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Pilot Interactions with an Electronic Display Suite to support Low-visibility Taxi

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1 SUMMARY

This paper focuses on how pilot interaction with a cockpit display suite improves ground taxi performance in low visibility. The display suite consists of a perspective moving map display, showing the real-time location of the ownship on the airport surface, and a "pathway-on-the-ground" form of head-up display (HUD). Performance benefits of both displays were assessed in a single-pilot medium-fidelity simulation and in a two-crew high-fidelity simulation. In both simulations, taxi performance was improved by the moving map display, and improved even further by the moving map/HUD combination. New analyses are reported that further clarify the source of the separate and combined effects of the moving map and the HUD.

2 INTRODUCTION

2.1 Taxiing with cockpit displays

In the last decade, powerful lasers, capable of projecting a coherent beam of light over large distances, have become widely available. These devices pose a clear threat to aircraft pilots. In the military sector, the concern is with the deliberate use of laser beams as weapons, aimed directly at the cockpit to impair the operators' vision. In the civilian realm, the concern is more with pilots making inadvertent eye contact with laser light from, for example, outdoor entertainment systems.

The laser threat has sparked considerable interest in the concept of a closed cockpit, in which the operators would be optically shielded from the outside world, and all information needed to pilot the aircraft would be provided by electronic displays. When designing such a cockpit, a host of human factors issues must be considered. What information should be present on the displays? How should the display of this information be configured to optimize the "fit" between the display and the information processing capabilities of the human operator? Would pilots use the displays in the manner anticipated by the designers? Most tantalizing of all, is it possible to design a display system that would actually improve pilots' performance compared to the traditional open cockpit?

The present article examines these issues in the context of commercial ground taxi operations. On each flight, pilots must navigate a cleared route from the gate to the departure runway, and again from the arrival runway to the gate. Even in modern glass cockpits, the only form of cockpit navigation aid for ground taxi is still a paper chart of the airport surface. Consequently, taxiing remains largely an eyes-out task: the pilot (or first officer) selects a series of landmarks on the paper map and then associates these landmarks with their visual counterparts in the out-the-window (OTW) scene.

The heavy reliance on the OTW scene means that taxiing is easily disrupted by reductions in visibility or by misleading or inadequate signage and surface markings [1]. Several years ago, researchers at NASA-Ames were tasked with developing a cockpit display

Figure 1. Photograph showing the T-NASA HUD symbology overlaid on the out-the-window night view approaching Runway 27R/9L on Taxiway Charlie at Chicago O'Hare. The cleared taxiway is demarcated by the series of rectangular centerline markers and the side cones. Hold short symbology (Full Motion Simulation only) includes the virtual stop sign, virtual stop bar, and the replacement of the side cones with X's at and past the stop bar. Note the A/C taking off on 27R/9L (upper left of figure).

suite to enable pilots to taxi safely and efficiently in low visibility. The result of this development project, called the Taxiway Navigation and Situation Awareness (T-NASA) system, consists of a Head-up Display (HUD) and a panel-mounted electronic moving map (EMM). An additional 3-D audio warning subsystem will not be discussed here.

Since T-NASA was designed for low-visibility conditions, a major consideration in the design of the system was to supply pilots with the information they need to taxi, thereby reducing their reliance on the OTW scene. Thus, although the T-NASA system was designed to work in conjunction with the OTW cues that remain even in low visibility, our research into the effects and usage of the T-NASA system addresses many of same human factors issues that would confront the designer of a closed cockpit.

We begin with a brief assessment of the information requirements of the ground taxi task, based largely on a human factors model of the information processing needed to navigate. We then describe how the information requirements guided our design of the T-NASA system [2]. Selected results of two simulations are then reported, both of which evaluated the impact of the T-NASA displays on taxi performance in low visibility. Interested readers are referred to earlier publications [3,4] for comprehensive reports of the simulations. Here, we focus on new analyses that provide evidence pertaining to pilots' usage patterns. The results of these analyses suggest that pilots take full advantage of the information provided on the displays, that they adapt their usage in response to dynamic aspects of the taxi environment, and that they use the information on the displays in the manner anticipated by the designers. These results strongly support the feasibility of designing a cockpit display for taxi in zero visibility conditions, such as a closed cockpit. We conclude with a discussion of how the T-NASA system might be modified to support taxiing in zero visibility.

2.2 A cognitive model of navigation

Researchers typically distinguish between two forms of knowledge needed to navigate an aircraft [5]. Knowledge of the spatial relation between the aircraft's current location (where we are) and the cleared route (where we should be) supports the task of local guidance. This closed-loop operation involves monitoring the real-time error (if any) between current position and the cleared route, and correcting the error via appropriate control inputs. The second form of knowledge, global awareness [5], combines knowledge of the aircraft's absolute position in a world-referenced (viewer-invariant) coordinate system with general knowledge about the immediate environment (i.e., the location and trajectory of nearby aircraft). Global awareness is necessary, for example, to recognize and react appropriately to hazardous situations.

Collectively, the two forms of spatial knowledge define a pilots' "navigation awareness" [5,6,7]. As long as navigation awareness is maintained, the pilot has a feeling of "foundness" that allows him or her to proceed rapidly and accurately along the cleared route [8]. If navigation awareness is lost, the pilot can become spatially disoriented. In the case of ground taxi, the results can range from the temporary increase in workload that accompanies the activities necessary to regain navigation awareness, all the way to catastrophic accidents.

2.3 The T-NASA System

Assuming that taxiing requires two quasi-distinct forms of knowledge posed something of a dilemma for the design of the T-NASA system. Local guidance is typically supported by visual cues in the OTW scene. These cues include optical flow field characteristics, edge rate information, and the geometry between the focus of optical expansion (the point in the visual field from which the optical flow appears to originate) and the taxiway centerline. Consequently, human factors researchers have proposed that the ideal display to support local guidance is fully ego-referenced, sharing as many features as possible with the pilots' actual forward field of view [5]. The problem is that a fully ego-referenced display is restricted to depicting a narrow cone of visual space that lies directly in front of the pilot. This restriction prevents ego-referenced displays from supplying information needed to support global awareness [5].

2.3.1 T-NASA HUD. Our solution to this problem was to design two displays, one for local guidance, the other for global awareness. The local guidance display consists of HUD symbology designed specifically for taxi. Figure 1 shows the symbology visible as the pilot approaches hold bars on taxiway "Charlie", a high-speed turn-off from Runway 27R at Chicago O'Hare. Note in particular the triangular-shaped edge cones and the series of regularly spaced square markers along the taxiway centerline. These symbols delineate the edges and the centerline, respectively, of the cleared taxiway. The symbols are "scene-linked" [9], such that, as the aircraft moves through the environment, the symbols undergo the same optical transformations that they would if they were physical objects out in the world. Visually, the scene-linked symbols resemble raised reflective pavement markers that highlight the edges and the centerline of a 2-lane highway during nighttime driving.

The T-NASA HUD symbology provides a variety of intuitive cues to support local guidance. For example, consider an aircraft taxiing along a straight section of a cleared taxiway, as in Figure 1. As long as the longitudinal axis of the aircraft is aligned with the taxiway centerline (and the pilot is looking straight ahead), the scene-linked centerline markers extend outward directly along the pilot's line of sight, just as the actual taxiway centerline does. If the longitudinal axis of the aircraft starts to deviate from the centerline (i.e., lateral error is introduced) an angle is created between the direct line of sight and the imaginary line through the centerline markers. If the deviation becomes extreme enough, the scene-linked objects shift outside the field-of-view of the HUD, disappearing completely. These changes provide obvious cues that the pilot is deviating from the correct course, and needs to correct the error with a control input. In this way, the scene-linked symbology reduces reliance on the out-the-window scene for inner-loop control; casually speaking, the HUD turns local guidance into a simple exercise of "follow the virtual highway on the ground".

Scene-linked symbology does more than provide cues to lateral error, however. Since the scene-linked symbols only outline the cleared route, they provide a fully ego-referenced preview of the cleared route (up to 300 m in our system). If the aircraft is positioned at the beginning of a long straightaway, the virtual cones along the side of the taxiway gradually foreshorten and converge with increasing distance. These perspective cues tell the captain that the current section is reasonably long. As the aircraft moves further along the straightaway, the scene-linked symbols eventually veer off to the left or to the right, signaling the distance to, and the severity of, the next turn. We will have more to say about possible usage of these cues shortly. For now, suffice to say that the scene-linked symbols provide predictive information about the cleared route that is not available in the OTW scene, even in good visibility.

2.3.2 T-NASA EMM Although the T-NASA HUD provides cues for local guidance, it gives little information to support global awareness. In principle, a pilot could exploit the HUD symbology, and navigate

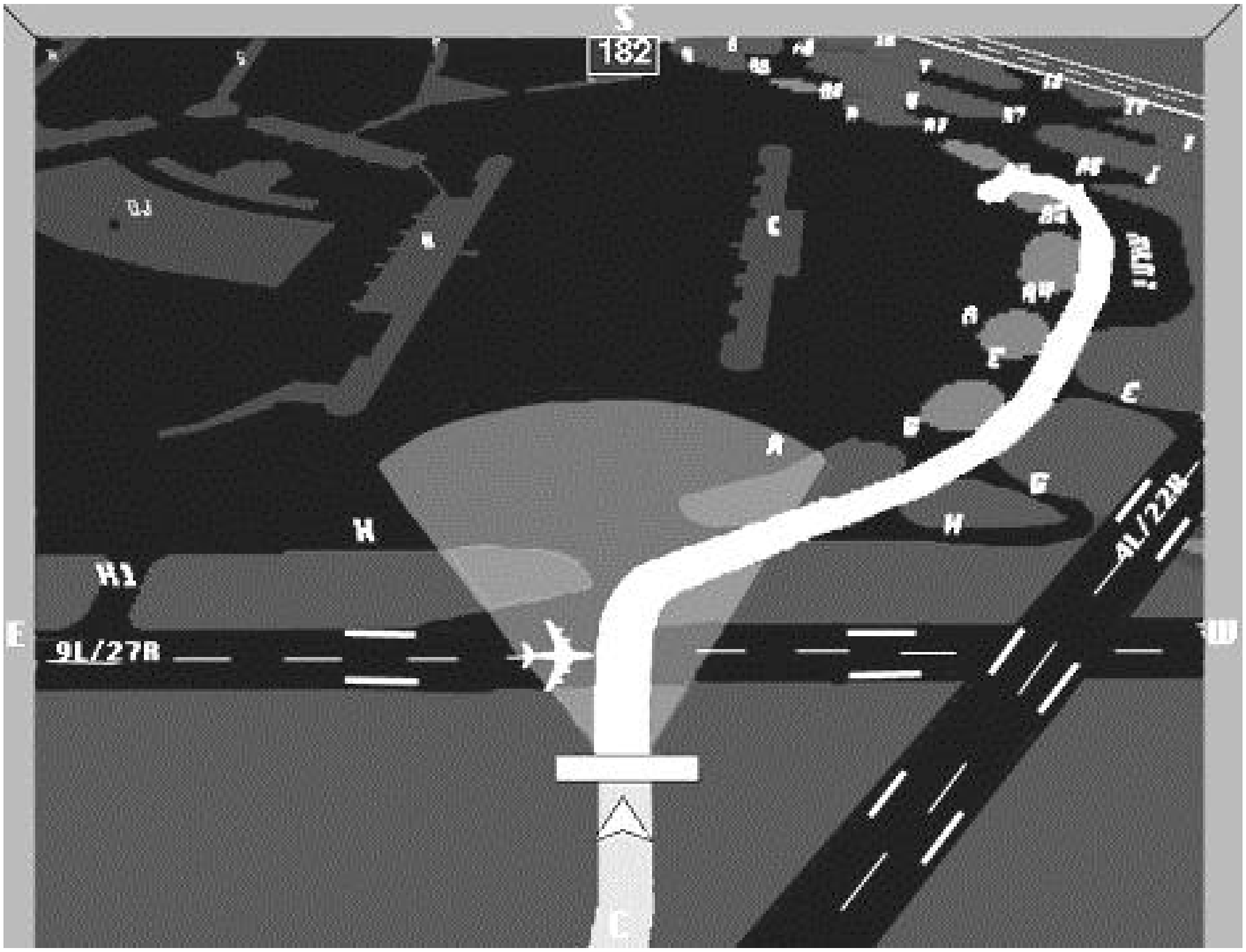

Figure 2. T-NASA EMM, showing the map view from the same location as Figure 1 (i.e., holding short of Runway 27R/9L on taxiway Charlie) at a low zoom level. The ribbon shows the cleared route; the actual colors were magenta, leading up to the stop bar, and yellow (caution) thereafter. Light gray areas were generally green. The wedge-shaped region in front of the ownship symbol highlights features in, or near, the pilots' forward field of view, such as the A/C taking off on 27R/9L (see Figure 1).

the route, and remain largely ignorant of his actual position on the airport surface and of any hazards in the vicinity. The other obvious limitation of the HUD is that it is not available to the First Officer (FO) in a two-crew flight deck. Shown in Figure 2, the EMM provides a perspective view of the airport surface from an eyepoint that is "tethered" to a location above and behind the ownship. The distance of the eyepoint along the tether is adjustable, creating five zoom levels from which the pilot can choose. Lower zoom levels, which correspond to greater distances between the eyepoint and the ownship, depict more of the airport surface, giving the pilot more of an "overview" of the airport and the location of the ownship within it. Higher zoom levels, on the other hand, restrict the region depicted on the EMM to the area around the ownship, but depict that region at higher resolution.

Being panel-mounted, the EMM gives both members of the crew a view of the airport area completely surrounding the ownship (although areas to the side of, and in front of, the ownship are favored over areas directly behind). As shown in Figure 2, the EMM also depicts nearby traffic on the airport surface, updating the position of the traffic in real time. Explicit route guidance is also provided, in the form of a magenta-colored ribbon extending along the cleared taxiway(s). These features directly support global awareness. Other features of the EMM were designed to facilitate the task of establishing and maintaining cognitive correspondence between the representation of a feature on the EMM and the actual feature in the OTW view. In the case of a paper map, this task can be quite difficult, requiring effortful cognitive operations such as mental rotation and size scaling [6]. The selection of a tethered perspective locks the EMM in a "track-up" orientation, always aligned with the pilots' forward field of view. This ensures that correspondence can be established without mental rotation. In addition, note the prominent pale "wedge" in front of the ownship symbol in Figure 2. The purpose of the wedge is to highlight features on the map that are in, or on the periphery of, the forward field of view. Previous work (5) has shown that the wedge is an effective aid to correspondence.

2.4 Research Issues

We noted earlier that the design of the T-NASA system touches on many human factors issues of interest to those interested in the design of closed cockpit displays. Having described the displays, we can now recast these questions from the T-NASA perspective.

2.4.1 Display usage. The first and most fundamental question is whether pilots would use the displays at all. For example, a lack of trust in computer-generated imagery, combined with simple mental inertia, might cause pilots to ignore the displays in favor of the more familiar "pilotage" techniques. That is, pilots might continue to navigate by associating landmarks on the paper map with the corresponding objects in the OTW scene. This strategy would not be encouraging when evaluating pilots' willingness to accept artificial sources of information.

2.4.2 Optimization. Assuming some usage of the T-NASA displays, how optimal is that usage? That is, would pilots make use of all the functionality that has been built into the displays? If not, what features would they ignore?

2.4.3 Usage Style. Again, assuming pilots make some use of the T-NASA displays, what is the best way to characterize their usage style? At the one extreme, a very passive style would be one that was not responsive to dynamic aspects of the route, and would involve a low level of interaction with the displays. A specific example would be if pilots selected a particular zoom level for the EMM, and simply left it there for the entire route. Again, this style would fail to exploit much of the functionality of the T-NASA system.

2.4.4 Performance Enhancement. Finally, is there any evidence that pilots utilize aspects of the T-NASA system, such as the predictive route cues on the HUD, that are not available in the OTW scene even in good visibility? This question speaks to both the optimization issue, and to the issue of whether electronic displays might support better performance than today's cockpits.

For answers to these questions, we now turn to two recent simulations that evaluated the effects of the T-NASA displays.

3 PART-TASK SIMULATION

The first simulation was carried out in a medium fidelity, fixed-based, single-pilot facility. The vehicle model emulated the handling characteristics of a B737. Vehicle control was accomplished via inputs to rudder and toe brakes, a throttle, and a nose-wheel tiller. The out-the-window visual scene, a high-fidelity rendering of Chicago O'Hare International Airport in low visibility (700 ft RVR), was driven by an SGI Onyx Reality Engine 2, rear-projected on an Electrohome screen measuring 2.43 m (width) by 1.83 m (height). HUD symbology was generated by an SGI Personal IRIS, projected through a Fresnel lens, and reflected into the participants' eyes through a half-silvered mirror. The EMM, similar to the version shown in Figure 2, was displayed on a 23-cm diagonal CRT located below and to the left of the pilot. The display consisted of a 3-D perspective depiction of Chicago O'Hare that could be viewed at any one of five zoom levels. Choice of zoom level was fully pilot selectable throughout each trial.

Nine commercial airline pilots completed a series of 24 gate-to-runway taxi sequences. Each route averaged 2 nmi in length, and took approximately 7 min to complete. For each pilot, eight routes were carried out in a Baseline condition, in which navigation support was limited to a Jeppesen paper map of Chicago O'Hare and the OTW cues (i.e., surface signage and markings). On 8 additional routes, pilots were provided with the paper map and the EMM. On the remaining routes, both the EMM and the HUD were provided. Thus there were three display conditions: Baseline (Jeppesen map only); EMM; and EMM+HUD.

3.1 Results

The results reported here are a mix of new and previously published [3,4] data. In the interests of brevity, we include statistical analyses only for the data being reported for the first time.

3.1.1 Display Usage. Arguably, the two most important dependent measures are taxi speed and route-following accuracy. On average, pilots taxiied at just under 17 kts in the Baseline condition. Taxi speed increased by a modest .76 kts in the EMM condition, and by a more substantial 3.2 kts in the EMM+HUD condition. To evaluate accuracy, the experimenter kept a running tally of each time a pilot deviated from the cleared route, by either failing to turn where required, or by making an incorrect turn. Summing across trials, subjects committed an average of 2.3 navigation errors in the Baseline condition, 1.0 error in the EMM condition, and only 0.1 error in the EMM+HUD condition.

To achieve effects on speed and accuracy of this magnitude, the pilots must have used the T-NASA

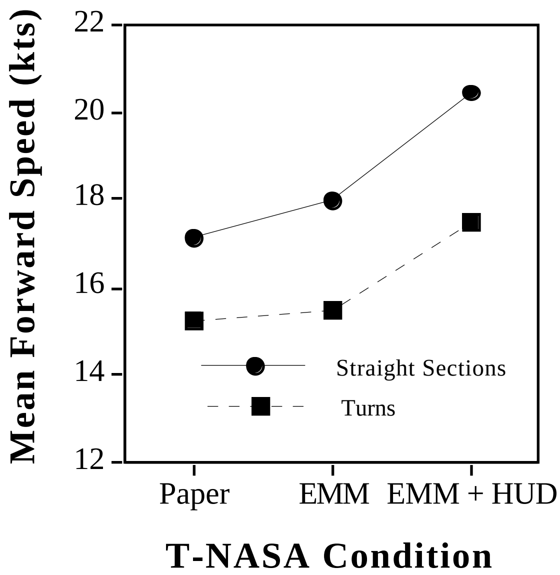

Figure 3. Mean forward taxi speed in part-task simulation as a function of T-NASA Condition and Route Topography (Straightaways versus Turns).

displays quite extensively. Further evidence for display usage can be found in a measure of route planning time. At the beginning of each trial, the aircraft was positioned in the apron area in front of a designated departure gate. The trial began when the out-the-window visual display appeared on the screen, and the EMM and HUD (if available) were illuminated. The latency from trial onset to first throttle push provides an estimate of how much planning took place before the pilot started taxiing. In fact, on Baseline trials pilots took an average of 66 sec before moving the throttle. This period was reduced to 29 sec in the EMM condition, and to 24 sec in the EMM+HUD condition. Statistical analyses revealed a significant main effect of T-NASA condition, $F(2,16) = 31.8$, $p < .001$. Individual comparisons revealed that the difference between the EMM condition and both the EMM + HUD ($t[8] = 2.59$, $p < .05$) and the Baseline ($t[8] = 5.28$, $p < .01$) conditions were significant.

Post-experimental questioning of the pilots revealed that in the Baseline condition, most of the time at the beginning of the trial was taken up in studying the paper map. We assume that the pilots were developing a mental picture of the route along with the landmarks they would need to recognize along the way. The explicit route guidance provided by the EMM and the HUD made this effort unnecessary, which is presumably why planning time shrank so dramatically when the displays were available. Of course, this assumes that on EMM and EMM+HUD trials, pilots acquired route information directly from the T-NASA displays.

3.1.2 Optimization and Usage Style. Having shown that the pilots used the displays, the next questions concern the extent to which the pilots exploited the functionality of the displays, and the usage style. One way to examine usage style is to select a dynamic feature of the route that is almost certain to effect a large change in taxi behavior. If the effects of the T-NASA displays were simply additive with the effects of this feature, this would suggest a passive or nonadaptive usage style. Alternatively, if the T-NASA conditions interact with the effects of the dynamic feature, we would have evidence that T-NASA usage varied along with dynamic changes in the route.

One obvious route dynamic is the degree of curvature in the route at any particular point. Measures such as taxi speed would obviously be impacted by this dynamic, as pilots typically taxi more slowly around turns than on straightaways. In order for the simulation software to overlay the HUD symbology directly on the appropriate positions along the cleared route, the database represented each route as a series of short segments. By measuring the amount of curvature in each segment, we were able to classify each section of each route as representing a straight or a turn segment. Data from straight sections were then combined, as were data from turn segments.

Figure 3 shows the effects of the T-NASA displays separately for straight and turn sections. As expected, pilots taxiied faster along straightaways than around turns, $F(1,8) = 26.0$, $p < .001$. The main effect of T-NASA condition was also significant, $F(2,16) = 7.0$, $p < .01$, reflecting the increase in forward speed as T-NASA displays were added. More important for present purposes, there was indeed a significant interaction between T-NASA condition and route topography, $F(2,16) = 3.95$, $p < .05$. Further analyses revealed that the interaction was due to the fact that, relative to the Baseline condition, the speed increase in the EMM+HUD condition was significantly greater on straightaways (3.37 kts) than on turns (2.27 kts).

These results suggest that pilots' use of T-NASA was indeed adaptive to the dynamics of the taxi environment. More specifically, the pattern of data indicates that the HUD provided information relevant to control of speed on straight sections that was not available (or was available but not utilized) on the EMM. We will have more to say about this after reporting the results of the second simulation.

Is there similar evidence for situation-adaptive usage of the EMM? An obvious place to look for such evidence is in pilots' use of zoom levels. Recall that they could choose to view the EMM at any one of five zoom levels. The highest (or most "zoomed in") level (i.e., 5)

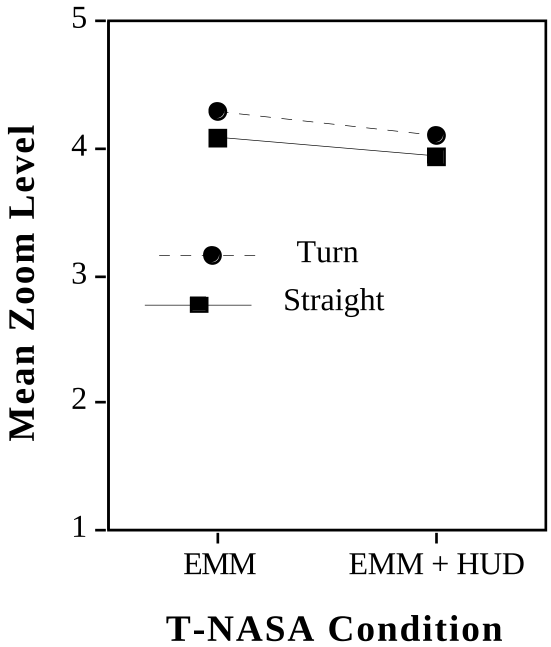

Figure 4. Mean weighted zoom level in part-task simulation as a function of T-NASA Condition and Route Topography. Note that higher zoom levels correspond to zooming in on the EMM.

yielded the highest resolution of the area around the ownship, but the least extensive view of the airport. The lowest (or most "zoomed out") level (i.e., 1) yielded the lowest resolution of the area near the ownship, but the most extensive view of the airport (as well as the cleared route). Again, our interest is in whether the pilots selected and then maintained a single zoom level throughout the route (a passive usage pattern), or actively adjusted zoom level in response to the dynamics of the environment.

To capture zoom behavior quantitatively, we first calculated the proportion of total time that each pilot spent at each zoom level on each trial. We then multiplied each proportion by the zoom level itself, and summed the five values. The result represents a weighted average zoom level that captures the central tendency of the pilots' zoom behavior. For example if, on a particular trial, a pilot spent 90% of his time at zoom level 5, and the remaining 10% at zoom level 3, the weighted average zoom level for that trial would be 4.8, quite close to 5.

Figure 4 shows the weighted average zoom level as a function of route topography (straightaway versus turn) and T-NASA condition (EMM versus EMM+HUD). Although the figure reveals a slight preference for lower zoom levels when the HUD was provided along with the EMM, the effect of T-NASA condition was not significant ($F < 1$). The other pattern apparent in the figure is that pilots preferred slightly higher zoom levels around turns than on straightaways, $F(1,8) = 12.07$, $p < .01$. One account of this pattern is that greater local resolution of the region immediately surrounding the aircraft was useful to the pilot on turns, so they zoomed in. Another possibility is that on straight sections, pilots wanted more information about the length of the current straightaway, and where the next turn was. Thus, they tended to zoom out on straight sections. Of course, both factors may have been at work.

3.2 Discussion of Part-task Simulation. The results of the part-task simulation can be summarized as follows. Pilots took less planning time, taxiied faster, and committed fewer navigation errors, when they had access to the T-NASA displays. For all three dependent measures, performance benefits were larger with the EMM+HUD combination than with the EMM alone. These results establish that the pilots were using the displays; they did not simply ignore them in favor of the more familiar pilotage strategy. In addition, the pilots showed sensitivity to a variable, route topography, that captures a dynamic aspect of the route. This suggests that not only did pilots use the displays, they adapted their use to fit dynamic aspects of the situation.

Although these results were encouraging, the part-task simulation had some evident limitations. Probably the most important is the single pilot nature of the facility. In a typical two-crew flight deck, the division of labor between the Captain and the FO gives most of the responsibility for maintaining geographic awareness to the FO. Navigation-related communication between crewmembers is quite frequent, much of it designed to either confirm or bolster the Captain's navigation awareness. In our study, it seems likely that the absence of a FO had the biggest impact on the baseline condition where, judging by the navigation errors, maintaining navigation awareness was most difficult. In addition, the part-task facility had no side-windows, preventing any left-window or cross-cockpit viewing of the OTW scene. Again, it seems plausible that this restriction was particularly harmful to the Baseline condition, where reliance on the OTW scene was greatest.

4 FULL-MOTION SIMULATION

If baseline performance was indeed depressed by these factors, the benefits of the T-NASA system were overestimated. Therefore, we recently completed a second evaluation of the system in NASA-Ames' Advanced Concepts Flight Simulator (ACFS), a two-crew, high fidelity, and six-degrees-of-freedom full-motion facility. The ACFS vehicle model emulates a

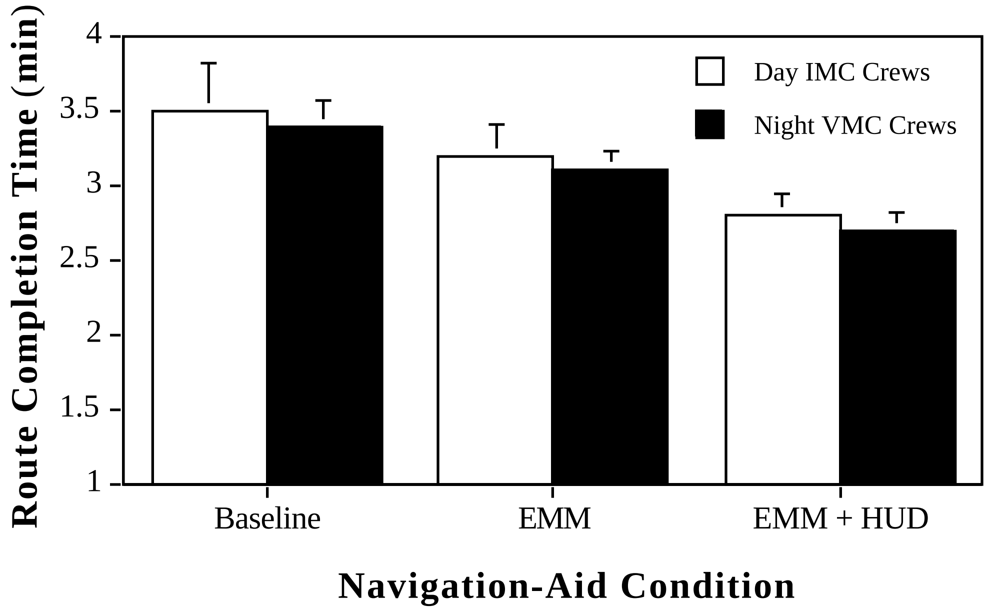

Figure 5. Route Completion Time (min) as a function of visibility (Day IMC crews versus Night VMC crews) and T-NASA Condition.

wide-body, low-wing B757 aircraft with twin turbofan engines; the flight deck contains a standard suite of glass cockpit displays and is outfitted with a Flight Dynamics HUD. A Flight Safety International VITAL VIIIi image generator provides a 180-degree field of view with full cross-cockpit viewing capability.

Thirty-two experienced commercial male pilots (16 Captains and 16 First Officers) participated in a daylong series of 21 autolandings and taxi-sequences at a simulated Chicago-O'Hare. Crews were formed by pairing a Captain and FO of the same aircraft type and airline. Half of the crews (Day crews) taxiied in daytime IFR (RVR = 700 ft) and the other half (Night crews) in nighttime VMC. In the Baseline condition, the only navigation aid in the cockpit was a paper chart of Chicago-O'Hare. In the EMM condition, the paper chart was supplemented by the T-NASA EMM, which replaced both the left-seat and right-seat Navigation Displays at weight-on-wheels. In the EMM+HUD condition, the Captain had access to both his EMM and the HUD taxi symbology.

Realism was enhanced by radio communication provided by a confederate Ground Controller and a pseudopilot, who played the role of the pilot of other ground traffic. The Ground Controller provided verbal communication to the pilots.

In all conditions, the crew was informed of their expected turn-off during final approach. A verbal clarance was issued to a destination terminal after rollout and turnoff.

4.1 Results

The ACFS simulation generated a large body of results from a large number of dependent measures. The interested reader is referred to [4] for a comprehensive report. Here, we focus on results most pertinent to display usage. Before describing these results, however, we will summarize the major findings.

Consider first the dependent measures of taxi speed and route-following accuracy. Visibility condition had no significant effect on these measures; the performance of Day crews was quite similar to Night crews [4]. The T-NASA displays had a large impact on crew performance by both Day and Night crews. Day crews taxiied at an average speed of 14.9 kts in the Baseline condition, 17.0 kts in the EMM condition, and 18.8 kts in the EMM+HUD condition. The corresponding values for the Night crews were 16.1, 17.2, and 19.0 kts, respectively. As for navigation errors, these were scored somewhat differently than in the Part-task simulation, but the same general pattern was repeated. A substantial number of errors were committed in the Baseline condition by both Day and Night crews. Errors were greatly reduced in the EMM condition, and virtually eliminated in the EMM+HUD condition.

One would expect that the combination of faster taxi speeds and fewer navigation errors would produce shorter route completion times, an important measure for determining whether the T-NASA system can buy

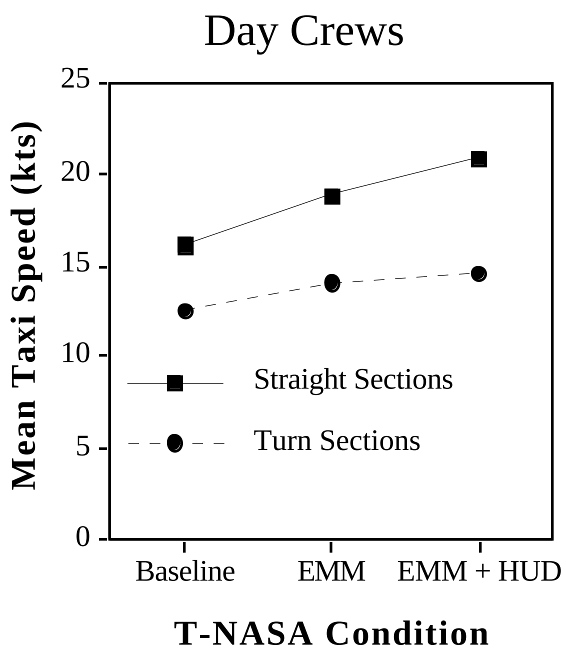

Figure 6. Mean Taxi Speed (kts) as a function of T-NASA Condition and Route Topography. Left Panel shows data for Day crews; Right Panel shows data for Night Crews.

its way onto commercial aircraft. Figure 5 shows the average completion time, measured from when the aircraft reached the vicinity of the runway turn-off to arrival at the apron area in front of the destination terminal. The figure shows that, although route completion times were quite similar for Day and Night crews, the T-NASA displays yielded substantial reductions. Compared to the Baseline condition, day crews completed their routes an average of 21 sec faster in the EMM condition, and 45 sec faster in the EMM+HUD condition. The corresponding values for the night crews were 22 sec and 45 sec, respectively.

4.1.1 Optimization and Usage Style. In the Part-task simulation, we found that the effects of the T-NASA system depended on route topography, which we took as evidence for an adaptive style of display usage. Would the same pattern emerge in the two-crew environment? To find out, we again separated route segments into either straight or turn sections. Figure 6 shows mean taxi speed as a function of T-NASA condition and route topography. As before, the Captains taxiied faster on straightaways than around turns, $F(1,14) = 897$, $p < .001$, and taxiied faster with the T-NASA displays than without them, $F(2,28) = 30.7$, $p < .001$. More important, there was a significant route topography by T-NASA condition interaction, $F(2,28) = 11.2$, $p < .001$. As is evident in the figure, compared to the Baseline Condition, the EMM condition yielded a modest speed increase that was roughly the same magnitude on straightaways as on turns. The EMM + HUD condition yielded a larger speed increase, more so on straightaways than on turns.

This description was supported by additional analyses. Including only the EMM and the EMM +HUD levels of the T-NASA condition variable, the interaction between condition and topography was significant, $F(1,14) = 8.4$, $p < .02$. However, when we compare only the Baseline and EMM levels, the interaction of T-NASA condition and topography failed to reach significance, $F(1,14) = 3.39$.

Turning now to zoom level behavior, recall that both the Captain and the FO had a dedicated EMM, and were encouraged to adjust their zoom levels independently. When considering pilot interactions with the EMM, then, we have the additional factor of crew role to consider. Figure 7 shows the average weighted zoom level selected by the Captains and First Officers as a function of T-NASA. To further determine the level of dynamic interaction with the EMM, we also analyzed zoom level preference as a function of route topography and T-NASA condition (EMM versus EMM+HUD). We see from the figure that first officers did indeed prefer lower zoom levels than the captains, $F(1,28) = 7.48$, $p < .05$. There was also a small but reliable tendency to zoom in on turns compared to straight sections, $F(1,28) = 10.3$, $p < .01$, replicating pilots' behavior in the part-task simulation. In addition, crew role and T-NASA condition interacted, $F(1,28) = 7.43$, $p < .05$. The first officers' choice of zoom level was unaffected by whether or not the Captain had access to the HUD, $F(1,14) < 1$. By contrast, the Captain consistently chose a lower zoom level in the EMM+HUD condition compared to the EMM condition, $F(1,14) = 9.68$, $p < .01$. This too replicates the trend found in the part-task simulation, though it was not significant in the previous study.

4.1.2 Performance Enhancement. One of the issues explored in this article is whether electronic displays can support better performance than is obtained in the standard cockpit, even in ideal conditions. Observers of a recent flight test of the T-NASA system [10,11] asked us whether the displays could be modified to improve compliance with hold short directives. In today's environment, failures to obey these directives occur in all conditions of visibility, and pose a significant challenge to the safety of ground operations. Accordingly, the ACFS simulation incorporated new hold-short symbology on both the HUD and the EMM. The effectiveness of this symbology was evaluated with four landings on Runway 22R. Prior to final approach, the crews were instructed to hold short of the active runway 27R, either on the high speed Charlie exit (Figures 1 and 2) or at the intersection of 22R and 27R (depending on the clearance received).

The HUD hold-short symbology was straightforward. Any stop bars implicated in the clearance were depicted conformally on the HUD; in addition, a virtual stop sign rose vertically up from the stop bar (see Figure 1). To remind the pilots that they weren't cleared to proceed past the hold short point, the cones outlining the edges of the cleared route were changed to virtual X's. Pilots were instructed to taxi to the location of the stop sign/hold bar and then stop. As soon as the hold short was lifted, the stop sign and conformal stop bar disappeared, and the edge cones replaced the X's.

On the EMM, the location of the stop bar was approximately represented on the map by a flashing yellow bar. To remind the crew that they weren't officially cleared past the hold short point, the ribbon representing the rest of their route was drawn in yellow (as in "caution"), rather than magenta. As soon as the hold was lifted, the flashing bar disappeared, and the cleared route returned to the normal magenta hue.

As we mentioned, four taxi sequences involved landing on Runway 22R/4L and holding short of runway 27R/9L, either at the intersection of the two runways, or on high-speed turnoff "Charlie". Each crews' performance at the appropriate hold bar was inspected using video and simulation replay capabilities. These inspections revealed that in the Baseline condition, one of the 16 crews failed to obey the instruction to hold short at the intersection of 22R/4L and 27R/9L, corresponding to a 6% noncompliance rate. However, the more interesting results occurred on Taxiway Charlie. As Figure 8 shows, Charlie contains two stop bars, one to hold departures short of 22R/4L, the other to hold arrivals short of 27R/9L. Our crews were instructed to exit 22R/4L on Charlie and hold short of 27R/9L. Therefore, the Captain should have halted the aircraft at the second stop bar. However, in the Baseline condition four crews (25%) halted at the initial (incorrect) stop bar, leaving part of their aircraft hanging out over an active runway (22R/4L). None of the crews committed this error in the EMM or the EMM+HUD conditions.

5 GENERAL DISCUSSION

The issue motivating this article was quite general. How do airplane pilots interact with cockpit displays, particularly displays designed to reduce reliance on the OTW view? This issue is particularly germane to the taxi task because taxiing, unlike many other phases of flight, is still primarily an eyes-out activity. The change in processing needed to support the task in a closed cockpit would be considerable.

Over the past twenty years, aviation human factors research has made great strides, to the point where we have the knowledge to design human-centered display systems replete with features designed to maximize pilot performance. In principle, we can design taxi displays that even provide even more information than is available in the OTW in clear visibility. In the end, however, the pilot chooses how to interact with displays. Unless he or she interacts with them in a optimal manner, and in a manner anticipated by the designer, the full potential of the displays to improve behavior may not be realized.

Our research with the T-NASA system speaks directly to this issue. The T-NASA displays were designed to allow pilots to taxi rapidly and accurately in low-visibility conditions [2]. Thus, from the outset, the design of the system was guided by the need to replace information normally acquired from OTW with information on electronic displays. In two simulations, we gathered data on the effect of, and pilots' use of, these displays.

5.1 T-NASA Usage

The most basic issue answered in these simulations is whether pilots would actively process the displays at all. Our results certainly establish that they did, as evidenced by the substantial increases in forward speed associated with the T-NASA system, and the accompanying reduction in navigation errors. Additional evidence that pilots were willing to use the system came in the form of the substantial reduction in

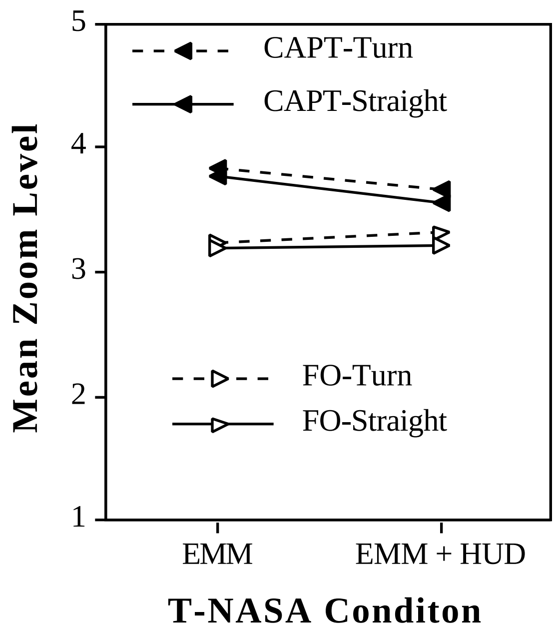

Figure 7. Mean Zoom Level as a function of crew role (Captain versus First Officer), Route Topography (Straight versus Turn), and T-NASA Condition. Note that higher zoom levels correspond to being zoomed in on the EMM.

planning time that accompanied the presence of the EMM and the HUD in the part-task simulation.

5.2 Optimization

A more subtle issue is how fully pilots exploited the functionality of the T-NASA system, using display features in a manner consistent with the their crew roles and the information requirements of the taxi task. Our results are quite encouraging in this respect. For example, First Officers are supposed to maintain a high level of global awareness, allowing the Captains to focus on the inner-loop control task. Consistent with this division of labor, the First Officers selected lower zoom levels than the Captains. For their part, the Captains selected lower zoom levels when the HUD was present than when it was absent. We suspect that when the EMM was the only available display, the Captains zoomed in to get some assistance with local guidance, as provided by the high resolution with which the area immediately around the aircraft is depicted. When the HUD was available to support local guidance, the EMM was no longer needed for this purpose. Accordingly, the Captains shifted back to using the EMM primarily for global awareness (which is, of course, the purpose for which the EMM was designed).

Another data pattern relevant to the optimization issue (as well as the issue of usage style; see below) is the interactions between T-NASA condition and route topography. Recall that the speed increase associated with the EMM+HUD combination was larger on straightaways than on turns. How might we account for this effect? Earlier, we noted a variety of look-ahead cues supplied by the scene-linked HUD symbols, such as the distance remaining along the straight section, and the severity and direction of the next turn. One straightforward possibility is that pilots exploited these cues to achieve a higher peak speed on the straightaways, followed by a smooth deceleration into the turn. It is important to note that the predictive cues that may have supported this performance are “emergent features” of the scene-linked symbology, and never explicitly pointed out to the participants. If these cues were exploited anyway, as the data suggest, we have a clear illustration that if useful functionality is built into an electronic display, pilots will utilize it.

The data also suggest a limit to this statement, however. Explicit route guidance was also available on the EMM, in the form of the prominent magenta route guidance. Thus, the EMM actually provided the same predictive information (i.e., distance remaining along the current straightaway, and the distance to and severity of the next turn), as the HUD. Why, then, were these cues not exploited in the EMM condition to maximize straightaway speed? One straightforward reason may be that the Captains’ preference for high zoom levels limited the availability of the cues (which require an extensive preview of the area in front of the aircraft) [3]. The lowest zoom level any Captain selected was Level 3. Alternatively, the fully-ego referenced nature of the HUD symbology may give it a more direct link to the motor processing system involved in inner-loop control, making the HUD cues easier to process. Additional research would be necessary to distinguish these possibilities.

5.3 Usage Style

The final usage issue that we explored was whether pilots interacted with the T-NASA system in an adaptive manner, adjusting their usage and information extraction strategies in response to dynamic changes in the environment. Again, our data indicate that they did. We have already discussed the evidence that the HUD predictive cues were used to maximize performance on straight sections of the routes. In addition, there was clear evidence in both simulations that the selection of zoom level was sensitive to route topography, with pilots preferring lower zoom levels on straightaways than on turns.

5.4 Performance Augmentation

Finally, our data speak directly to the issue of whether cockpit displays can be designed to improve on the natural performance levels supported by traditional cockpits. We have noted that the route-related

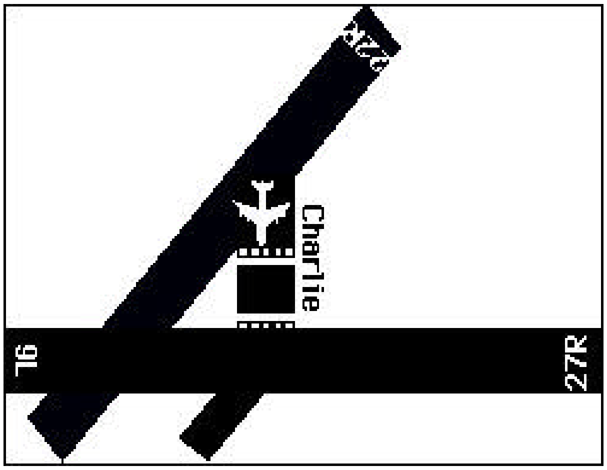

Figure 8. Idealized depiction of the Chicago-O'hare layout in the vicinity of Taxiway Charlie (not to scale). The ownship is shown holding short of the incorrect stop bar.

predictive cues on the HUD are not present in the regular OTW view, even in clear visibility. Thus, it is possible that even in clear daytime conditions, the HUD would produce a speed advantage on straightaways. On a less speculative note, by augmenting the natural scene with virtual stop signs, virtual hold bars, and flashing bars on the EMM, the T-NASA system was clearly able to achieve a higher level of compliance with hold short directives than in the baseline condition. Since pilots were able to clearly see the stop bars on the surface of the runways in our simulation, this advantage, too, is likely to extend to clear weather conditions. Furthermore, in post-experimental briefings, a number of pilots pointed out that the real-time depiction of other traffic on the EMM was the single greatest safety feature of the T-NASA system, and would be so even in clear visiblity. This, of course, is a straightforward reflection of the fact that much of the ground traffic in the vicinity of the ownship is not visible in the forward field of view.

5.5 Modifications for a closed cockpit

Despite the encouraging evidence regarding pilot interaction with the T-NASA system, the fact remains that T-NASA was not designed for a zero visibility environment (such as a closed cockpit). We are quite certain that modifications would have to be made to T-NASA in this environment. What might these modifications be?

One outstanding difficulty with the present system is that the HUD's limited field of view causes the scene-linked HUD symbology disappeared around sharp turns. In low visibility conditions, there are still enough cues in the forward field of view to complete the turn; however, this would not be the case in a zero visibility environment. One possibility would be to add a predictor in the form of a "noodle" extending in front of the aircraft. A second possibility would be to add additional scene-linked symbols, positioned so that they remain in view around turns Still a third possibility would be to include some form of non scene-linked symbology, such as a version of the command guidance symbology featured on today's Flight Dynamics HUD.

Even with the turn issue resolved, we suspect that limiting he scene-linked symbols to those that outline the cleared route might not be an optimal design for zero visibility. Some geographical context for the cleared route might be useful, perhaps by outlining all the taxiways in the HUD's field of view with scene-linked symbols. In future HUDs, the cleared route could still be highlighted perceptually by drawing the relevant scene-linked symbols in a different color from the rest.

Finally, a word is in order concerning efforts currently underway that would simply replace the OTW taxi view with a synthetic version of the view, generated from a database and displayed on a helmet-mounted display (12). While this approach has some obvious attractions for a closed cockpit, a fully ego-referenced image of the outside world would not support the same level of global awareness as T-NASA, nor would it provide the predictive cues of the HUD symbology. Thus, at a minimum, we would argue that as a primary display for ground taxi in a closed cockpit, a veridical synthetic image is not a complete solution.

6 REFERENCES

1. McCann, R. S., Foyle, D. C., Andre, A. D., & Battiste, V. (1996). Advanced navigation displays in the flight deck: Effects on ground taxi performance under low-visibility conditions. *SAE Transactions: Journal of Aerospace*, *105*, 1419-1430.

2. Foyle, D. C., Andre, A. D., McCann, R. S., Wenzel, E., Begault, D., & 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.

3. McCann, R. S., Andre, A. D., Begault, D., Foyle, D. C., & Wenzel, E. (1997). Enhancing taxi performance under low-visibility: Are moving maps enough? *Proceedings of the 41st annual meeting of the HFES, 37-41*. Santa Monica, CA: HFES.

4. 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*. 1998 World Aviation Congress CP #985541. SAE: Warrendale, PA.

5. Wickens, C. D., & Prevett, T. (1995). Exploring the dimensions of egocentricity in aircraft navigation displays. *Journal of Experimental Psychology: Applied*, *1*, 110-135.

6. Aretz, A. J. (1991). The design of electronic map displays. *Human Factors*, *33*, 85-101.

7. Battiste, V. (1993). Geographic orientation. In B. Huey and C. Wickens (Eds.), *Workload transition: Implications for individual and team performance* (pp. 171-190). Washington, DC: National Academy Press.

8. Mainwaring, S. D. (1991). *Information integration in cognitive maps: Conceptual analysis of dissertation data*. Unpublished manuscript.

9. Foyle, D. C., McCann, R. S., & Shelden, S. (1995). Attentional issues with superimposed symbology: Formats for scene-linked displays. In R. S. Jensen (Ed.), *Proceedings of the Eighth International Symposium on Aviation Psychology* (pp. 98-103). Columbus, OH: The Ohio State University.

10. Andre, A. D., & Hooey, B. L. (1998) The human factors of conducting flight research: Lessons learned from the evaluation of T-NASA. *Proceedings of HFES 42nd annual meeting*, 67-71. Santa Monica, CA: HFES.

11. Andre, A. D., Hooey, B. L., Foyle, D. C., & McCann, R. S. (1998). Field evaluation of T-NASA: Taxi Navigation and Situation Awareness System. *Proceedings of the AIAA/IEEE/SAE 17th Digital Avionics System Conference*, 47:1-47:8.

12. Redeiss, H. A. (1996). *"Airport visualization and operations system"*. Final Report, NASA SBIR NAS2-14334.