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Head-Up Display Symbology for Surface Operations: Eye Tracking Analysis of Command-guidance vs. Situation-guidance Formats

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This study investigated pilots' taxi performance and distribution of visual attention with four different head-up display (HUD) symbology formats: Command-guidance, Situation-guidance, Hybrid, and a baseline, No-route guidance. Taxi speed and centerline accuracy were highest with Hybrid and Situation-guidance whereas Command-guidance and No-guidance resulted in increased visual attention to the head-down map display and side window displays. These results are thought to be due to lack of sufficient preview information with the Command-guidance symbology. The conformal route information of the Situation-guidance and Hybrid HUD formats provided a common reference with the environment, which may have supported better distribution of attention.

Introduction

Airport surface operations have been cited as the least technologically advanced and one of the most difficult phases of flight (Kelley & Adam, 1997). Pilots must maintain awareness of their cleared taxi route, their position relative to the cleared route, as well as their position on the airport surface. To maintain awareness, pilots must monitor airport signage and markings and compare this information to a paper airport diagram. In low visibility or at night, pilots often reduce their taxi speed to avoid traffic conflicts and maintain adequate position awareness.

One way that low-visibility surface operations may be improved is by using Head-Up Displays (HUDs) to depict the cleared taxi route (Foyle, et al., 1996). There are two general HUD symbology concepts for providing navigation information: Command-guidance and situation-guidance. Command-guidance symbology directly provides commanded control information and is commonly displayed as a non-conformal error from the ideal path. In contrast, situation-guidance symbology provides navigational information as a conformal representation of the path without displaying the required control inputs or the error deviation (Foyle et al., 2002).

Command-guidance symbology provides the pilot with information related to the control inputs required to minimize deviations from the cleared route. The pilot's role in such a system has been described as a "low-level servo" (Beringer, 1999). Examples of command-guidance symbologies are displays used in most current commercial aircraft that incorporate an aircraft reference symbol, flight director and command-guidance cue. In flight simulations, pilots flying with command-guidance HUDs fly with less error, both vertical and horizontal, compared to head-down command-guidance and head-up pathway symbologies (Weintraub & Ensing, 1992).

One potentially negative aspect of command-guidance symbology is that it produces more control inputs than other displays (Beringer, 1999). This is due to the command-guidance symbology constantly displaying guidance information as error from the ideal course, so that even small deviations require a course correction. This leads to the pilots making small s-turns about the ideal course. Also, it has been hypothesized that command-guidance symbology does not support efficient division of attention between the HUD symbology and the out-the-window environment (Foyle, et al., 1992, Foyle, McCann & Shelden, 1995), because it is often presented as a superimposed symbology at a fixed-location on the HUD. The resulting differential motion between the fixed-location symbology and the dynamic, out-the-window scene can lead to attentional fixation on the command-guidance symbology (McCann, Foyle & Johnston, 1993).

Situation guidance symbology presents the cleared taxi route by augmenting the environment with conformal, scene-linked symbology (Foyle, McCann & Shelden, 1995). It is conformal in that the symbology overlays and moves in unison with the environment (Ververs & Wickens, 1998) and it is scene-linked in that it represents objects placed in the actual environment with appropriate optical motion cues (Foyle, et al., 1992). Situation-guidance symbology does not provide the pilot with specific control inputs necessary to track the route, but instead augments the visual scene to allow the pilot to use external cues. A potential benefit of situation-guidance symbology is that it provides a better understanding of the desired path relative to current aircraft position and enables more effective path recovery as compared to command-guidance symbology (Beringer, 1999). Also, it has been shown to reduce cognitive tunneling, compared to fixed-location symbology (Foyle, McCann & Shelden, 1995). In sum, the benefits of situation-guidance symbology indicate improved attention distribution; however, this may come at a cost of increased tracking error (Beringer, 1999).

Previous Research

A previous study (Foyle, et al., 2002; Wilson, et al., 2002) was conducted to compare pilot performance using three different types of HUD symbology: Command-guidance, Situation-guidance and a Hybrid symbology that combined aspects of the Command-guidance and Situation-guidance displays. It was hypothesized that compared to the Command-guidance symbology, pilots taxiing with the Situation-guidance symbology would have higher taxi speeds and better situation awareness, but at the cost of increased centerline deviation. Since the Hybrid symbology combined elements from both formats, it was hypothesized that it would lead to increased taxi speeds and better situation awareness, with no subsequent increase in centerline deviation.

As hypothesized, when pilots taxied with the Situation-guidance and Hybrid symbologies, they had significantly higher taxi speeds compared to the Command-guidance symbology. It was hypothesized that centerline deviation would be least with the Hybrid and Command-guidance symbology, because of the command-guidance cue. However, results showed that while pilots had the least deviation with the Hybrid symbology, they actually had more deviation with the Command-guidance symbology compared to the Situation-guidance symbology. It was concluded that the increased centerline deviation with the Command-guidance symbology was due either to aspects inherent to the Command-guidance symbology concept, or to the specific symbology presentation that was instantiated in the study. Specifically, the Command-guidance symbology included a guidance cue and a graphical plan-view representation of the centerline. The plan-view centerline provided preview of approximately 100 ft. of the upcoming taxi route. This form of preview may have been insufficient as pilots referenced the head-down taxi navigation map for upcoming turn information. When the pilot went “head-down”, this may have contributed to the decreased taxing accuracy. To better understand this finding of decreased accuracy, the present study was conducted implementing three changes to the previous study. First, the Command-Guidance Symbology was modified to investigate the effect of preview in the form of an arrow with a text-based turn distance countdown instead of a plan view centerline. Second, the use of an eye tracker to record eye movement data was added to determine whether pilots’ distribution of visual attention differs as a function of symbology type and to address questions related to symbology usage. Third, a baseline condition was added to evaluate taxi performance and visual attention with each HUD symbology condition relative to current-day, no guidance, conditions.

Method

Participants

Fourteen commercial airline captains, thirteen male and one female, participated in the study. The pilots’ age ranged from 33 to 54 years (M= 44 yrs). The flight hours logged as captain ranged from 1,000 to 12,000 hours with a mean of 4,503 hours. All of the participants were certified by their airline to use a HUD, and HUD hours logged ranged from 250 to 8,000 hours (M=2,223 hrs).

Apparatus

A medium-fidelity part-task simulator at NASA Ames Research Center was used. The airport was Dallas-Fort Worth International Airport (DFW) with a visibility of 1200 ft runway visual range (RVR). The airport environment included terminal buildings, runways, taxiways, grass medians, taxiway signage and markings, moving and non-moving aircraft and ground vehicles. Aircraft controls included a side-stick tiller control with left/right rotation for nose-wheel steering, non-differential throttle and rudder pedals with toe brakes. The aircraft control model closely resembled a Boeing 737. Eye tracking data was collected using an Applied Science Laboratories (ASL) 5000 Integrated Eye/Head tracking system at a data collection rate of 60 Hz.

Out-the-window scene. The forward out-the-window scene was rear projected on a 2.44 m horizontal (H, 53.13 deg) by 1.83 m vertical (V, 41.11 deg) screen located 2.44 m in front of the pilot’s eye point. The HUD symbology was graphically presented on the forward screen, such that the HUD display area was 31.42 deg (H) by 15.60 deg (V). The side window scenes, subtending a visual angle of 29.57 deg, were presented on two 48.26 cm (19-in diagonal) monitors, one on each side, at a viewing distance of .91 m.

Map and clearance display. A north-up taxi chart of DFW was copied onto a transparency and overlaid on a computer monitor with a white background. At the bottom of the monitor was a text display with the taxi clearance for each trial. The map and clearance display area was 33.02 cm (H) by 24.13 cm (V) at a viewing distance of 1.07 m (17.54 x 12.87 deg).

HUD Symbology

Four HUD symbology formats were developed to explore performance and symbology usage differences among Command-guidance, Situation-guidance, Hybrid, and No-route guidance symbologies. All symbology types had text taxiway labels and a groundspeed indicator as shown.

The Command-guidance symbology (Figure 1) is composed of a command-guidance cue, turn-distance countdown, and turn-direction indicator. The guidance cue is similar to command-guidance symbology commonly used for maintaining flight path in the air (Weintraub & Ensing, 1992; Foyle, Hooey, Wilson, & Johnson, 2002). The inner circle, the command-guidance cue, moves left and right in relation to the outer circle (fixed aircraft reference symbol) based on taxiway centerline deviation. The pilot's task is to taxi the aircraft such that the two circles are concentric, which will result in recapturing or maintaining the centerline of the cleared taxi route. The turn-direction arrow and turn-distance countdown provided preview for the next turn in the cleared route.

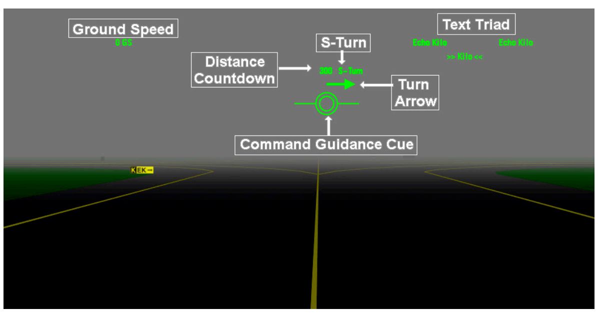

Figure 1: Command-guidance symbology (symbology in green, white, boxed labels not shown in experiment)

The Situation-guidance symbology (Figure 2) uses the HUD format of the Taxiway Navigation and Situation Awareness System (Hooey, Foyle & Andre, 2001). The cleared route is augmented with scene-linked symbology that overlays objects in the world including an augmented taxiway centerline, taxiway-edge cones, turn signs, and turn flags which extend beyond the cones in turns.

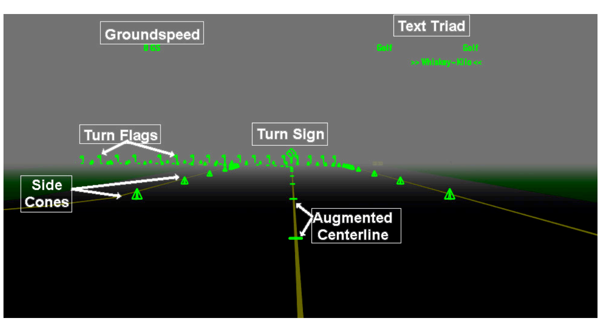

Figure 2: Situation-guidance symbology

The Hybrid symbology (Figure 3) combines aspects of the Command-guidance and Situation-guidance symbologies by providing control commands as well as conformally highlighting the cleared route. In the Hybrid symbology, there is a command-guidance cue, but without the turn-arrow or turn-distance countdown of the Command-guidance symbology. The Hybrid symbology has the scene linked taxiway edges and centerline of the Situation-guidance symbology without the turn flags and signs.

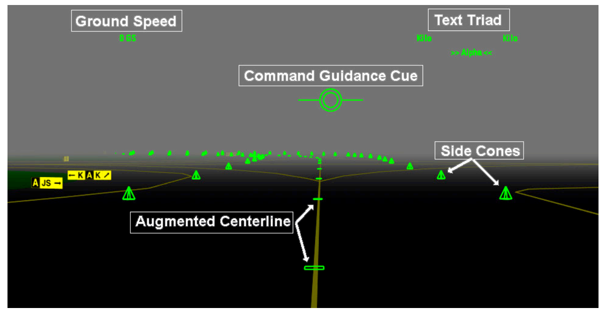

Figure 3: Hybrid symbology

The No-route guidance symbology (not shown) was implemented to simulate current taxi operations. The HUD provided only a ground speed indicator and taxiway text labels. This was provided in lieu of a first officer, who would normally assist the captain by calling out the upcoming taxiways.

Experimental Design

The study was a within-participants design, with HUD symbology format (Command-guidance, Situation-guidance, Hybrid and No-route Guidance) as a four-level factor. Each participant completed 16 experimental trials: Four consecutive trials of each of the four HUD formats. Order of presentation of the HUD symbology formats was randomized.

Scenarios. All scenarios consisted of taxi-only routes, with no landing or take-off. On average, the taxi routes were 15,600 ft in length, and contained six 90-degree turns. Each experimental taxi trial required approximately 8.75 minutes to complete, such that the entire experiment required a full day of testing. Each scenario included other aircraft and airport vehicles that were included for simulation realism and evaluation. (A near-incursion and situation awareness probes were included but are not reported here).

Procedure

Simulator training and familiarization consisted of eight trials (two trials each of the four HUD symbology formats) presented in randomized order. Through these training trials, pilots experienced instances of all scenario events with the exception of an aircraft incursion, and were briefed on the appropriate procedures for responding to the events. Upon completion of training, participants completed four blocks of four trials each, with a 10 minute break between each block. During each experimental trial, pilots followed a taxi clearance that was presented by voice from a pseudo air traffic controller (the experimenter) as well as presented in text on the map display. Pilots were told to taxi as they would in the real world with a full commercial flight and that taxi speed, accuracy, and safety were all equally important.

Results

Taxi Performance

Taxi performance with the four HUD symbology formats was assessed with two dependent variables: Average moving (non-zero) taxi speed (kts) and Root Mean Square Error (RMSE) from taxi centerline.

Taxi Speed. Increased taxi efficiency is one of the goals of a taxi HUD. Therefore, average moving taxi speed is an important measure of performance. It also serves as a surrogate measure of a pilot's confidence, as pilots taxi slower with greater navigation uncertainty. Consistent with the previous study, taxi speed differed as a function of HUD symbology, $F(3,39)=17.57$, $p< .001$. Taxi speed was greatest with the Situation-guidance (M=19.00 kts) and Hybrid (M=18.72 kts) symbologies, with no significant difference between the two. Situation-guidance and Hybrid symbologies were both significantly faster than the Command-guidance symbology (M=16.38; $t(13)=5.29$, $p<.001$, $t(13)=5.30$, $p<.001$, respectively) and the no-guidance symbology (M=16.26; $t(13)=5.66$, $p<.001$; $t(13)=3.81$, $p<.01$, respectively). Presumably, the situation-guidance elements (enhanced centerline and cone augmentations) common to both the Situation-guidance and Hybrid symbologies better supported efficient taxi and navigation awareness than the command-guidance cue. Interestingly, Command-guidance did not yield increased taxi speeds over the No-guidance condition.

Taxi Accuracy. A second goal of the taxi HUD is to improve taxi accuracy, measured here as Root Mean Square Error (RMSE) deviation from the centerline. Recall that although Command-guidance was expected to produce superior taxi accuracy over the other symbology type, this hypothesis was not supported in the previous study. The current study aimed to further investigate this surprising finding with a different form of Command-guidance symbology (text vs. graphical turn preview). The results of the current study replicated the previous study. The RMSE data averaged across the entire trial, and averaged over turns only, are presented in Figure 4, however, as the results were identical, only the overall results are discussed. Taxi accuracy varied as a function of HUD symbology, $F(3,39)=11.94$, $p<.001$. The Command-guidance and No-guidance symbologies had the highest RMSE and were not significantly different. RMSE with Command-guidance symbology was higher than with Situation-guidance, $t(13)=2.30$, $p<.05$, and Hybrid, $t(13)=6.36$, $p<.001$. RMSE with No-guidance symbology was also higher than with Situation-guidance, $t(13)=3.70$, $p<.01$ and Hybrid, $t(13)=4.40$, $p<.001$. There was no significant difference between the Situation-guidance and Hybrid symbologies.

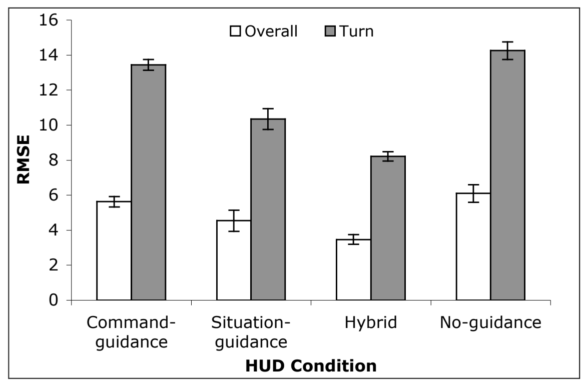

Figure 4. RMSE averaged over entire trial and turns only, (+/- 1 SE).

Pilot Visual Scanning

An important aspect of this study was to determine how pilots allocate visual attention while taxiing with different symbology types. There were three areas of interest: the taxi navigation map display; the forward screen, representing the forward aircraft window and HUD symbology; and the side monitors, representing the aircraft side windows. Figure 5 depicts the percent of total time allocated to each area over the entire trial for each HUD condition.

Allocation of Visual Attention to the Forward View. The forward screen provided a 53 deg (H) field of view of the airport taxiways and traffic immediately in front of the ownship and the HUD symbology overlay. Given the importance of scanning the environment for traffic and maintaining forward navigation awareness, it can be assumed that pilots only glanced away from the forward screen when they needed to gather navigation information from the map or side monitors that was not otherwise provided in the forward scene or symbology. Figure 5 demonstrates a significant difference in forward screen usage among HUD conditions, $F(3,39)=35.15$, $p<.001$. Pilots spent the most time looking at the forward screen when taxiing with the Hybrid symbology, which was significantly more than Situation-guidance, $t(13)=2.19$, $p<.05$. Both the Hybrid and Situation-Guidance displays yielded more time on the forward screen than either the Command-guidance, ($t(13)=4.25$, $p<.01$, $t(13)=2.28$, $p<.05$, respectively) or No-guidance, ($t(13)=9.09$, $p<.001$; $t(13)=8.11$, $p<.001$, respectively). Pilots allocated more time to the forward screen with Command-guidance symbology than No-guidance, $t(13)=7.81$. $p<.001$.

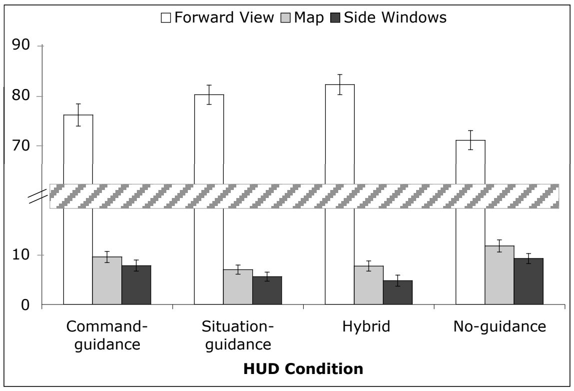

Figure 5. Percent Time of Visual Attention Allocated to Forward View, Map, and Side Windows. (+/- 1 SE)

Allocation of Visual Attention to the Taxi Map. The taxi map provided navigation awareness information about the cleared taxi route and the ownship distance to, and direction of, the next turn. The amount that pilots relied on the map for this information differed as a function of the HUD symbology, $F(3,39)=8.70$, $p<.001$. Specifically, when taxiing with the two symbologies that possessed situation-guidance elements (Situation-guidance and Hybrid), pilots spent less time viewing the map than when taxiing with the Command-guidance display, ($t(13)=2.45$, $p<.05$; $t(13)=2.97$, $p<.05$, respectively) or No-guidance ($t(13)=4.53$, $p<.001$; $t(13)=4.09$, $p<.001$, respectively. Situation-guidance and Hybrid formats yielded approximately equivalent map usage, as did Command-guidance and No-guidance. Presumably, the situation-guidance information available in the Situation-guidance and Hybrid symbologies provided more navigation awareness information than was available in the Command-guidance or No-guidance conditions.

Allocation of Visual Attention to the Side View. The side monitors were used by pilots for navigation (i.e., reading airport signage) and to follow centerlines through turn maneuvers. The total percent of time that pilots allocated their visual attention to the side monitors differed among HUD conditions and is shown in Figure 5, $F(3,39)=11.80$, $p<.001$. Overall, pilots spent the most time looking at the side monitors when taxiing with the No-guidance symbology, compared to when taxiing with the Command-guidance symbology, $t(13)=2.93$, $p<.05$, Hybrid symbology, $t(13)=4.2$, $p<.01$, and Situation-guidance symbology $t(13)=3.52$, $p<.01$. The Command-guidance symbology yielded significantly more time looking at the side monitors than did the Situation-guidance, $t(13)=2.60$, $p<.05$, and Hybrid, $t(13)=3.82$, $p<.01$, symbologies. Pilots spent the least amount of time looking at the side monitors with the Hybrid and Situation-guidance symbology, with no significant difference between the two conditions.

It is particularly relevant to examine side monitor usage for turn performance alone because it is during the turns when pilots look to the side for navigation guidance, if it is not available in the HUD. As expected, the percent time on the side monitors was significantly different as a function of HUD symbology, $F(3,39)=14.57$, $p<.001$. Pilots, when maneuvering turns, spent more time looking at the side monitors with the No-guidance symbology (M= 3.5%), than with Situation-guidance (M=2.2%), $t(13)=3.37$, $p<.01$, Command-guidance (M=2.0%), $t(13)=3.61$, $p<.01$, and Hybrid (M=1.0%), $t(13)=4.71$, $p<.001$. This reflects the need for additional information to support the turn that was not available in the front screen or HUD. Pilots taxiing with Hybrid symbology spent significantly less time looking at the side monitor in turns than did pilots taxiing with the Situation-guidance, $t(13)=3.65$, $p<.01$, and Command-guidance, $t(13)=3.09$, $p<.01$. There was no significant difference between Situation-guidance and Command-guidance during turns.

Guidance Cue Usage. Recall that the RMSE data showed that centerline deviations were lower with the Hybrid symbology than the Command-guidance symbology. Given that both symbologies included the same guidance cue for centerline tracking, this difference was somewhat of a surprise in this and the previous study. Recall also that the two conditions differed in that the Command-guidance symbology used the guidance cue as a primary navigation source, while the Hybrid symbology utilizes the guidance cue in conjunction with situation-guidance symbology.

To better understand the RMSE difference, the percent of forward screen time that pilots dwelled on the guidance cue was examined for the Command-guidance and Hybrid conditions. When averaged across the entire trial, there was not a significant difference in the time spent looking at the guidance cue with the Command-guidance and the Hybrid symbologies. However, there was a significant difference during turns. When maneuvering turns, pilots spent more time on the guidance cue with the

Hybrid symbology (M=3.9%) than when taxiing with the Command-guidance symbology (M=2.5%), $t(13) = 2.52$, $p < .05$. This suggests that the situation-guidance elements embedded in the hybrid symbology may have supported taxiing with the guidance cue and yielded more accurate taxi. Without this information, pilots were forced to take their eye off the forward screen and guidance cue and rely on the map and side monitors for navigation information to supplement the guidance cue resulting in greater centerline deviation.

Discussion

The Command-guidance and the No-guidance symbologies produced the highest RMSE deviation from the centerline and slowest taxi speeds, while the Situation-guidance and Hybrid symbologies produced the lowest RMSE and the fastest speeds. The eye-tracker results provided insight into pilots' usage of the displays, which may help to explain the RMSE deviation seen with the Command-guidance symbology. Pilots taxiing with the Command-guidance symbology spent less time looking at the forward screen, and more time looking at the taxi map and side monitors than did pilots taxiing with Situation-guidance and Hybrid symbologies. When taxiing with the Command-guidance symbology, pilots may not have had as much route knowledge, through preview, as with the Situation-guidance and Hybrid symbologies. Pilots with the Command-guidance symbology may have been forced to rely more on the map and airport signage, through the side windows, to confirm their positions and upcoming turns.

Pilots spent more time using the guidance cue during turns with the Hybrid symbology than the Command-guidance. With the Hybrid symbology, pilots attended more to the forward screen and the taxi task, utilizing both the guidance-cue and situation-guidance elements, without having to utilize the map and side monitors, thus improving taxi accuracy as evidenced by the least centerline deviation. This suggests that the Hybrid symbology may better support turns.

Pilots exhibit better taxi performance when they spend more time attending to the forward screen and less time looking at the map and side monitors to determine their position. In general, the guidance cue as a stand-alone navigation tool (Command-guidance), without the aid of scene-linked navigation aids does not seem to support accurate taxiing. When used in conjunction with scene-linked navigation (Hybrid), the guidance cue enabled more accurate taxi performance. However, questions remain about whether that benefit of improved accuracy outweighs the possible cognitive tunneling on the guidance cue, resulting in reduced division of visual attention.

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