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HEAD-UP DISPLAY SYMBOLOGY FOR SURFACE OPERATIONS: COMPARISONS AMONG SCENE-LINKED SYMBOLOGY SETS FOR OPTIMUM TURN NAVIGATION

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ABSTRACT

Recent work has shown that T-NASA's "scene-linked" head-up display (HUD) symbology improves the pilot's ability to taxi in low-visibility conditions. However, due to the HUD's limited field-of-view (FOV), the current symbology frequently disappears from view during turns. We discuss the results of a study comparing 4 different types of scene-linked turn symbologies. Using a visually-based part-task simulator, 11 airline pilots taxied a simulated B-737 through 42 taxi routes at Chicago's O'Hare International Airport. The taxi routes contained several turns with varying degrees of angularity. Visibility for all routes was conducted in daytime, 300 ft RVR conditions. The results of the study indicate that scene-linked markers (poles with flags) that are placed beyond the turn provide relative distance cues that can be used for improved turn performance, effectively mitigating FOV limitations for HUD scene-linked symbology.

GENERAL

The present study focuses on the scene-linked HUD symbology designed for use with the Taxiway Navigation and Situation Awareness (T-NASA) System. Scene-linked HUD symbology is referenced to the world, and moves and transforms optically as if it were an actual object in the world (see Foyle, Ahumada, Larimer & Sweet, 1992; Foyle, McCann & Shelden, 1995). Due to the limited field-of-view (FOV) of the HUD, it has been found that scene-linked turn symbology may disappear from the HUD. The main goal of the present study is to evaluate different scene-linked HUD turn symbologies that remain in the HUD FOV during turns, leading to improved turn navigation performance and pilot acceptability. The determination of scene-linked symbology that complements the HUD FOV limitations effectively extends the conditions under which the symbology can be used, and improves our understanding of the scene-linked symbology concept.

T-NASA SYSTEM

Scene-linked HUD symbology is part of a system known as the Taxiway Navigation and Situation Awareness (T-NASA) System (For a description, see Foyle, Andre, McCann, Wenzel, Begault & Battiste, 1996). This system has been developed to improve efficiency and to enhance safety of airport surface operations. T-NASA is a compilation of several different technologies that work together to form one complete system. T-NASA consists of an electronic moving map (EMM), the scene-linked symbology on a HUD, and a 3-D audio warning alert system. The EMM provides global and local situational awareness to the pilots as well as traffic, route, and taxi speed information. The HUD display incorporates scene-linked symbology that creates a conformal scene-linked enhancement of the environment during surface operations. The 3-D audio system was not implemented in the present experiment.

In order to enhance the forward FOV during taxi operations at night and/or in low-visibility conditions, scene-linked HUD symbology has been developed. The T-NASA scene-linked HUD symbology consists of taxiway edge cones, taxiway centerline markers, and directional turn signs. These are projected onto the HUD combiner creating a virtual path of the taxi route that enhances the out-the-window (OTW) scene. The scene-linked symbology concept provides for simultaneous attentional allocation to both the near (inside the cockpit) and far (OTW) domains (Wickens, 1997). Several studies have shown that conformal (e.g., scene-linked) symbology is effective in fusing symbology to the far domain (Wickens & Long, 1995). This enhances the OTW scene by contributing to the division of attention across the OTW scene and the HUD (Foyle, Sanford & McCann, 1991; Foyle, McCann & Shelden, 1995). Additionally, conformal scene-linked symbology provides environmental (i.e., natural object) cues that aid the perception of judging distance and location of objects in space (Wickens, 1997). A recent full-mission simulation showed positive results for such symbology for surface operations (McCann, Hooey, Parke, Foyle, Andre & Kanki, 1998). That study compared performance among a Baseline paper chart, the T-NASA EMM display alone, and the T-NASA EMM+HUD using the scene-linked symbology. Taxi speed for the EMM+HUD condition increased by 21% compared to the paper chart, while taxi errors were eliminated (see Figure 1, top and bottom panels, respectively).

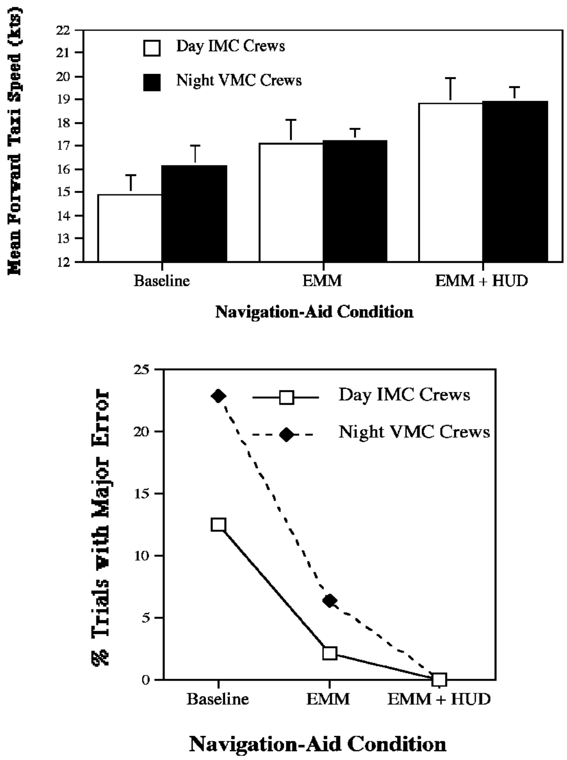

Figure 1. Taxi speed (top) and off-route navigational error (bottom) for the Baseline paper chart, EMM, and EMM+HUD conditions (from McCann, Hooey, Parke, Foyle, Andre & Kanki, 1998).

Additionally, the EMM+HUD condition yielded faster taxi speeds (approximately 2 kts), and eliminated off-route navigational errors compared to the EMM condition. The results of this study show that the addition of scene-linked HUD symbology provides a substantial increase in navigational accuracy and taxi speed when paired with the EMM, compared to that of the EMM alone. These results are promising, however, the disappearance of symbology during turns due to the limited HUD FOV merits further research. This was clearly noted as an issue by the pilots during flight tests at Atlanta Hartsfield International Airport (Andre, Hooey, Foyle & McCann, 1998).

FOV AND TURN SYMBOLOGY

The restricted immediate FOV has been identified as a major problem in aviation human factors (e.g., Brickner & Foyle, 1990). Humans have a FOV that measures approximately 100 deg horizontally (H) by 60 deg vertically (V), (Harrington, 1964). Placed in an aircraft with minimal window space (e.g., commercial airliners) a pilots' FOV is substantially reduced. To complicate matters even further, we then request that pilots decrease their FOV even more by having them look through a (relatively) small HUD in environments of low visibility and/or darkness. We have now successfully decreased the pilots' FOV from 100 deg (H) by 60 deg (V) to approximately 30 deg (H) by 20 deg (V).

The limited HUD FOV may only be a minor issue in general, but becomes critical when attempting to navigate through a turn. As stated earlier, the scene-linked symbology (side cones and centerline markings) disappears when one enters and attempts to navigate accurately through a turn. There are several factors, in addition to the HUD FOV, that contribute to this problem. First, there is the issue of eye height. Consider that when sitting in a commercial transport cockpit, the pilot's eyepoint is considerably higher than when on the ground, 10 ft or more. Second, the aircraft nose blocks a substantial part of the lower front view, making it quite difficult to see anything in front of the aircraft nose. Even in perfect weather, the pilot is unable to see the edge of the taxiway when initiating a turn. Since scene-linked symbology is conformal, the edge cones associated with a turn segment would (and do) naturally disappear from view, just as the actual edge of the taxiway disappears from view. For example, in our simulation, the closest scene-linked object that can be seen is 69 ft from the pilot's eyepoint, due to the limited FOV (downward) of the HUD. The pilot is essentially "looking over the top" of the symbology cones and the taxiway edge. This is further compounded by the fact that the pilots use a technique called "judgmental oversteer" to assist them in aligning the aircraft with the centerline during a turn.

Based on anecdotal experience with the original T-NASA symbology with taxiway edge cones, we suspect that the limited HUD FOV may lead to suboptimal turn performance. Pilots, during their initial familiarization with this T-NASA symbology, tended to keep both the left and right taxiway edge cones in view on the HUD. Completing a turn in this manner leads the pilot to undercut the turn – tracking a path that is off of the actual centerline, and toward the inside of the turn.

NEW TURN SYMBOLOGY

The goal of the new symbology design was to establish a scene-linked enhancement that would assist pilots throughout the entire turn. To preclude "looking over the top" of the symbology, simple poles were added. The poles extended upward from the ground, clearly visible into the HUD's limited FOV and would be expected to contribute the least amount of clutter. Two pole positions were included: On the taxiway edge, extending upward from the cones; and, offset beyond the taxiway edge and cones. Placement at the taxiway edge (edge poles) provides a *direct* indication of the location of the taxiway edge. These edge poles remain fully visible as the pilot approaches the turn,

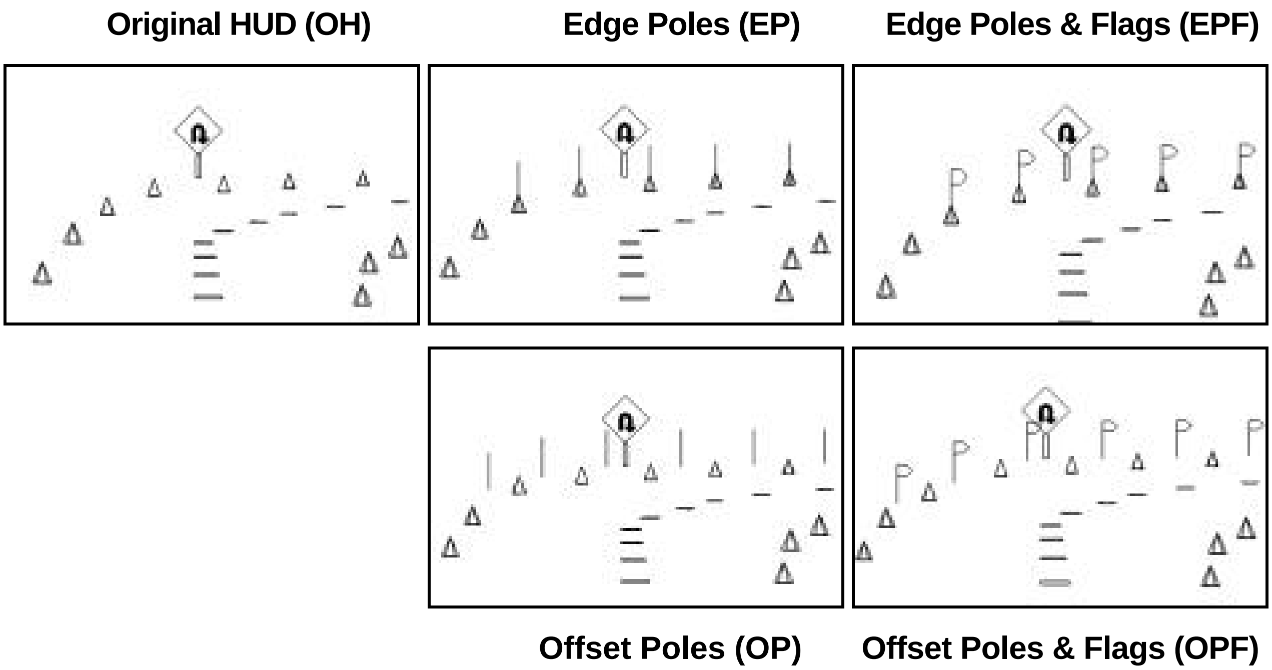

Figure 2. Schematic drawings (not to scale) of the five scene-linked HUD turn symbology sets (as labeled). The "No Symbology" condition is not shown. For the two conditions with Edge Poles (EP and EPF), the poles (with or without flags) were attached to the cones at the taxiway edge. For the two conditions with offset poles (OP and OPF), the poles (with or without flags) were 43 ft beyond the taxiway edge cones.

but only partially visible (the top) as the turn is initiated (since the taxiway edge is not visible at that point). Placement of the pole beyond the turn (offset poles), offset from the taxiway edge and cone symbology provides a *relative* indication of the location of the taxiway edge (by judging the relative distance from the edge to the offset poles, and from the eyepoint to the offset poles). These offset poles remain fully visible during the turn approach and throughout the turn.

For both the edge poles and offset poles, two additional symbology sets were developed by adding a turn flag (showing the direction of the turn) to the tops of the poles. It was expected that this may enhance speed cues, visual distance cues (since the visual cue, looming, emerges), as well as assist in local situation awareness regarding direction of turn.

Thus, four new symbology sets were defined: Edge Poles (EP), Edge Poles with Flags (EPF), Offset Poles (OP), and Offset Poles with Flags (OPF). For these latter four conditions, all turn symbology was drawn on the HUD only for turns that measured 25 deg or greater. Offset poles (with or without flags) were 43 feet beyond the edge cones. Edge cones were 1.8 ft in height, and all poles (with, and without flags) were 7.8 ft tall. The pilot's modeled visual eyepoint height for the HUD symbology and OTW scene was 12 ft.

DESIGN

Six turn symbology conditions were tested in this within-participant design (see Figure 2): Baseline (No HUD), Original T-NASA HUD (edge cones, centerline and turn signs, OH), Edge Poles (EP), Edge Poles with Flags (EPF), Offset Poles (OP), and Offset Poles with Flags (OPF). The order of the six different symbology conditions was randomized within each block of 6 trials. Each block of these six conditions was repeated seven times, yielding a total of 42 trials per subject (7 replication blocks of 6 different HUD conditions). For each subject, the order of the forty-two unique taxi routes, containing 2-8 turns each, was randomized; thus randomizing the assignment of a route to the 42 combinations of HUD condition and replications.

PARTICIPANTS

Eleven male, line Air Transport Pilots (ATP) with current medical were recruited. Their vision was either 20/20 or correctable to 20/20. The pilots had previously participated in a half-day session with the same symbology sets. Participants received no explicit performance feedback during that half-day session. Those data are not presented here, and that session was considered to be simulator and system familiarization.

SIMULATION AND PROCEDURE

A Silicon Graphics Indigo2 Extreme computer was used to present the taxi environment simulation and collect data. The visual environment was a graphics model of the Chicago O'Hare International Airport rear-projected onto a 1.8 m (V) x 2.4 m (H) screen using an

Electrohome rear-projector unit. The OTW simulation was updated at 60 Hz. The HUD unit consisted of an XKD Projector unit that projects the symbology onto a silvered mirror measuring 20.3 cm (V) x 24.1 cm (H), 19.6 x 24.5 deg visual angle. The HUD unit was suspended from a metal A-frame. The HUD symbology was updated at a rate of 60 Hz.

Since the electronic moving map (EMM) is part of the actual T-NASA System, it was necessary to include it in the design. The map allowed the pilots a perspective aerial view of the airport. Pilots could see their cleared taxi route and any moving traffic on the airport surface. The FOV of the EMM was fixed for this study in order to force the participants to rely on the HUD symbology as much as possible. The EMM appeared as a 20.3 cm x 15.2 cm display on a 43.2 cm Sony Trinitron color-monitor and was updated at a rate of 10-12 Hz. The seated participant controlled the simulated aircraft, a Boeing 737, by using a throttle and stick/tiller located on the right and left sides, respectively, of the participant's chair. Fully-operational rudder pedals with toe brakes were also provided. Participants were provided with a small headset with "hot mic" in order to facilitate two-way communication.

RESULTS

Dependent Measures

The 42 taxi routes, assigned randomly to conditions, independently for each subject, contained both straight sections, and turns of various angles (shallow- to full U-turns). The turn symbology was displayed on the HUD only for turn angles of 25 deg or greater. All data reported in this paper refer only to performance during turns with angles of 25 deg or greater (yielding 2-8 analyzed turns per route).

Three dependent measures were used to evaluate turn performance for the six HUD conditions: Speed of the aircraft, in kts; RMSE (root mean squared error) centerline deviation, in ft; and, Mean Deviation from the centerline, in ft. The latter two deviation measures were calculated from the distance between the route centerline and the center-of-gravity (CG) of the aircraft, centered between the main landing gear. The RMSE dependent measure yields a measure of the average distance between the CG and the centerline. In contrast, the Mean Deviation measure is a *signed* measure of the average CG-centerline distance, with distances toward the inside of the turn assigned positive values, and distances toward the outside of the turn assigned negative values. Thus, positive values of the Mean Deviation measure represent undercut turns, and negative values represent wide turns. The Mean Deviation measure indicates whether there is any systematic *bias* to undercut turns or take them wide. Note that it is possible to have poor centerline-tracking accuracy (RMSE), while demonstrating a bias toward wide turns (negative Mean Deviation), undercut turns (positive Mean Deviation), or no bias at all (zero Mean Deviation).

Analysis

The three measures were analyzed with a two-way (6 HUD conditions x 7 replications) within-participants analysis of variance (ANOVA). When replication blocks 1-7 and 2-7 were analyzed, significant effects (p<.05) of replication were present for at least one dependent measure. For replication blocks 3-7, no significant effects including replication were found, and thus can be considered to represent asymptotic performance (see Table 1). All data reported in this paper are for replication blocks 3-7.

	ANOVA Effect		
Dependent Measure	HUD	Replication	HUD x Replication
Speed	F(5,50)=16.64 p<.001	F(4,40)=1.20, ns	F<1
RMSE	F(5,50)=3.52, p<.01	F(4,40)=1.69, ns	F<1
Mean Deviation	F(5,50)=2.78, p<.05	F<1	F(20,200) =1.34, ns

Table 1. Turn data ANOVA results for replication blocks 3-7, for the three dependent measures.

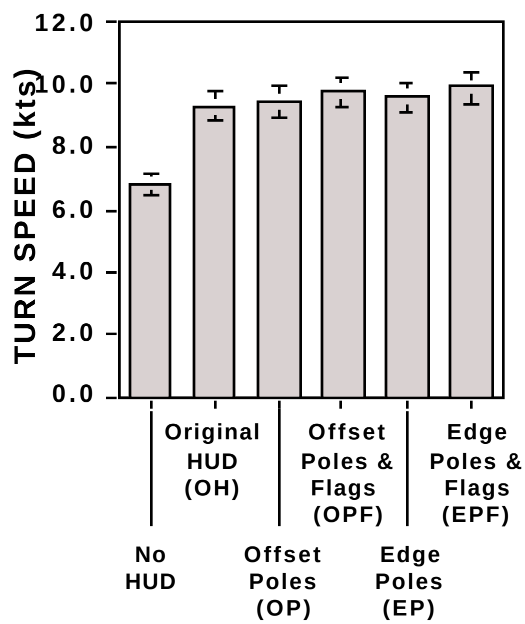

Figure 3. Turn speed (kts) data for the No HUD symbology condition and five scene-linked HUD turn symbology conditions (as labeled). Error bars represent plus/minus 1 standard error.

<u>Speed analyses</u>. Multiple paired-differences t-tests indicated that turn speed in the No HUD condition was

significantly slower than all 5 symbology conditions. Comparing the No HUD condition with the OH, OP, OPF, EP and EPF conditions, t(10)=5.26, 4.52, 5.99, 5.43, 4.97, respectively, all p<.001. All comparisons among the other conditions were not significant, p>.10.

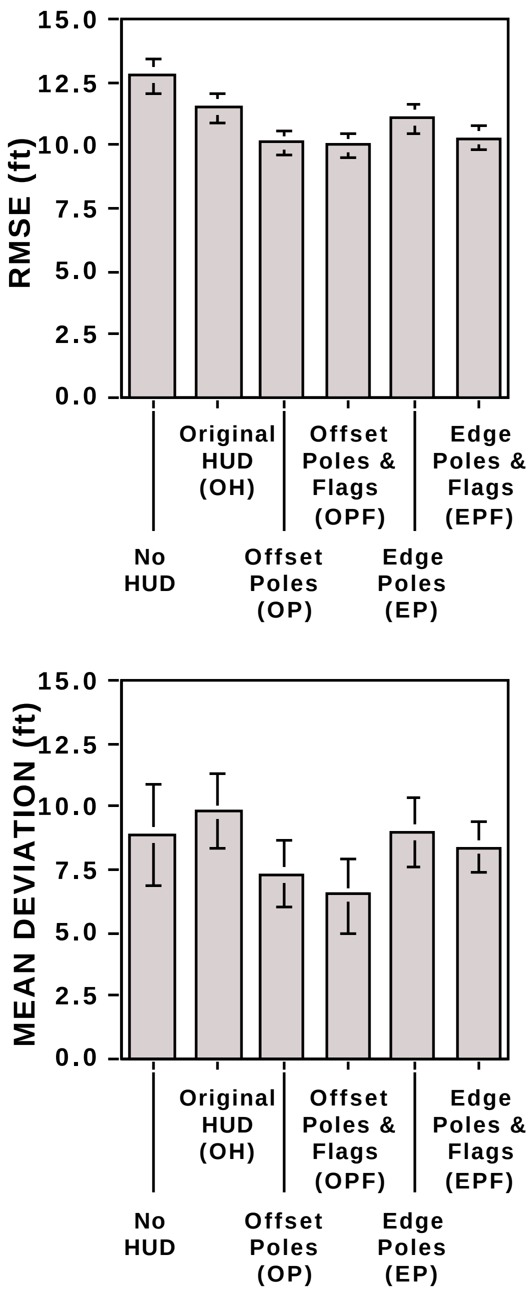

Figure 4. Centerline error data. RMSE deviation (ft, top), and Mean deviation (ft, bottom) data for the No HUD symbology condition and five scene-linked HUD turn symbology conditions (as labeled). Error bars represent plus/minus 1 standard error.

<u>RMSE analyses</u>. Multiple paired-differences t-tests indicated that turn RMSE in the No HUD condition was significantly worse than the 4 new symbology conditions: For OPF, EP and EPF, t(10)=2.44, 2.26, 2.42, respectively, all p<.05; and, for OP, t(10)=2.10, p=.06 (marginal). Additionally, compared to the OH condition, the two offset pole conditions yielded better centerline tracking: For OPF, t(10)=2.62, p<.05; and, for OP, t(10)=2.04, p=.07 (marginal). All comparisons among the other conditions were not significant, p>.10.

<u>Mean Deviation analyses</u>. The positive values obtained for the Mean Deviation data indicates that, on average, the pilots undercut the turns, independent of their accuracy. Multiple paired-differences t-tests indicated that both offset pole conditions yielded turn performance that was more unbiased and less undercut than the OH condition: For OP, t(10)=3.41, p<.01; and, for OPF, t(10)=4.03, p<.01. The two offset pole conditions yielded less biased (undercut) turns than their counterpart edge pole conditions: OP vs. EP, t(10)=2.78, p<.05; and, for OPF vs. EPF, t(10)=2.42, p<.05. Additionally, the OPF vs. EP comparison was significant, t(10)=3.88, p<.01; and, the OH vs. EPF comparison was marginal, t(10)=1.99, p=.074. All comparisons among the other conditions were not significant, p>.10.

DISCUSSION

These analyses indicate that without HUD symbology (No HUD), turn navigation was slower than when HUD symbology (all 5 HUD symbology conditions) was available. The two offset pole conditions (OP, OPF) yielded more accurate centerline tracking (RMSE) performance than the OH, and No HUD conditions. These two offset pole conditions (OP, OPF) also produced turn performance that was more unbiased, with less of a tendency to undercut the turns, than the original HUD (OH) condition, as well as when compared to their counterpart edge pole conditions (EP and EPF, respectively).

As mentioned previously, anecdotal evidence from other studies with the OH symbology suggested a tendency to undercut turns. The present finding validates this because when the HUD symbology is placed on the taxiway edge (OH, EP and EPF) there was an increased tendency to undercut the turns. Presumably, pilots have a tendency to attempt to keep the edge cones (with or without poles and flags) in the HUD FOV, producing an undercut turn. The offset pole symbology (OP and OPF) mitigates this problem, producing turns that are less undercut.

One goal of this study was to determine the most optimal turn symbology among the 4 new symbology conditions (OP, OPF, EP, and EPF) designed so that the symbology stays in the relatively limited FOV of the HUD. The two offset pole conditions (OP and OPF) yield turn performance that is relatively faster, more accurate, and less biased towards producing undercut turns. Comments from the pilots indicate that the turn flags were subjectively preferred because of the directional information, which pilots felt would help them maintain situational awareness and orientation. Thus, the Offset Poles and Flags (OPF) HUD symbology condition produces the most optimal objective and subjective turn data. Further simulations with the T-NASA system will use the OPF scene-linked HUD symbology.

The results of this study also extend our understanding of the scene-linked symbology concept. As discussed previously, scene-linked symbology, by definition, is required to "fit" inside the limited HUD FOV. The fact that the original HUD (OH) symbology was not always visible in turns was disconcerting to pilots and would likely prevent such symbology from being implemented. The present study indicates that modifications to the scene-linked symbology successfully optimized turn performance while remaining visible.

The finding that the two offset-pole scene-linked symbology conditions (OP and OPF) were the conditions that yielded the best turn navigation performance extends our understanding of the required visual cues that support turn performance. The original HUD and edge-pole conditions (EP and EPF) provided direct visual references for the turn, since they were directly overlaid on the turn edge. However, because of the limited FOV of the HUD, the visual cues provided by the cones and the top portion of the pole (or pole and flag) were not sufficient to support the best turn navigation performance. The offset pole conditions, in contrast, provided a deterministic, relative distance cue that could be used to determine the distance from the taxiway turn edge, allowing the pilot to navigate the turn with the best turn performance of those conditions tested.

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