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COMPARING PILOTS' TAXI PERFORMANCE, SITUATION AWARENESS AND WORKLOAD USING COMMAND-GUIDANCE, SITUATION-GUIDANCE AND HYBRID HEAD-UP DISPLAY SYMBOLOGIES

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This study investigated pilots' taxi performance, situation awareness and workload while taxiing with three different head-up display (HUD) symbology formats: Command-guidance, Situation-guidance and Hybrid. Command-guidance symbology provided the pilot with required control inputs to maintain centerline position; Situation-guidance symbology provided conformal, scene-linked navigation information; while the Hybrid symbology combined elements of both symbologies. Taxi performance was assessed with average taxi speed and root mean square error (RMSE) from the centerline. Situation awareness and workload were assessed using a 3-Dimension SART and a 7-point scale, respectively. Taxi speeds were highest and RMSE from centerline lowest with Situation-guidance and Hybrid symbologies. Situation awareness was highest and workload lowest with Situation-guidance and Hybrid symbologies. These results are thought to be due to cognitive tunneling induced by the Command-guidance symbology. Situation-guidance (and Hybrid) HUD symbologies provided a common reference with the environment, which may have supported better distribution of attention.

INTRODUCTION

Surface operations have been cited as the least technologically advanced and one of the most difficult phases of a 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 do this, they must monitor airport signage and markings and compare this information to a paper taxi Chart. In low visibility, 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 primary concepts in HUD symbology: Command-guidance and situation-guidance symbologies. Advantages and disadvantages to pilot performance and situation awareness of these symbology concepts are discussed below.

Command-Guidance Symbology

The 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 (Weintraub & Ensing, 1992). In flight simulations, pilots flying with command-guidance HUDs fly with less error, both vertical and horizontal, compared to head-down displays and pathway displays. Another benefit is that command-guidance HUDs provide better guidance in turns compared to head-down command-guidance and head-up pathway symbologies (Beringer, 1999).

A potentially negative quality of command-guidance symbology is that it produces more control inputs than other displays (Beringer, 1999). This is due to command-guidance symbology displaying guidance information from present or predicted error from the ideal course, so that even small deviations require a course correction. Also, it has been hypothesized that command-guidance symbology does not support efficient division of attention (Foyle et al., 1992, Foyle, McCann & Shelden, 1995), because it is often presented as superimposed symbology at a fixed-location on the HUD. Differential motion between the fixed-location symbology and the dynamic, out-the-window scene can lead to visual and attentional fixation or cognitive tunneling (McCann, Foyle & Johnston, 1993) on the command-guidance symbology at the cost of attending to the environment.

Situation-Guidance Symbology

Situation-guidance symbology presents the cleared taxi route by augmenting the environment with conformal, scene-linked symbology (Foyle, McCann & Shelden, 1995). Situation-guidance symbology is conformal in the sense that the symbology overlays and moves in unison with the environment (Ververs & Wickens, 1998). It is scene-linked in that it represents objects placed in the actual environment with appropriate optical motion cues as one's aircraft moves through the environment (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 to do so. A potential benefit of situation-guidance symbology is that it provides the pilot 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). Furthermore, conformal, scene-linked situation-guidance symbology has been shown to reduce cognitive tunneling, compared to fixed-location symbology (Foyle, McCann & Shelden, 1995). Taken together, the benefits of situation-guidance symbology seem to indicate improved attention distribution compared to command-guidance symbology, however, this may come at a cost of increased tracking error (Beringer, 1999).

This study compared three pilot group's taxi performance using three different types of HUD symbology: Command-guidance, Situation-guidance, and a Hybrid symbology that combines 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 will have higher taxi speeds, better situation awareness and lower workload, but at the cost of increased centerline deviation. Since the Hybrid symbology combines elements from the other formats, it was hypothesized that it would lead to increased taxi speeds, better situation awareness, lower workload, but with no subsequent increase in centerline deviation.

METHOD

Participants

Twenty-seven male pilots were recruited, nine in each of three groups. The first group consisted of commercial airline pilots with at least 500 hrs of HUD experience. Mean pilot age was 50 yrs, and actual HUD hours ranged from 750 to 5500 hrs (*M*=1968). Their number of hrs logged as captain ranged from 852 to 7000 (*M*=3650). The second group consisted of commercial airline pilots with no HUD experience. Mean pilot age was 50 yrs, and number of hours logged as captain ranged from 1100 to 13000 (*M*=7122). The third group consisted of general aviation pilots with no HUD experience. Mean pilot age was 40 yrs, and hours logged ranged from 310 to 1900 (*M* = 990).

Apparatus

Simulation. A part-task simulator at NASA Ames Research Center was used. The simulated environment was Dallas-Fort Worth International Airport with a visibility of 1000 ft runway visual range. The aircraft control model was a Boeing 737. Aircraft controls included a side-stick control, non-differential throttle, rudder pedals and toe-brakes. The forward out-the-window scene was rear projected on a 2.44 m horizontal (H, 53.13 deg visual angle) 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 were presented on two 48.26 cm (19-in diagonal) monitors, one on each side of the participant, at a viewing distance of .91 m (29.57 deg). An electronic moving map display (EMM) with a continuously available text clearance was used in place of a paper taxiway diagram. The cleared route was not graphically represented on the EMM. The EMM presented ownship location, as well as the airport environment approximately 800 m surrounding the ownship. (for more information, see Hooey, Foyle & Andre, 2000). The EMM and text display was 15.24 cm (H) by 20.32 cm (V) at a viewing distance of 1.07 m (8.17 x 10.88 deg).

HUD Symbology. Three HUD symbology formats were developed to explore performance differences among command-guidance, situation-guidance, and possible hybrid HUD symbologies. The Command-guidance symbology (Figure 1) is composed of a command-guidance cue, plan-view centerline, lateral aircraft reference, ground-speed indicator and current and upcoming taxiway labels. The command-guidance cue is similar to command-guidance symbology commonly used for maintaining flight path in the air (Weintraub & Ensing, 1992). 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 cleared taxi route. This is essentially a pursuit tracking task. The plan-view centerline is an overhead, downward-looking view of the upcoming 50 m (approximately) of the cleared route. On either side of the plan-view centerline are lateral aircraft reference markers, which represent the main landing gear of the aircraft. The pilot must keep the plan-view centerline between the aircraft reference markers.

The Situation-guidance symbology (Figure 2), uses the HUD format of the Taxiway Navigation and Situation Awareness (T-NASA) System (see Hooey, Foyle & Andre, 2000). Taxiway centerline and edges of the cleared route are augmented with scene-linked symbology. These augmentations include taxiway-edge cones, augmented taxiway centerline, as well as turn flags and signs, which extend beyond the cones in turns.

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 plan-view centerline and lateral aircraft reference marks of the Command-guidance symbology. The Hybrid symbology has the taxiway edges and centerline of the Situation-guidance symbology without the turn flags and signs.

Questionnaires. Questionnaires were

administered at the end of each trial, each HUD block, and at the completion of the study. The post-trial questionnaires assessed situation awareness and workload. The post-block questionnaires assessed situation awareness and symbology usage. The post-study questionnaire included rankings of the HUD symbology in various taxi situations.

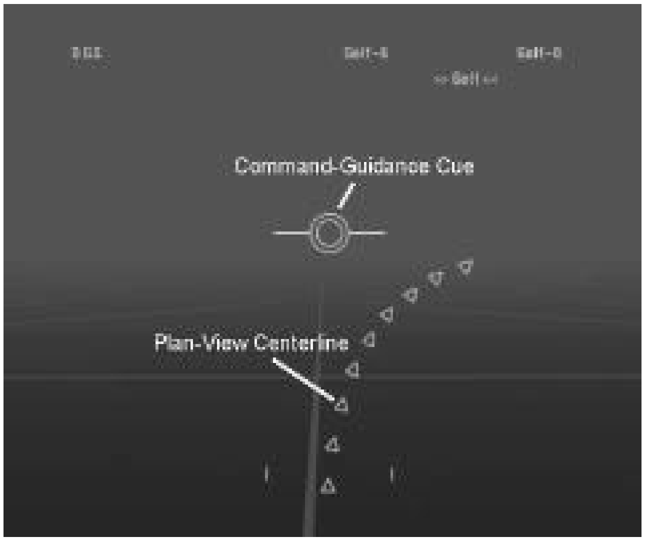

Figure 1. Command-guidance symbology overlaid on the forward scene (only center portion with HUD shown). Symbology shown is the command-guidance cue (labeled) depicting on-route tracking (i.e., concentric circles); the plan-view centerline (labeled) depicting an upcoming right turn, and lateral reference markers; ground speed indicator (upper left, showing 0 kts); and, text showing current and upcoming taxiways (upper right).

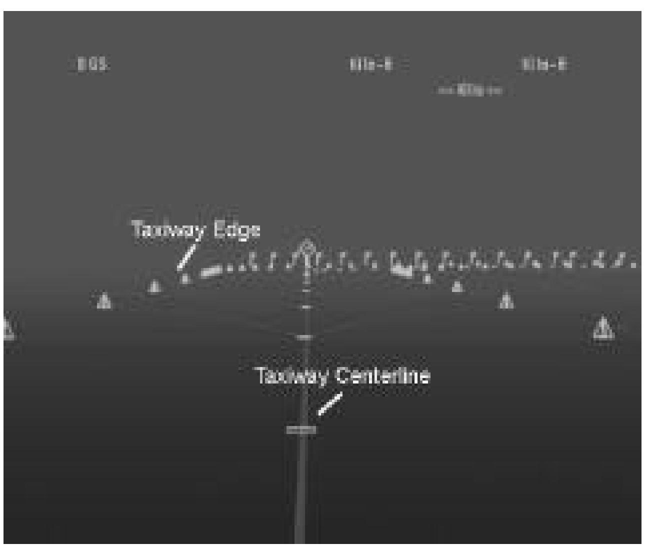

Figure 2. Situation-guidance symbology. Symbology shown is 3-dimensional taxiway edge cones (labeled) depicting an upcoming right turn; augmented taxiway centerline (labeled); ground speed indicator (upper left, showing 0 kts); and, text showing current and upcoming taxiways (upper right).

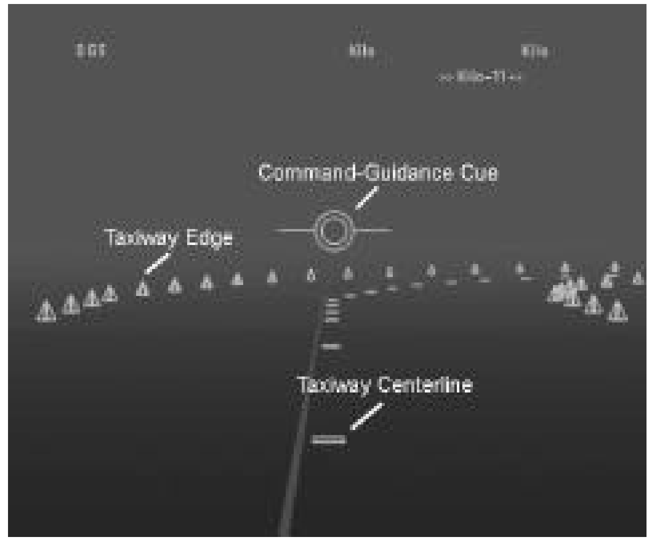

Figure 3. Hybrid symbology. Symbology shown is the command-guidance cue (labeled); taxiway edge cones (labeled); augmented taxiway centerline (labeled); ground speed indicator (upper left, showing 0 kts); and, text showing current and upcoming taxiway (upper right).

Experimental Design

This study was a mixed design, with pilot group (commercial HUD, commercial non-HUD and general aviation non-HUD) as a between-subjects factor and HUD type (Command-guidance, Situation-guidance and Hybrid) as a within-subjects factor. Subjects experienced a total of 9 training trials (three per HUD format), followed by 21 experimental trials (7 trials of each HUD symbology, presented in blocks). The experimental trials were randomized for each subject. The order of the three HUD types was counterbalanced across subjects.

Each trial was approximately 6 min long. Pilots followed a taxi clearance that was presented by voice from a pseudo air traffic controller as well as presented in text on the EMM.

RESULTS

Several measures were used to test the hypothesis that with the Hybrid symbology, pilots would show increased situation awareness, increased taxi speed and lower workload, compared to the Command-guidance symbology, similar to that expected when using the Situation-guidance symbology. However, centerline deviation was expected to be less with the Hybrid and Command-guidance symbologies, than with the Situation-guidance symbologies. All variables were analyzed using a 3 x 3 x 7 mixed design ANOVA (Pilot group x HUD symbology x Trial). There were no differences among levels of pilot group or trial for any of the measures.

Taxi Performance

Pilots' taxi performance with the three HUD symbologies was assessed using two performance variables: Average taxi speed (kts) and root mean square error (RMSE, ft) of centerline tracking performance. Regarding taxi speed, a significant effect of HUD symbology type was observed, $F(2,48)=17.40$, $p<.001$. Taxi speed was lowest with the Command-guidance symbology ($M=14.71$), which was significantly lower than both Hybrid ($M=17.36$), $t(26) = 4.86$, $p<.001$, and Situation-guidance symbologies ($M=17.32$), $t(26)=6.67$, $p=.001$. The difference between the Situation-guidance and Hybrid symbologies was not significant. That pilots taxied faster with Situation-guidance and Hybrid symbologies than the Command-guidance symbology suggests that they may have had more confidence and greater perceived situation awareness with the Situation-guidance and Hybrid symbologies.

Regarding taxi accuracy, a significant effect of HUD type was observed, $F(2,48)=13.61$, $p<.001$. RMSE was smallest with the Hybrid symbology ($M=4.20$), and was significantly less than with both Command-guidance ($M=5.66$), $t(26)=4.90$, $p<.001$, and Situation-guidance symbologies ($M=4.86$), $t(26)=3.27$, $p=.01$. Contrary to expectations, RMSE was significantly less with Situation-guidance symbology compared to Command-guidance, $t(26)=3.27$, $p<.05$. This is possibly due to the pilots' tendency to overcorrect for small tracking errors with the Command-guidance symbology, thus increasing overall error.

Rated Situation Awareness

Situation awareness could be affected by the amount of time spent attending to HUD symbology, since the pilot's primary focus during taxi should be outside the aircraft. After each HUD block, subjects were asked to rate how often, from 1 (never) to 7 (always), they found themselves looking at the HUD when they should have been paying attention to the external environment. Only HUD condition was significant, $F(2,48)=5.41$, $p<.01$. The amount of time that pilots reported attending to the HUD was highest with the Command-guidance symbology ($M=3.63$), and was significantly higher than both Situation-guidance ($M=2.70$), $t(26)=2.56$, $p<.05$, and Hybrid symbologies ($M=2.63$), $t(26)=2.63$, $p=.01$. Differences between the Situation-guidance and Hybrid symbologies were not significant.

Subjects also completed a 3-dimension Situation Awareness Rating Technique (SART, Taylor, 1990). Ratings, from 0 (low) to 100 (high), included demand on attentional resources, supply of attentional resources, and understanding of the situation. An overall situation-awareness score was computed using the formula: SART = Understanding - (Demand - Supply). Only HUD condition was significant, $F(2,48)=17.58$, $p<.001$. The SART score was lowest with the Command-guidance symbology ($M=41.89$), and was significantly lower than both Hybrid ($M=88.52$), $t(26)=5.12$, $p<.001$, and Situation-guidance symbologies ($M=86.44$), $t(26)=4.94$, $p=.001$. The difference between the Situation-guidance symbology and the Hybrid symbology was not significant.

Pilots rated their overall situation awareness after each trial on a scale from 1 (very low) to 5 (very high). Significant differences among HUD conditions were observed for overall situation awareness, $F(2,48)=19.28$, $p<.001$. Overall situation awareness was lowest with the Command-guidance symbology ($M=3.84$), and significantly lower than the Situation-guidance ($M=4.31$), $t(26)=4.39$, $p<.001$, and Hybrid HUD symbologies ($M=4.31$), $t(26)=4.94$, $p<.001$. There was no significant difference reported in overall situation awareness between the Situation-guidance symbology and the Hybrid symbology.

Rated Workload

Pilots also rated their overall workload after each trial on a scale from 1 (very low) to 5 (very high). Significant differences among HUD conditions were observed, $F(2,48)=38.31$, $p<.001$. Overall workload was highest with the Command-guidance symbology ($M=3.48$), and significantly higher than both the Situation-guidance ($M=2.69$), $t(26)=6.81$, $p<.001$, and Hybrid HUD symbologies ($M=2.69$), $t(26)=6.92$, $p<.001$. There was no significant difference found in overall workload between the Situation-guidance symbology and the Hybrid symbology.

DISCUSSION

This study investigated three types of symbology presentation formats for head-up displays during taxi operations: Command-guidance, Situation-guidance and a Hybrid (combining aspects of Command-guidance and Situation-guidance symbologies). It was hypothesized that pilots taxiing with the Hybrid symbology would show increased situation awareness, increased taxi speed, and lower workload, similar to that expected when using the Situation-guidance symbology. However, it was expected that centerline deviation would be less with the Hybrid and Command-guidance symbologies, than with the Situation-guidance symbology.

The results confirmed the hypothesis that pilots taxiing with the Situation-guidance and Hybrid symbologies would show increased situation awareness, increased taxi speeds and decreased workload. As hypothesized, the centerline deviation was smallest with the Hybrid symbology. Surprisingly, the centerline deviation was highest with Command-guidance symbology, and not in fact, with the Situation-guidance symbology. In a sense, the taxi performance measures support the situation awareness and workload measures. Average taxi speed was higher and RMSE was lower with the Situation-guidance and Hybrid symbologies compared to the Command-guidance symbology, which may indicate that pilots taxiing with the Situation-guidance and Hybrid symbologies had more resources available to perform their primary task of taxiing, compared to the Command-guidance symbology.

These results may be due to several aspects of the symbologies. Pilots taxiing using command-guidance may have experienced cognitive tunneling due to the nonconformal nature of the HUD (McCann, Foyle & Johnston, 1993). Attentional fixation, increased workload and increased RMSE could be due to the constant corrective action to maintain centerline position required by the control commands. In contrast, situation-guidance HUD symbology is conformal with the environment, provides optical flow cues, and leaves error judgement and subsequent control decisions to the pilot, perhaps allowing for increased division of attention and reduced workload (Foyle et al., 1996).

There were no observed differences between the Situation-guidance and Hybrid symbologies on situation-awareness or workload measures. It may be that pilots using the Hybrid symbology were able to rely more heavily on the embedded situation-guidance information to taxi and rely on the guidance cue only when needed for specific control inputs.

With Situation-guidance and Hybrid HUD symbologies, pilots experienced increased taxi speeds, less error from the centerline, improved situation awareness and decreased workload compared to the Command-guidance symbology during simulated surface operations. Since surface operations at major airports is a very demanding task, a display that increases workload and decreases situation awareness may interfere with the pilot's primary responsibility of maintaining awareness outside the aircraft. Results of this study suggest that a Situation-guidance or Hybrid symbology would provide the pilot with the best taxi performance, highest situation awareness and lowest workload.

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REFERENCES

Beringer, D. B. (1999). Flight command-guidance indicators or situation-guidance displays: My way or the highway? *Proceedings of the 10th International Symposium on Aviation Psychology*. Columbus, OH: Ohio State University.

Foyle, D. C., Ahumada, A. J., Larimer, J., & Sweet, B. T. (1992). Enhanced/synthetic vision systems: Human factors research and implications for future systems. *SAE Transactions: Journal of Aerospace, 101*, 1734-1741.

Foyle, D. C., Andre, A. D., McCann, R. S., Wenzel, E. M., Begault, D. R., & Battiste, V. (1996). Taxiway navigation and situation awareness (T-NASA) system: Problem, design philosophy, and description of an integrated display suite for low-visibility airport surface operations*.* *SAE Transactions: Journal of Aerospace*, *105*, 1411-1418.

Foyle, D. C., McCann, R. S., & Shelden, S. G. (1995). Attentional issues with superimposed symbology: Formats for scene-linked displays. In R. S. Jensen, & L. A. Rakovan (Eds.), *Proceedings of the 8th International Symposium on Aviation Psychology*, 98-103. Columbus, OH: Ohio State University.

Hooey, B. L., Foyle, D. C., & Andre, A. D. (2000). Integration of cockpit displays for surface operations: The final stage of a human-centered design approach. *SAE Transactions: Journal of Aerospace*, *109*, 1053-1065.

Kelley, D. R., & Adam, G. L. (1997). The human factors of runway incursions caused by "pilot error:" A survey of U.S. airline pilots. In R. S. Jensen & L. Rakovan (Eds.) *Proceedings of the 9th International Symposium on Aviation Psychology*, 911-917, Columbus, OH: Ohio State University.

McCann, R. S., Foyle, D. C., & Johnston, J. C. (1993). Attentional limitations with head-up displays. In R. S. Jensen(Ed.), *Proceedings of the 7th International Symposium on Aviation Psychology*, 70-75. Columbus OH: Ohio State University.

Taylor, R. M. (1990). Situational awareness rating technique (SART): The development of a tool for aircrew systems design. *Situational Awareness in Aerospace Operations*, AGARD-CP-478, 3-1 - 3-37.

Ververs, P. M., & Wickens, C. D. (1998). Conformal flight path symbology for head-up displays: Defining the distribution of visual attention in three-dimensional space. University of Illinois Institute of Aviation Technical Report (ARL-98-5/NASA-98-1). Savoy, IL: Aviation Research Lab.

Weintraub, D. J., & Ensing, M. (1992). *Human Factors issues in head-up display design: The book of HUD* (SOAR 92-2). Dayton, OH: CSERIAC.