

HUD Symbology for Surface Operations: Command Guidance vs. Situation Guidance Formats

David C. Foyle

NASA Ames Research Center

Becky L. Hooley

Monterey Technologies, Inc.

John R. Wilson

San Jose State University

Walter A. Johnson

Rockwell Collins Flight Dynamics

ABSTRACT

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 speed, centerline tracking accuracy, workload and situation awareness were assessed. Taxi speed, centerline accuracy, and situation awareness were 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. 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

Surface operations have been cited as the least technologically advanced and one of the most difficult phases of a flight [1]. 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. Under low visibility, in poor weather or at night, or when at an unfamiliar airport, pilots often reduce their taxi speed to avoid traffic conflicts and maintain adequate awareness of their location [1, 2]. Pilot taxi performance, and surface operations in

general, may be improved by using head-up displays (HUDs) to depict the cleared taxi route [3]. Recently, industry efforts in this direction have begun.

There are two general concepts for providing navigational guidance with HUD symbology: Command-guidance and situation-guidance symbology formats. Command-guidance symbology directly provides commanded control information typically displayed as a non-conformal error to be nulled. In contrast, situation-guidance symbology, provides navigational information as a conformal, natural representation without explicitly providing the specific control inputs or error deviation. Advantages and disadvantages to pilot performance and situation awareness of these symbology concepts are discussed below.

COMMAND-GUIDANCE SYMBOLOGY - 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" [4]. Examples of command-guidance symbologies are the HUD formats used in most current commercial aircraft that incorporate an aircraft reference symbol, flight director and command-guidance cue [5]. In simulation, 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 [4].

One potentially negative quality of command-guidance symbology is that it produces more control inputs than other displays [4]. This is due to command-guidance symbology constantly displaying guidance information as 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 between the HUD symbology and the out-the-window environment [6, 7], because it is often presented non-conformally 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 on the command-guidance symbology at the cost of attending to other elements of the airport surface environment [8].

SITUATION-GUIDANCE SYMBOLOGY - Situation-guidance symbology presents the cleared taxi route by augmenting the environment with conformal, scene-linked symbology [7]. Situation-guidance symbology is conformal in the sense that the symbology overlays and moves in unison with the environment [9]. It is scene-linked in that virtual objects are represented such that they appear to be placed in the actual environment with appropriate optical motion cues as one's aircraft moves through the environment [6]. Situation-guidance symbology does not provide the pilot with the specific control inputs necessary to track the route, but instead augments the visual scene to allow the pilot to use natural, 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 [4]. Furthermore, conformal, scene-linked situation-guidance symbology has been shown to reduce cognitive tunneling, compared to non-conformal, fixed-location symbology [see 10]. The benefits of situation-guidance symbology seem to indicate improved attention distribution compared to command-guidance symbology. This benefit, however, may come at a cost of increased tracking error [4].

The primary purpose of the present study was to evaluate pilots' taxi performance when 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. Since cognitive tunneling was a potential by-product of the HUD formats, and current in-flight HUD formats use command-guidance cues, three groups of pilots were tested, varying in HUD experience.

METHOD

PARTICIPANTS - A total of twenty-seven male pilots participated in the study, with nine in each of three pilot experience conditions. The three pilot groups were: Commercial airline captains with at least 500 hrs of HUD experience, of which 50 hrs were within the last year; Commercial airline captains with no HUD experience; and, General Aviation pilots with no HUD experience. All pilots maintained current ratings.

For the HUD-experienced commercial airline pilots, mean pilot age was 50 yrs. Mean flight hours logged as Captain was 3650 hrs (852-7000 hrs range), with mean HUD experience of 1968 hrs (750-5500 hrs range). For the commercial airline pilots without HUD experience, mean pilot age was 50 yrs. Mean flight hours logged as Captain was 7122 hrs (1100-13000 hrs range). For the General Aviation pilots (without HUD experience), mean pilot age was 40 yrs, with mean flight hours logged of 990 hrs (310-1900 hrs range).

EXPERIMENTAL DESIGN - The study was a factorial, mixed design. Pilot experience group was a between-participants factor with three levels: Commercial with HUD experience; Commercial without HUD experience; and, General Aviation without HUD experience. HUD symbology format (Command-guidance, Situation-guidance, and Hybrid) was a within-participants factor such that each pilot was tested on all three HUD symbology formats.

Initial simulator training/familiarization consisted of nine trials: Three trials each of the three HUD symbology formats, counterbalanced for order, and presented as a block. Data are not reported from these training/familiarization trials. These training trials were followed by 21 experimental trials: Seven trials in a row of one of the three HUD symbology formats. Order of presentation of the HUD symbology formats was balanced for order effects. Each taxi trial required approximately 6 min to complete, such that the entire experiment required a full day of testing. On average the taxi routes were 11,500 ft in length, and contained six 90-deg turns. The number of turns ranged from 3 to 10, and some routes contained a 45-deg turn. All routes were taxi only, with no landing or take-off. The routes either were departing from the terminal to a runway, from the runway to a terminal, or movement from one terminal to another.

Scenarios - Throughout the simulation, "scenario events" were included for simulation realism and evaluation (listed below). Visibility drop events occurred on two of the seven experimental trials for each HUD format. All other scenario events occurred once within each of the seven same-format HUD trials. Events were not simultaneous within a trial. Pilots experienced instances of all scenario events during the training/familiarization

trials, and were briefed on the appropriate procedures for responding to the events. During training/familiarization, pilots were exposed to aircraft traffic, but did not experience an aircraft traffic taxi incursion. For the visibility drop event, pilots were instructed to follow the HUD symbology and continue taxiing. For all other events, pilots were instructed to stop and contact ATC for instructions. Pilots were not given information as to which, if any, scenario events would occur on an upcoming trial.

Evaluation Scenario Events:

- Taxi hold lights after a 90-deg turn
- Taxi hold lights during an S-turn
- Aircraft traffic taxi incursion

Taxi hold lights were a line of red lights embedded in the pavement crossing the taxiway. The taxiway hold lights were placed after a 90-deg turn, or in a meandering S-turn, at locations unknown by the pilot.

For the aircraft traffic taxi incursion scenario event, the incurring aircraft traffic was a moving, medium-sized commercial aircraft that crossed the pilots' cleared taxi route at a 90-deg intersection without warning. An algorithm adjusted the incurring aircraft's speed such that it would cross directly in front of the pilot's aircraft, requiring the pilot to stop.

Simulation-realism Scenario Events:

- Visibility drop (for approximately 400 ft) to zero/zero visibility entering or exiting a taxi turn
- Required contact of ATC at "Contact ATC" sign site
- ATC temporary taxi rerouting

These events were included for simulation realism and no data analyses related to them are presented herein.

SIMULATION - A medium-fidelity part-task simulator at the NASA Ames Research Center was used. The airport environment was Dallas-Ft. Worth International Airport with visibility of 1000 ft runway visual range. The airport environment included terminal buildings, runways, taxiways, grass medians, taxiway signage, taxiway and runway markings, moving aircraft, and non-moving ground vehicles. Aircraft controls included a side-stick control with left/right rotation for nose-wheel control, non-differential throttle, and rudder pedals with toe brakes. The aircraft simulation control model was a B737.

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 0.91 m (29.57 deg).

A panel-mounted electronic moving map display (EMM) was used in place of a paper taxiway diagram (see Figure 1). The taxi route clearance was given verbally by the experimenter/ATC located outside the test room via microphone/headphone and read back by the pilot subject. The taxi route clearance was continuously available as text on the EMM. 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. No aircraft traffic was presented on the EMM (for more EMM information, see [11]). 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).

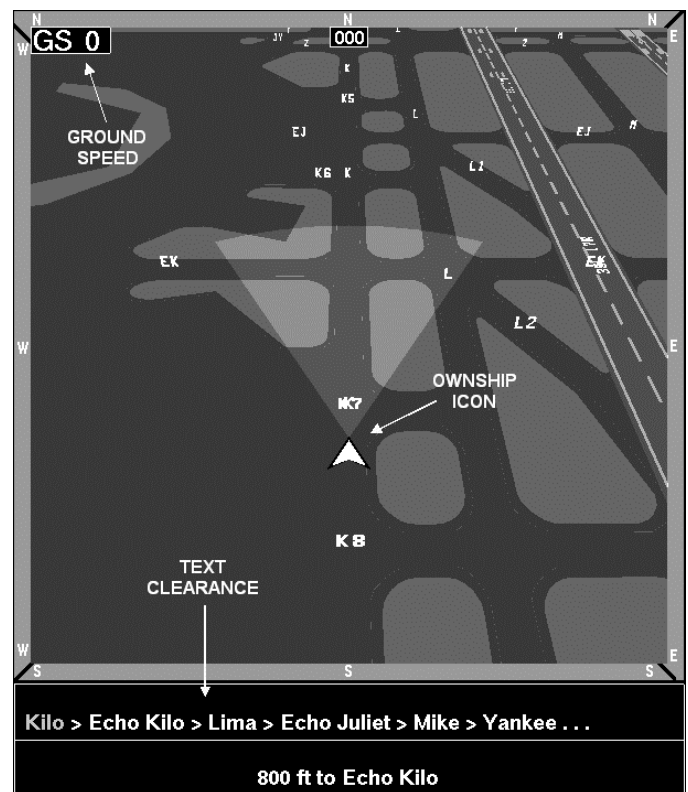


Figure 1. Electronic Moving Map showing taxiways and runways. Ownship position is shown as white chevron near the middle of the display (at the base of the gray forward-view triangular region). Below the graphical moving map is the taxi route clearance text display.

HUD SYMBOLOGY FORMATS - Three HUD symbology formats were used to represent the upcoming cleared taxi route: Command-guidance symbology; Situation-guidance symbology; and, Hybrid (with selected display components from the command-guidance and situation-guidance symbologies).

Command-guidance Symbology - The Command-guidance symbology (Figure 2) is composed of a

command-guidance cue, aircraft reference symbol, plan-view centerline, lateral reference markers, ground-speed indicator and current and upcoming taxiway labels. This symbology is non-conformal in nature. The command-guidance cue is similar to the command-guidance symbology commonly used for maintaining flight path in the air [5]. 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 and deviation rate. Taxiing the aircraft such that the aircraft reference symbol and the command-guidance cue circles are concentric will result in capturing or maintaining the cleared taxi route with minimum centerline error. This is essentially a compensatory, error-nulling tracking task with lead. The plan-view centerline is an overhead, downward-looking view of the upcoming 50 m of the cleared route. On either side of the plan-view centerline are lateral reference markers, which represent the main landing gear of the aircraft. The pilot must keep the plan-view centerline between the lateral reference markers (i.e., taxi centerline between the main gear) when following the route and tracking the centerline. The plan-view centerline provides preview of the upcoming turn.

Situation-guidance Symbology - The Situation-guidance symbology (Figure 3), uses the conformal HUD symbology format of the Taxiway Navigation and Situation Awareness (T-NASA) System [see 11]. Taxiway centerline and edges of the cleared route are augmented with scene-linked symbology such that the HUD symbology representations appear to be actual objects in the world, and move and transform optically appropriate with distance and ownship movement through the environment. These augmentations include 3-dimensional taxiway-edge cones, augmented taxiway centerline, as well as turn flags and signs, which extend beyond the cones in turns. Centerline tracking guidance is not given explicitly, but is provided implicitly to the pilot via the scene-linked symbology augmentations (virtual centerline, virtual taxiway edge cones).

Hybrid Symbology - The Hybrid symbology (Figure 4) combines aspects of the Command-guidance and Situation-guidance symbologies by providing explicit control commands as well as implicit conformal symbology that highlights the cleared route. In designing the Hybrid symbology, the goal was to create symbology containing a conformal route representation with centerline tracking guidance. In the Hybrid symbology, the command-guidance cue and aircraft reference symbol are present, but the plan-view centerline and lateral reference markers of the Command-guidance symbology were eliminated and replaced by conformal symbology. The conformal route information is provided by the scene-linked taxiway edges and centerline of the Situation-guidance symbology, which gives preview information of upcoming turns. The turn flags and signs of the Situation-guidance format were eliminated

because their main function is to reinforce centerline tracking required by judgmental oversteer – a function now enabled by the command-guidance tracking cue.

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 subjective situation awareness and workload.

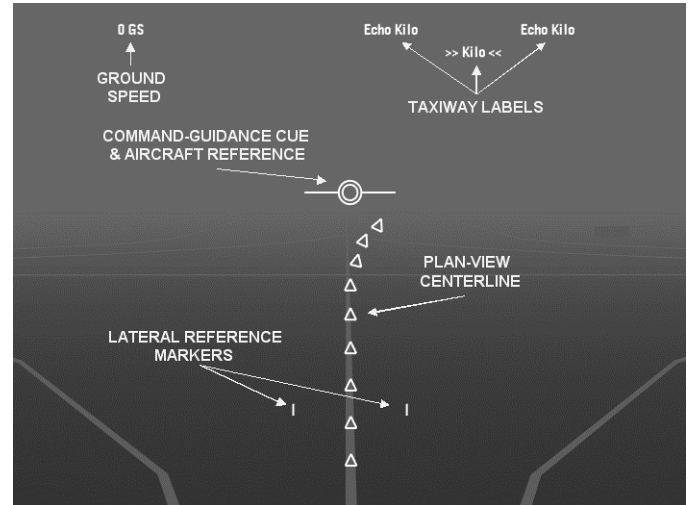


Figure 2. Command-guidance symbology overlaid on forward scene. Symbology shown is the command-guidance cue (inner circle) and aircraft reference symbol (outer circle) depicting on-route tracking (i.e., concentric circles); the plan-view centerline depicting an upcoming right turn (100 ft away), and lateral reference markers; ground speed indicator (upper left, showing 0 kts); and, text showing current and upcoming taxiways (upper right).

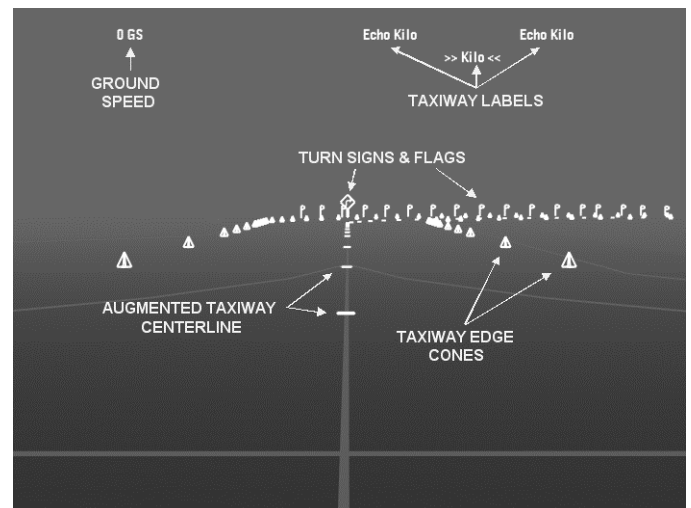


Figure 3. Situation-guidance symbology. Symbology shown is 3-dimensional taxiway edge cones depicting an upcoming right turn (700 ft away); augmented taxiway centerline; turn sign and flags; ground speed indicator (upper left, showing 0 kts); and, text showing current and upcoming taxiways (upper right).

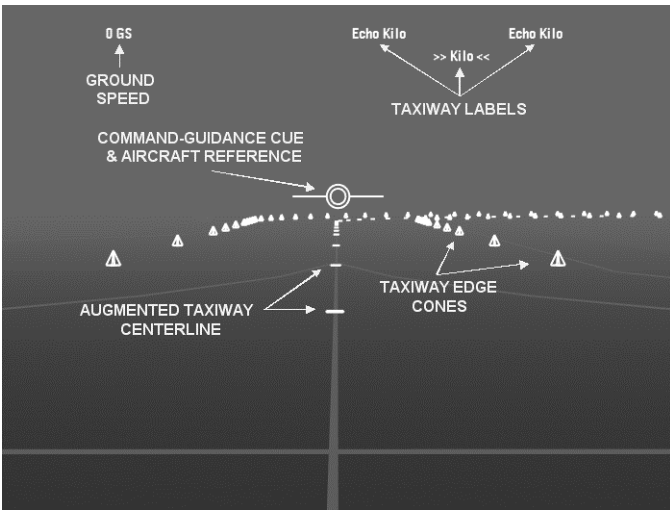


Figure 4. Hybrid symbology. Symbology shown is the command-guidance cue and aircraft reference symbols (from the Command-guidance symbology); and taxiway edge cones and augmented taxiway centerline (from the Situation-guidance symbology) depicting an upcoming right turn (700 ft away); ground speed indicator (upper left, showing 0 kts); and, text showing current and upcoming taxiway (upper right).

HYPOTHESIS PREDICTIONS - Several dependent measures were collected to test the hypothesis that the HUD formats with conformal route information (Situation-guidance and Hybrid formats) would result in better situation awareness compared to the HUD format with non-conformal route information (Command-guidance). Additionally, it was expected that, relative to the Command-guidance format, the Situation-guidance and Hybrid formats would show increased taxi speed, and lower rated workload. In contrast, it was expected that the HUD formats with non-conformal representation of centerline deviation (that is, the Command-guidance and Hybrid formats, both with the command-guidance tracking cue) would show improved centerline tracking relative to the HUD format with only a conformal representation (the Situation-guidance format). Specifically, centerline error was expected to be less with the Hybrid and Command-guidance formats, than with the Situation-guidance format.

TAXI PERFORMANCE RESULTS AND DISCUSSION

Taxi route performance with the three HUD symbology formats was assessed with two dependent variables:

- Taxi Speed - Average moving (non-zero) taxi speed (kts)
- Taxi Accuracy - Root Mean Square Error (RMSE, ft) from the taxi centerline

All variables, except as noted, were analyzed using a 3 x 3 mixed-design analysis of variance (ANOVA). Factors were: Pilot Experience group x HUD format, with Pilot

Experience group (9 pilots each) as the only between factor. For each HUD condition, average data from four of the seven experimental trials were included in the analyses in this section. The three trials with runway hold lights, ATC rerouting, and incurring traffic were excluded from these analyses to avoid tainting performance data by these off-nominal scenario events.

For both taxi speed and taxi accuracy, the data were analyzed and presented in two ways: Straight taxi route segments and matched turn segments. Analyses for the straight taxi route segments included data only from the straight taxi route segments, and excluded any turns, between the beginning and end of the route. The matched turn segments were common route segments containing three 90-deg turns, embedded in a unique, full route. Four of these matched turn segments were developed, and each was presented once with each of the three HUD formats. The average length of these four matched turn segments was 2,041 ft, ranging from 2,007 to 2,066 ft in length. Thus, when analyzing the matched turn segments data, any differences among HUD formats observed cannot be due to route differences, since performance is derived from taxiing on four *identical* turn segments. The matched turn segments were developed to allow for the use of unique taxi routes on each of the 21 experimental trials to limit learning effects. At the same time, these matched turn segments controlled for route geometry effects. This allowed for a more sensitive analysis of turn data.

TAXI SPEED - In the simulation, pilots were instructed to taxi as they would during actual real-world operations, and at the speed that they felt comfortable for each HUD format. For the taxi speed analysis, the average moving taxi speed (kts) was calculated, excluding any stopped (0 kt) data. Analyses were conducted separately for straight taxi segments, and for the matched turn segments. There were no significant effects involving Pilot Experience group for either analysis.

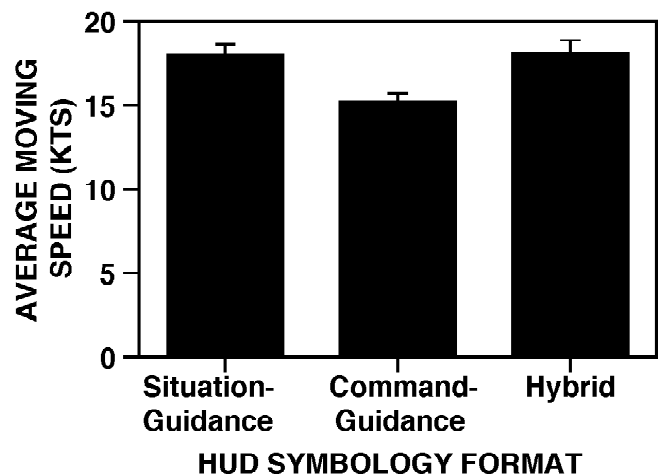


Figure 5. Average moving taxi speed (kts) for straight taxi segments. Error bars represent +1 standard error.

Taxi Speed (Straight Segments) - For the straight segments, a significant effect of HUD symbology type on taxi speed was observed ($F(2,48)=18.12, p<.001$). As can be seen in Figure 5, average moving taxi speed for the straight segments was slowest with the Command-guidance symbology, when compared to the Situation-guidance format ($t(26)=6.57, p<.001$) and the Hybrid format ($t(26)=4.94, p<.001$). The difference between the Situation-guidance and Hybrid formats was not significant.

Taxi Speed (Matched Turn Segments) - An identical pattern of speed is seen for turns (see Figure 6), when matched turn segments are analyzed (HUD format main effect with $F(2,48)=10.75, p<.001$). Similarly, the Command-guidance HUD format yielded slower turn speed than either the Situation-guidance ($t(26)=5.59, p<.001$) or Hybrid formats ($t(26)=3.66, p<.001$). Again, there was no significant difference between the Situation-guidance and Hybrid symbology formats.

The finding that pilots taxied faster with Situation-guidance and Hybrid symbologies than the Command-guidance symbology may be indicative of increased confidence and greater perceived situation awareness with the Situation-guidance and Hybrid symbologies.

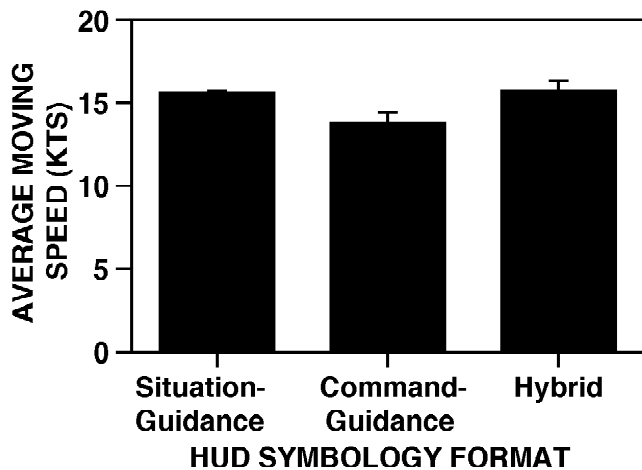


Figure 6. Average moving taxi speed (kts) for matched turn segments. Error bars represent +1 standard error.

TAXI ACCURACY - As a measure of taxi accuracy, RMSE (ft) from the taxiway centerline was calculated. Separate analyses were conducted for straight taxi segments, and for the matched turn segments. No significant effects involving Pilot Experience group were found for either analysis.

Taxi Accuracy (Straight Segments) - For the straight taxi segments, the type of HUD symbology format produced a significant effect on taxi centerline tracking accuracy as measured by RMSE ($F(2,48)=6.54, p=.003$). As can be seen in Figure 7, centerline tracking error was equal for the Command-guidance and Situation-guidance formats ($t(26)=0.86, p=.395$). The Hybrid format

produced less error when compared to the Situation-guidance format ($t(26)=3.44, p=.002$) and the Command-guidance format ($t(26)=3.28, p=.003$).

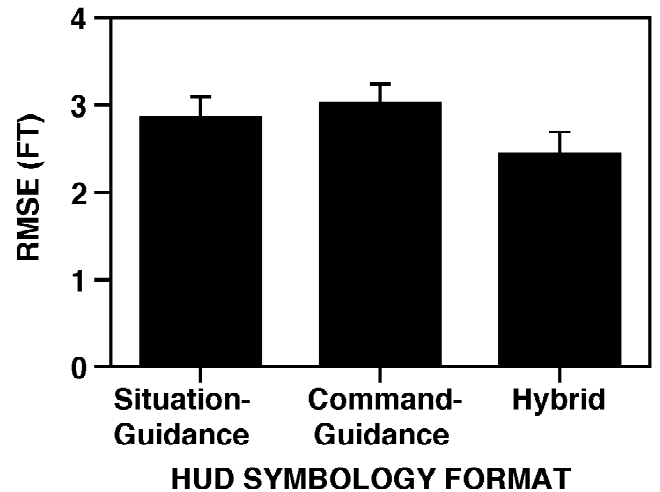


Figure 7. Centerline accuracy (RMSE, ft) for straight taxi segments. Error bars represent +1 standard error.

Taxi Accuracy (Matched Turn Segments) - A slightly different pattern, with larger observed differences, was shown in the matched turn segments analysis (shown in Figure 8). An overall main effect of HUD type on matched turn segment taxi accuracy was found ($F(2,48)=6.87, p=.002$). The Command-guidance HUD symbology produced the worst turn tracking accuracy (compared to the Situation-guidance format, $t(26)=2.78, p=.01$, and the Hybrid format, $t(26)=2.67, p=.013$). There was no statistically significant difference between the Situation-guidance and Hybrid formats.

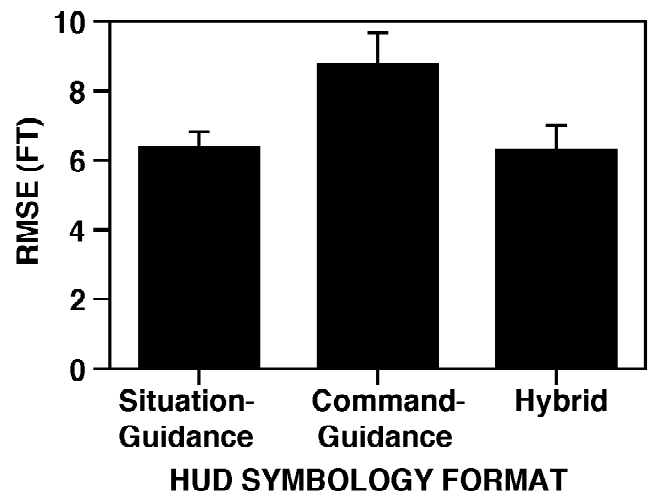


Figure 8. Centerline accuracy (RMSE, ft) for matched turn segments. Error bars represent +1 standard error.

Contrary to expectations, RMSE for the Command-guidance symbology was worse than the Hybrid symbology for both straights and turns. No difference was expected since both have the command guidance

tracking cue. It was expected that the Command-guidance format would produce better centerline tracking than the Situation-guidance format. This was not what was found: The Command-guidance format produced equal centerline tracking performance to the Situation-guidance format for straight taxi segments, but worse for turns. In turns, there may be a tendency for pilots to overcorrect for small tracking errors with the Command-guidance symbology, thus increasing overall error. It should also be noted that the differences, although reliable (significant), differ by no more than 2.5 ft, which may or may not be operationally relevant.

WORKLOAD RESULTS AND DISCUSSION

An objective measure of the psychomotor aspect of workload, and one subjective measure of overall workload were collected and analyzed for the three HUD formats. The objective measure was the standard deviation of steering angle control input, while the subjective measure was overall workload rating. In addition, but not reported here, pilots separately rated visual, psychomotor, mental, and effort aspects of workload. Pilots were instructed to incorporate these workload dimensions into their overall workload ratings, which is reported here.

STEERING CONTROL INPUT - As a measure of steering control input, the standard deviation of the angular rotation of the joystick tiller was calculated. (In the simulation, this was then mapped to a function driving the aircraft nose wheel.) A measure of steering control input is included because the three HUD symbology formats differ fundamentally in the manner and degree to which the route information is presented to the pilot: As a scene augmentation (Situation-guidance) which the pilot must interpret, or as an error to null (Command-guidance), or both (Hybrid). These differences would be expected to be seen in the characterization of the steering inputs. The analysis of steering angle standard deviation (SD) is used here because it can be used as a parametric measure of the smoothness of the required steering inputs. Additionally, it can be considered an objective measure of the psychomotor aspect of workload. Larger values of steering angle SD indicate more variable steering angle inputs. For the steering input analysis, the standard deviation (in deg) of the input steering angle was calculated. Analyses were conducted separately for straight segments, and the matched turn segments. Again, no effects of Pilot Experience group were statistically significant for either measure (straight taxi segments or matched turn segments).

Steering Input Standard Deviation (Straight Segments) - For the analysis across the straight taxi segments, no effect of HUD type on steering angle SD was found ($F(2,48)=0.12, p=.890$, see Figure 9). Thus, for the straight taxi segments, the three HUD formats produced

equal levels of control inputs (as measured by steering angle SD).

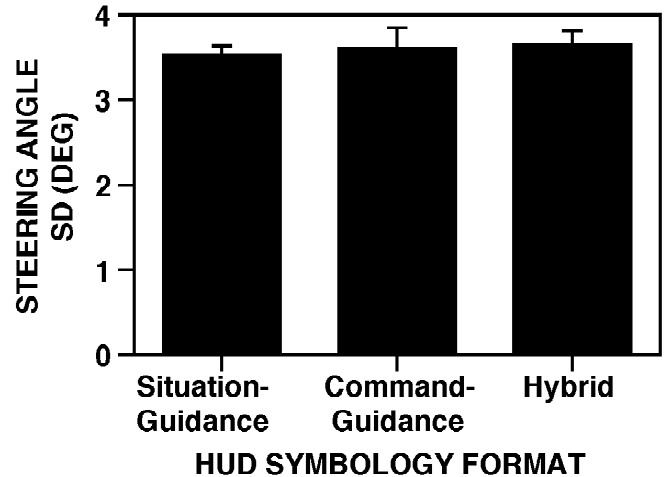


Figure 9. Steering angle standard deviation (deg) for straight taxi segments. Error bars represent +1 standard error.

Steering Input Standard Deviation (Matched Turn Segments) - For the matched turn segments, a different pattern for steering angle SD was found (shown in Figure 10) than for the straight segments. HUD format type produced a main effect on steering angle SD for matched turn segments ($F(2,48)=33.41, p<.001$). The Command-guidance symbology produced the largest steering angle SD (compared to the Situation-guidance format, $t(26)=6.79, p<.001$, and the Hybrid format, $t(26)=6.52, p<.001$). There was no statistical difference between the Situation-guidance and Hybrid HUD formats.

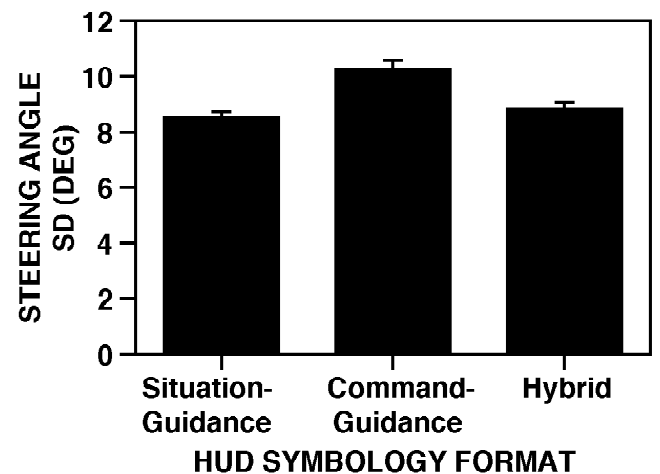


Figure 10. Steering angle standard deviation (deg) for matched turn segments. Error bars represent +1 standard error.

The steering angle SD analyses for straight and matched turn segments showed that HUD formats produced equal SD control inputs for straight taxi

segments, but with larger SD for the Command-guidance format in turns. This indicates that psychomotor workload for the three HUD formats is equal in the straight segments, but higher for the Command-guidance format in turns.

RATED WORKLOAD - Pilots rated their overall workload after each trial on a scale from 1 (very low) to 5 (very high). A 3 x 3 (Pilot Experience group x HUD format) ANOVA was conducted on data averaged over the seven experimental trials. Significant differences among HUD conditions were observed, $F(2,48)=38.31$, $p<.001$ (see Figure 11). Overall rated workload was highest with the Command-guidance symbology, and significantly higher than both the Situation-guidance ($t(26)=6.81$, $p<.001$) and Hybrid HUD symbologies ($t(26)=6.92$, $p<.001$). There was no significant difference found in overall rated workload between the Situation-guidance and the Hybrid symbology formats.

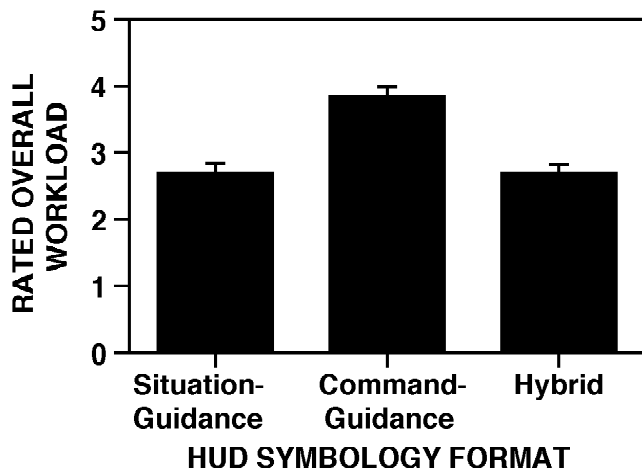


Figure 11. Rated overall workload (1=very low, 5=very high). Error bars represent +1 standard error.

There appears to be some consistency between the subjective overall workload ratings and objective psychomotor measures of workload observed in this study. In turns, the steering input SD measure produced higher values for the Command-guidance formats, and equal and lower values for Situation-guidance and Hybrid formats. The same pattern was observed for rated overall workload.

The finding that, in turns, the Command-guidance HUD format produced consistently higher steering angle SD is indicative of more numerous and/or larger steering inputs for that condition. Since this measure is an objective measure of psychomotor workload, the conclusion is that the Command-guidance format yielded higher psychomotor workload. Since the Hybrid and Situation-guidance formats produced equal and lower standard deviation steering inputs, this would suggest that adding the conformal route information when the command-guidance cue is available (as in the Hybrid format) eliminates this higher psychomotor workload.

Possibly, the added conformal route information in the Hybrid format may eliminate the need for corrections to minor centerline deviations, because they are no longer as salient in the symbology.

SITUATION AWARENESS RESULTS AND DISCUSSION

Two objective measures and one subjective measure of situation awareness were collected and analyzed for the three HUD formats. The objective measures were the response time to initiate stopping for unexpected hold lights and an incurring aircraft. The subjective measure was overall situation awareness rating.

AIRPORT EVENT DETECTION - The evaluation scenario events listed and described previously (taxi hold lights and an incurring taxiing aircraft) were included to allow for the assessment of airport situation awareness using objective dependent measures for the three HUD formats. By producing events on the airport surface that required detection and response, response time to these events can be used as a measure of situation awareness, and may suggest cognitive tunneling. Longer response times would indicate lower situation awareness of the airport environment, and possibly the presence of cognitive tunneling on the HUD symbology, since the pilot did not notice the environmental event as quickly. For these events, the required response was to stop the aircraft immediately. By design, the hold lights and incurring aircraft events were unexpected and only detectable when close, thereby requiring relatively quick, large stopping responses. For these events, the throttle control data and braking responses were analyzed. These responses are typically done in quick succession to stop the aircraft. The first production of either a throttle decrease or a brake response defined detection and determined the detection response time.

Two types of taxi hold lights were presented unexpectedly to the pilot at unpredictable aircraft locations: Taxi hold lights appearing after a 90-deg turn, and within an S-turn. Only the 90-deg turn data are presented here (the data from the S-turn hold lights showed a similar pattern). For each pilot, one 90-deg hold light detection event occurred in each of the three HUD format conditions. As another measure of environment situation awareness, the detection of an incurring aircraft taxiing across the pilot's cleared path was evaluated. As mentioned previously, the incurring aircraft traffic was a moving, medium-sized commercial aircraft that crossed the pilot's cleared taxi route at a 90-deg intersection, and appeared without warning. No aircraft traffic, including the incurring aircraft, appeared on the EMM. An algorithm adjusted the incurring aircraft's speed such that it would cross directly in front of the pilot's aircraft, requiring the pilot to stop to avoid the aircraft.

These two detection events were analyzed using a 3 x 3 x 2 mixed-design analysis of variance (ANOVA). Factors were: Pilot Experience group (between factor) x HUD format (within factor) x Detection Event (within factor); with 9 pilots in each group. Each pilot produced one observation in each HUD condition, for a total of 27 data points. For three subjects in the Command-guidance condition, the aircraft incursion detection event was not completed as planned (because of the pilot's taxi performance immediately before the event). These three subjects were not included in the ANOVA.

Hold Lights Response Time (90-deg Turn) - The elapsed time between the onset of the taxi hold light and the initial detection response was calculated. Mean response times are shown in Figure 12.

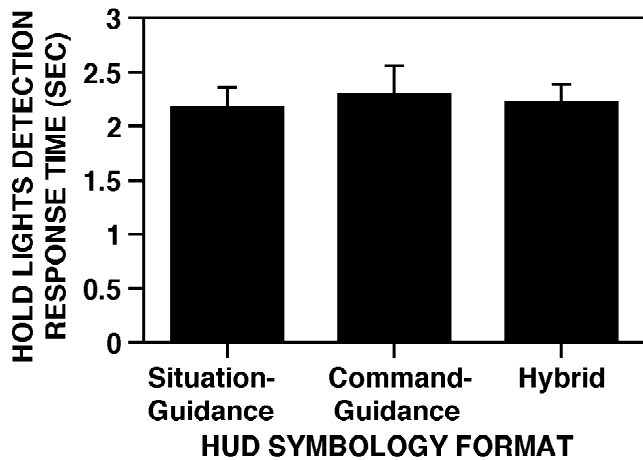


Figure 12. Response detection time to unexpected hold lights (90-deg). Error bars represent +1 standard error.

Aircraft Incursion Response Time - The response time to detect the incurring aircraft, measured from the time that the aircraft first appeared was calculated. Mean response times for the Situation-guidance, Command-guidance, and Hybrid formats are shown in Figure 13.

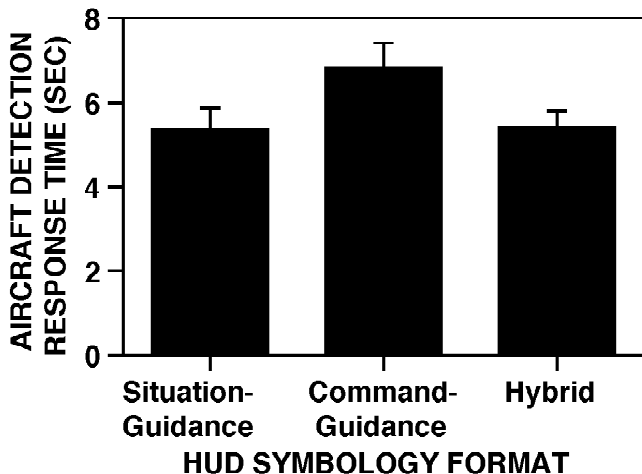


Figure 13. Response detection time to unexpected aircraft incursion. Error bars represent +1 standard error.

A main effect of Detection Event was found ($F(1,21)=100.87, p<.001$) and indicates that average detection time, not surprisingly, differed for the two events. No interaction effects were significant. More importantly, since there were no interactions, the pattern was the same for both the detection of the aircraft incursion and the hold lights. Also, a main effect of HUD format ($F(2,42)=3.86, p=.029$) was found. The significant effect of HUD format is a result of slower event detection times with the Command-guidance format (as seen by planned comparisons with the Situation-guidance format, $t(23)=2.58, p=.017$; and the Hybrid format, $t(23)=1.94, p=.065$; and, no significant difference between the Situation-guidance and Hybrid formats). It should be noted that the Command-guidance format produced the slowest detection for both detection events, even though the two events differ in object type and placement (during straight segments for the incursion, exiting a turn for the hold lights). No significant effects involving Pilot Experience group were obtained.

In addition to the objective performance measures of situation awareness reported above, subjective measures (ratings) of situation awareness and workload were collected after each taxi trial.

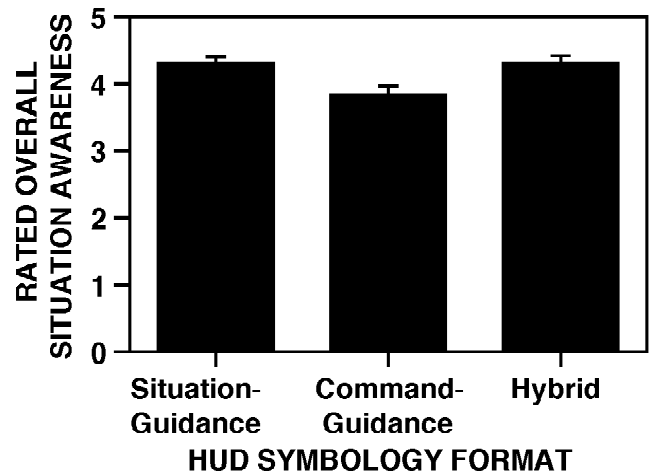


Figure 14. Rated overall situation awareness (1=very low, 5=very high). Error bars represent +1 standard error.

RATED SITUATION AWARENESS - Pilots rated their overall situation awareness after each trial on a scale from 1 (very low) to 5 (very high). A 3 x 3 (Pilot Experience group x HUD format) ANOVA was conducted on data averaged over the seven experimental trials. Significant differences among HUD conditions were observed for overall situation awareness, $F(2,48)=19.28, p<.001$. As can be seen in Figure 14, overall situation awareness was rated lowest with the Command-guidance symbology, and significantly lower than the Situation-guidance ($t(26)=4.39, p<.001$) and Hybrid HUD symbologies ($t(26)=4.94, p<.001$). There was no significant difference

reported in overall situation awareness between the Situation-guidance symbology and the Hybrid symbology. Other measures of rated situation awareness showed similar patterns (see [12] for more information).

The Command-guidance format produced reliably lower ratings of situation awareness, while the Situation-guidance and Hybrid formats produced equal and higher situation awareness ratings. This pattern is identical to that found with the two airport event detection objective measures: The Command-guidance format produced longer detection response times to the hold lights and incurring aircraft, when compared to the Situation-guidance and Hybrid formats. The objective and subjective situation awareness measures taken together suggest that the Command-guidance format lowers situation awareness, possibly because of cognitive tunneling on the symbology. The finding that the Situation-guidance and Hybrid formats support better situation awareness may be because of the conformal route representation in each. Since the conformal route on the HUD and the out-the-window view share a common representation of the forward taxiway, this may act to mitigate cognitive tunneling by allowing for the division of attention between the HUD symbology and the out-the-window environment.

SUMMARY OF RESULTS

TAXI SPEED AND ACCURACY - The results related to taxi speed and centerline accuracy are different for straight and turn segments. In turns, the Command-guidance HUD symbology format resulted in less accurate centerline tracking ability, and slower taxi speeds. In straight segments, the Hybrid format produced better centerline tracking, and the Situation-guidance and Hybrid formats produced faster taxiing.

WORKLOAD - As discussed above, in turns, both the subjective workload ratings and the steering input measure of workload yielded the same pattern of results. The steering input SD measure produced higher values for the Command-guidance formats, and equal and lower values for Situation-guidance and Hybrid formats. This is the same pattern observed for rated overall workload. Both results are consistent with higher workload in the Command-guidance format condition during turns.

SITUATION AWARENESS - Of the three HUD formats, the Command-guidance symbology produced the slowest response times to detect unexpected runway hold lights and an incurring aircraft. Consistent with these objective detection events, the Command-guidance HUD format produced lower situation awareness ratings than the Situation-guidance and Hybrid formats.

GENERAL DISCUSSION

Three types of HUD symbology formats for taxi operations were developed and evaluated: Command-guidance, Situation-guidance and a Hybrid format (combining aspects of Command-guidance and Situation-guidance formats). Because they contained conformal route information, it was hypothesized that pilots taxiing with the Situation-guidance and Hybrid symbology formats would show increased situation awareness, increased taxi speed, and lower workload, when compared to the Command-guidance format. However, because they contained command-guidance tracking cues, it was expected that taxi centerline deviation would be less with the Hybrid and Command-guidance symbologies, than with the Situation-guidance symbology, which contained no such tracking cue.

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. For taxi centerline accuracy, however, a different pattern than predicted was obtained. It was expected that both the Command-guidance and Hybrid symbology would produce better centerline tracking performance than the Situation-guidance format. The Hybrid format did produce the most accurate centerline tracking in straight segments, and equal to that of the Situation-guidance format in turns. The Command-guidance format, contrary to expectations, produced the worst centerline tracking performance (although equal to that of the Situation-guidance format in straight segments). The Hybrid symbology, combining conformal route information with a command-guidance cue, produced the best overall centerline tracking accuracy.

The taxi performance measures are mostly consistent with the workload and situation awareness measures. Both taxi speed and accuracy were generally better with the Situation-guidance and Hybrid symbologies than with the Command-guidance symbology. This was seen in both subjective situation awareness ratings and objective detection of unexpected out-the-window events. When non-conformal representations were used (i.e., the Command-guidance format), objective and subjective situation awareness was decreased. Conversely, the inclusion of conformal representations improved situation awareness.

Pilots taxiing using only the command-guidance tracking cue may have experienced cognitive tunneling due to the non-conformal nature of the HUD symbology [8]. The constant corrective action to maintain centerline position required by the control commands of the command-guidance tracking cue, produced increased workload and increased centerline deviation. This, coupled with the non-conformal nature of the command-guidance tracking cue, may have induced cognitive tunneling. In

contrast, the conformal route information provides optical flow cues, and leaves error judgment and subsequent control decisions to the pilot, perhaps allowing for increased division of attention and reduced workload [3]. This 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, presumably because of the conformal route representation contained in these formats.

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 conformal, situation-guidance information to taxi and rely on the guidance cue only when needed for specific control inputs. A follow-up experiment using eye-tracking measurement is planned which will clarify this issue.

CONCLUSION

Situation-guidance and Hybrid HUD symbologies produced increased taxi speeds, better centerline tracking, improved rated situation awareness and decreased workload compared to the Command-guidance symbology during simulated surface operations. Surface operations at major airports is a very demanding task, and navigational displays should not increase workload or decrease situational awareness, since this may interfere with the pilot's primary responsibility of maintaining awareness outside the aircraft. Results of this study suggest that situation guidance symbology (i.e., conformal route representation) possibly with the additional inclusion of a command tracking cue provides the pilot with the best taxi performance, highest situation awareness and lowest workload.

ACKNOWLEDGMENTS

Funding for this project was supplied by NASA's Airspace Operations (AS) base research and technology program, Human-Automation Integration Research project, RTOP 711-41-12. The authors gratefully acknowledge the technical expertise of George Lawton, Glenn Meyer, and Dominic Wong of Raytheon ITSS for their assistance with the simulation and symbology algorithms, and Jennifer Williams of San Jose State University for help with data collection and analysis.

REFERENCES

1. 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.
2. McCann, R. S., Hooey, B. L., Parke, B., Foyle, D. C., Andre, A. D., & Kanki, B. (1998). An evaluation of the Taxiway Navigation and Situation Awareness (T-NASA) system in high-fidelity simulation. *SAE Transactions: Journal of Aerospace*, 107, 1612-1625
3. 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.
4. 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.
5. Weintraub, D. J., & Ensing, M. (1992). *Human Factors issues in head-up display design: The book of HUD* (SOAR 92-2). Dayton, OH: CSERIAC.
6. 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.
7. 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.
8. 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.
9. 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.
10. Fadden, S., Ververs, P. M., & Wickens, C. D. (1998). Costs and benefits of head-up display use: A meta-analytic approach. *Proceedings of the 42nd Annual Meeting of the Human Factors and Ergonomic Society*, 16-20. Santa Monica, CA: HFES.
11. 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.
12. Wilson, J.R., Hooey, B.L., Foyle, D.C. & Williams, J.L. (2002). Comparing pilots' taxi performance, situation awareness and workload using command-guidance, situation-guidance and hybrid head-up

display symbologies. Paper to appear in the *Proceedings of the 46th Annual Meeting of the Human Factors and Ergonomic Society*. Santa Monica, CA: HFES.

CONTACT

The first author can be contacted at MS 262-4, NASA Ames Research Center, Moffett Field, CA, 94035-1000, USA. Related papers and other information are available from the NASA ARC Human-Centered Systems Laboratory (HCSL) URL at:

<http://human-factors.arc.nasa.gov/ih/hcs/>