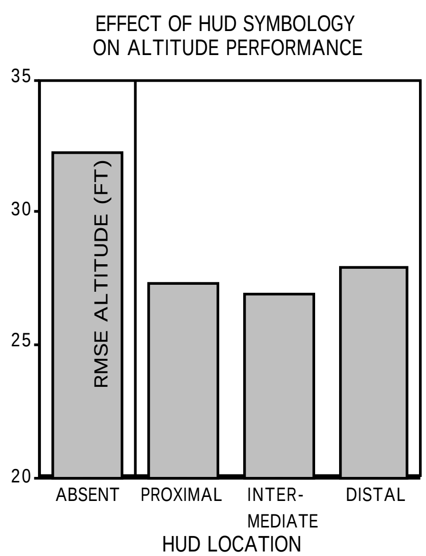

Figure 2: Effect of HUD symbology on altitude maintenance performance (RMSE).

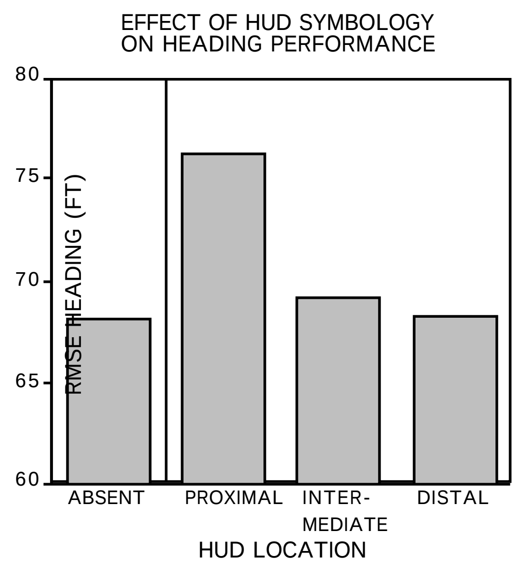

Figure 3: Effect of HUD symbology on heading (ground track) performance (RMSE).

Altitude Maintenance Performance

HUD symbology had a reliable main effect on altitude performance, $F(3,13) = 10.61$, $p < .0001$. An omega-squared analysis estimated that HUD symbology presence accounted for 67% of the total variance in altitude performance. Replication did not produce a main effect, nor did it interact with HUD information location.

Several planned comparisons were conducted. Altitude performance (across location) was reliably better when altitude information was presented than when it was absent ($F(1,13) = 13.09$, $p < .003$). Altitude performance was better when the HUD symbology was present in the proximal location than when it was absent ($F(1,13) = 10.07$, $p < .007$). Altitude performance was equal in the intermediate and proximal location conditions ($F < 1$), and performance in these two conditions (intermediate and proximal) was equal to performance in the distal location condition ($F(1,13) = 2.73$, $p < .12$). Altitude performance improved reliably when an altitude indicator was presented in the HUD symbology. Figure 2 illustrates that altitude performance was unaffected by the distance between the superimposed altitude indicator and the heading information in the terrain.

Heading (Ground Track) Performance

HUD location produced a reliable main effect on heading performance, $F(3,13) = 12.27$, $p < .0001$. An omega-squared analysis estimated that HUD symbology location accounted for 44% of the total variance in heading performance. Replication did not reliably affect performance when the conservative criterion produced by the Scheffe test was applied. However, replication did produce marginally significant heading results, $F(1,15) = 2.03, p < .02$. The marginal reliability of replication was attributable to a simple practice effect. Replication did not interact with HUD information location.

Several planned comparisons were conducted. Heading (ground track) performance was better when the HUD symbology was absent than when it was present in the proximal condition ($F(1,13) = 16.51, p < .001$). Performance in the intermediate and distal location conditions was better than in the proximal condition ($F(1,13) = 41.36, p < .0001$). Moreover, heading performance in the HUD absent, intermediate and distal locations combined was better than in the proximal altitude indicator location condition ($F(1,13) = 36.34, p < .0001$). Heading performance was equal in the absent, intermediate and distal conditions. It was impaired in the proximal superimposed symbology condition. Figure 3 illustrates that a decrement in heading performance was observed in the proximal condition.

To summarize, altitude performance improved reliably, regardless of location, when a HUD containing digital altitude information was presented; altitude performance was equal in each of the HUD symbology location conditions; a decrement in heading (ground track) performance relative to the HUD absent condition was observed only in the proximal condition; heading performance was equal in the absent, intermediate and distal conditions. Improved altitude performance was associated with a decrement in heading performance only in the proximal condition.

DISCUSSION

The location-based attentional model predicted that performance on both the altitude maintenance and ground track tasks would be best when the HUD symbology and terrain information were located near each other (the proximal condition). The results of this study do not provide any support for the location-based attentional model. In fact, the results were opposite of those predicted by this model. Performance did not improve when the HUD symbology and terrain information were located near one another. Instead, the proximal condition was the only condition to yield an altitude/heading performance trade-off. Furthermore, when the two sources of information were more distant from one another (the intermediate and distal conditions) altitude performance improved without an associated decrement in heading performance. The altitude/heading performance trade-off was absent in the intermediate and distal conditions. 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/heading performance trade-off in the proximal condition supports the contention that the HUD symbology and the terrain are parsed into separate perceptual objects. However, the absence of the altitude/heading performance trade-off in the intermediate and distal conditions does not support the strongest form of the object-based attentional model.

Altitude performance improved equally when HUD symbology was used to present an altitude indicator, regardless of the distance between the HUD symbology and the terrain information. Improved altitude performance was only associated with a decrement in heading performance in the proximal condition. The presence of an altitude/heading performance trade-off when the two sources of information were located near one another 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 heading information located in the terrain not being processed efficiently. 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 proximal condition, but not in the intermediate and distal conditions.

The absence of an altitude/heading performance trade-off when the two sources of information were more distant, in the intermediate and distal conditions, may be due to the need to visually/attentionally scan between the superimposed altitude indicator and the terrain information. When visual/attentional scanning is required, attentional tunneling is broken, and the altitude/heading performance trade-off is not observed. Visual/attentional scanning seems to improve the cognitive processing of information provided by separate perceptual objects (Weintraub et al., 1985). In summary, the location-based attentional model was not supported. The object-based attentional model was partially supported, as the HUD symbology and terrain information were parsed into separate perceptual objects. However, the efficient processing of information from separate perceptual objects occurred when visual/attentional scanning was required.

IMPLICATIONS AND CONCLUSIONS

It appears that superimposing digital flight information as a separate perceptual object from terrain information may not cause performance problems unless the HUD symbology relevant to the task being performed is located near the task-relevant information in the external terrain. However, this situation may occur in aviation situations, especially during runway approaches when the runway should be located near the center of the pilots' field of view along with some superimposed symbology. Therefore, this study reaffirms the need to investigate methods of alleviating attentional tunneling.

Although the HUD symbology and terrain information were perceived as separate object, this did not hinder performance when attentional scanning was required. Placing attentional scanning cues in the superimposed symbology may adequately alleviate the problems encountered due to attentional tunneling. The attentional scanning cues should encourage the pilots to survey the other sources of relevant information periodically. Extrapolating from the results of this study, it seems possible that such a design alteration might reduce the performance problems that have been associated with the use of superimposed symbology. It should be noted that the current study and results relevant to HUD location presumably do not apply to conformal or integrated displays. Placing the velocity vector on the runway during landing is a useful, natural display. In terms of this paper, the symbology and the runway attentionally form a single object, and no attentional switching between the symbology and the runway is required.

It is important to note that only one piece of HUD information was presented in this experiment. Consequently, the results may not be completely representative of flight performance in aviation situations where full HUD symbology is presented. Furthermore, the complexity of the full symbology should be considered when investigating any alteration of or addition to the HUD design. Display complexity may alter attentional scanning strategies. Additionally, attentional scanning strategies may be affected by flight variables such as turbulence levels. Each of these issues should be considered in future research. The results of this study indicate that further investigation of a design change that could effectively encourage attentional scanning might be useful. Such a design change might reduce the attentional segregation problems that have been encountered with superimposed symbology due to differences in information location.

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