Paper to appear in proceedings of the NATO RTO SCI and SET Symposium on Enhanced and Synthetic Vision Systems. September, 10-12, 2002. Ottawa, Canada.

A HUMAN-CENTERED METHODOLOGY FOR THE DESIGN, EVALUATION, AND INTEGRATION OF COCKPIT DISPLAYS

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ABSTRACT

Researchers at NASA Ames Research Center have developed a suite of displays for low-visibility taxi operations for commercial aircraft. The Taxiway Navigation and Situation Awareness (T-NASA) system is comprised of a head-up display and head-down electronic moving map that collectively provide navigation and traffic surveillance information to the pilots. A three-stage process was defined and followed that included a human-centered design process, a human-factors evaluation approach, and a procedural integration analysis. It is expected that this human-centered process will help ensure the success of the T-NASA system. Further, this process may be modified and adapted for use with other enhanced vision / synthetic vision (EVSV) systems.

INTRODUCTION

Enhanced Vision and Synthetic Vision (EVSV) systems are being developed for commercial and military aircraft to enhance awareness of terrain and traffic, particularly in low-visibility conditions. For these technologies to be successful, research must be conducted to ensure that they adhere to human factors design principles, improve pilot performance, and do not create new problems or safety concerns for the pilot. Recently, a human factors process was developed to guide the development of synthetic vision displays for low-visibility surface operations. The process included three phases: 1) a human-centered design process, 2) multi-method, multi-dimensional evaluations, and 3) identification of potential integration issues. The human factors process was applied to a set of synthetic vision displays for low-visibility surface operations, called the Taxiway Navigation and Situation Awareness (T-NASA) system. By adhering to the three-stage process, T-NASA designers were able to develop a human-centered system that improved taxi efficiency, safety, workload, and situation awareness while identifying and addressing potential integration issues such as implications of traffic surveillance failures, HUD-induced complacency, mixed-equipped fleets, and pilot-ATC interactions. It is expected that this process will ensure the success of the T-NASA system once fielded and integrated into commercial aircraft cockpits. This process, as applied to the T-NASA system, is offered here as an example of a successful human factors methodology. It is believed that this process may easily be modified and adapted for other EVSV systems.

TAXIWAY NAVIGATION AND SITUATION AWARENESS (T-NASA) SYSTEM

Taxiing is a demanding and high-workload phase of flight (Kelly & Adam, 1997). Pilots rely largely on visual navigation aids on the airport surface in order to navigate their assigned taxi route. In low-visibility and night conditions, airport surface operations become less efficient as taxi speeds decrease and the likelihood of making a navigation error increases (Hooey & Foyle, 2001; McCann, Hooey, Parke, Foyle, Andre & Kanki, 1998). These and other factors translate into costly delays for airlines, inconveniences for passengers, and potential safety concerns such as runway incursions. In response to these airport surface efficiency and safety concerns, the Taxiway Navigation and

Situation Awareness (T-NASA; see Figure 1) system was designed. T-NASA is comprised of a head-up display (HUD) and head-down electronic moving map (EMM).

Figure 1. The Taxiway Navigation and Situation Awareness (T-NASA) displays: Head-Up Display (HUD) with scene-linked taxi symbology and Electronic Moving Map (EMM)

T-NASA Head-Up Display (HUD)

The HUD presents symbology on a combiner glass so that the information appears to be projected over the view of the world beyond the cockpit. In current-day commercial aircraft, HUDs are typically mounted in front of the left seat, for use by the Captain during take-off and landings. The T-NASA HUD taxi symbology (Figure 2) uses computer-generated, scene-linked symbology (Foyle, Ahumada, Larimer & Sweet, 1992) overlaid upon the airport surface to provide route guidance and navigation information. Using differential global positioning systems (DGPS) and on-board electronic airport databases, the HUD provides information about the ownship position relative to the taxiways and runways. The HUD symbology augments visual cues that are degraded in low visibility and provides information that the pilot normally utilizes during clear-visibility conditions. The scene-linked symbology appears to integrate perceptually with the actual out-the-window scene, thus providing intuitive, or ecological, cues to support taxi. Specifically, a series of virtual cones are located along both edges of the cleared taxiway, and a series of squares overlay the centerline of the taxiway to mark the cleared taxi route. The HUD also displays ground speed in the upper left corner, and a textual display intended to promote awareness of location on the airport surface in the upper right corner. Turns are denoted by virtual turn signs that indicate the angle of the turn. Directional flag poles are placed beyond the turn to provide a visual reference while completing a turn, as the side cones drop from the limited field of view inherent in the HUD. The HUD supports ATC-issued hold short commands by depicting a virtual hold bar which overlays the hold position on the taxiway and a virtual stop sign to further increase the salience of the hold short instruction. The HUD does not present traffic information in order to avoid clutter and obscuration of relevant out-the-window objects. Therefore, when necessary, traffic information is gathered by glances to the EMM.

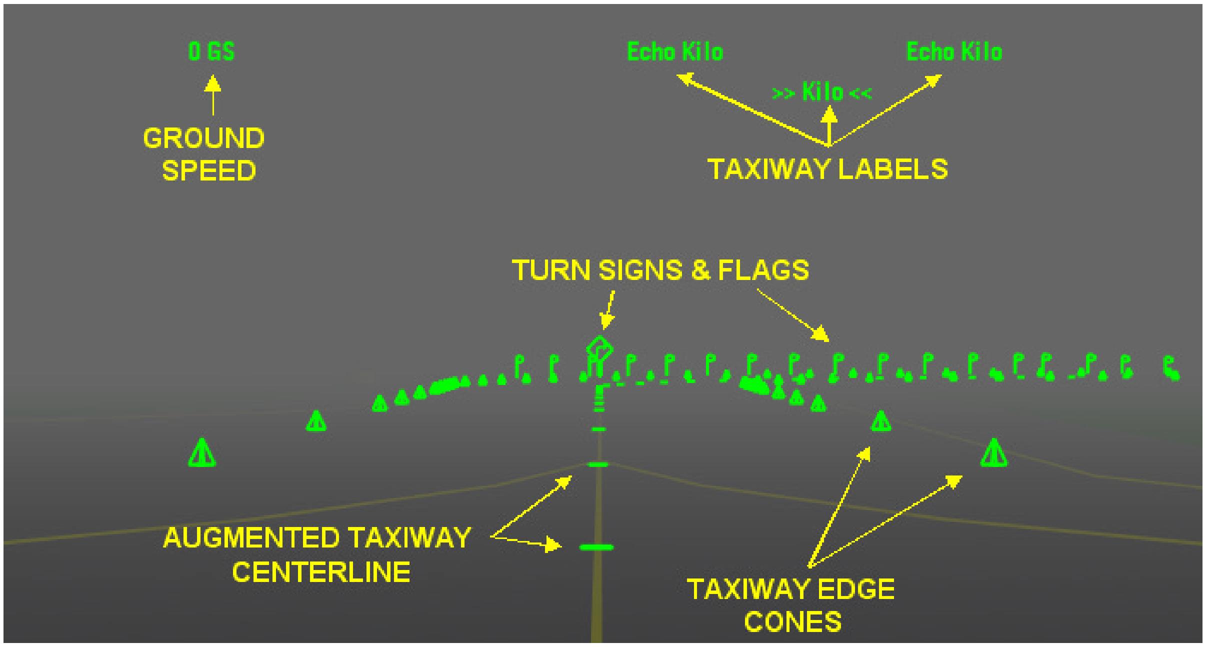

Figure 2. T-NASA Head-Up Display (HUD)

T-NASA Electronic Moving Map (EMM)

The EMM (Figure 3) provides both pilots of a two-crew cockpit with routing, guidance, and surveillance information in a head-down moving map format. Like the HUD, the EMM also uses DGPS and electronic databases of the airport surface to depict ownship position relative to the airport surface. Ground-based surveillance (such as ASDE-3 RADAR and Airport Movement Area Safety System, AMASS) provide data required to depict airport traffic on the EMM.

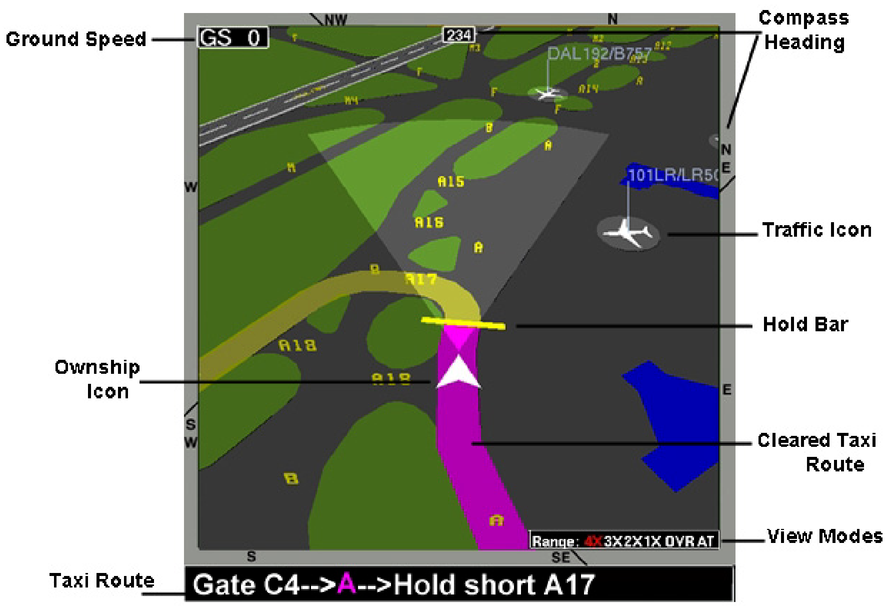

Figure 3. T-NASA Electronic Moving Map (EMM; showing track-up perspective view)

The EMM is available while airborne upon pilot demand and presents a runway-up view of the airport surface and runway occupancy bars which highlight occupied runways. Immediately upon touchdown, the navigation display automatically switches to the EMM in a track-up perspective view (from above and behind the ownship aircraft). The EMM depicts the ownship position relative to the airport surface. Routing and guidance information is presented via a thick magenta strip that highlights the cleared taxi route. The map also supports hold short directives by depicting a yellow flashing hold bar for both ownship and traffic. Also, the cleared route beyond the hold bar is shown in yellow. Real-time traffic icons depict traffic located on the airport surface. A three-stage color-coding scheme is implemented that indicates potential traffic incursion threats. The map has four zoom levels in the track-up perspective mode, a north-up overview mode for planning, and a taxi Automatic Terminal Information Service (ATIS) mode, which each pilot can independently adjust to his/her own preference.

HUMAN-CENTERED DESIGN PROCESS

A human-centered design process was developed (see Figure 4 below) which culminated in a design philosophy that was used to guide the design of the T-NASA system (Foyle, Andre, McCann, Wenzel, Begault & Battiste, 1996).

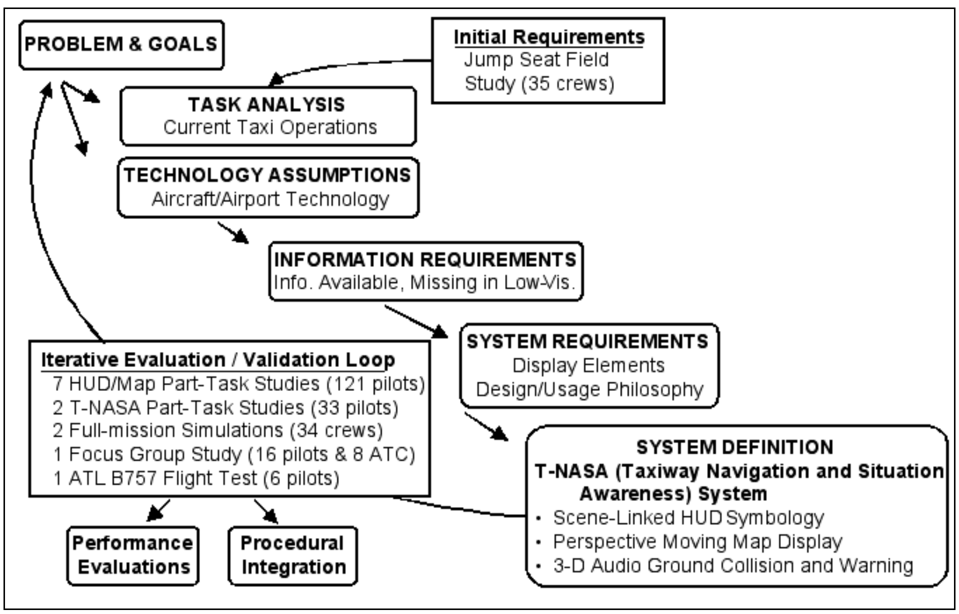

Figure 4. T-NASA Human-Centered Design Process

The process began with a clear statement of the goal of the display system. Specifically, the goal was to improve taxi efficiency and safety in low-visibility operations (CAT IIIB, but not zero visibility) by providing cockpit displays in commercial transport aircraft with two-person crews. A task analysis was conducted by observing two-person commercial transport crews in both clear and low visibility to develop an understanding of the taxi task (Andre, 1995). In parallel, technology that was available or expected to be available upon implementation of the system was defined in order to identify constraints and limitations. Subsequently, the precise nature of the information that pilots require for successful taxi operations was identified (see Lasswell & Wickens, 1995; McCann, Foyle, Hooey & Andre, 1999). Armed with a full understanding of taxi operations and the specific information requirements, a set of desired system characteristics and a design philosophy were developed (Foyle et al, 1996). First, it was determined that local guidance and local route-following cues should be provided in a way that would allow pilots to capitalize on their experience and remain eyes-out while taxiing. In essence, this meant a conformal, ecological display that reinstates visual cues so pilots can use the same local guidance cues (i.e., centerline and taxiway edges) in low visibility as they do in clear weather. Second, it was determined that global awareness should be provided by depicting both global navigation and traffic awareness on a 360-deg representation of the airport surface. This information was used to develop a set of system requirements and a formalized design philosophy that guided all design decisions. Specifically, given these two divergent goals, and the very different display requirements inherent in each, it was determined that T-NASA would be comprised of two complementary displays: a conformal, ecological head-up display (HUD) that constantly supports the local control task, and a head-down electronic moving map (EMM) display requiring only occasional, short glances to maintain global awareness but not intended for steering control or centerline tracking.

The design philosophy determined not only the information that should be presented, but also the information that should NOT be presented. A clear example can be seen in the design of the EMM. As determined in the design philosophy, the map was not intended for primary control of the aircraft. As such, the ownship icon purposefully does not depict wing span or the location of the aircraft gear. Routing and guidance information is presented via a thick magenta strip that highlights the cleared taxi route. Again, the magenta strip does not depict centerline information to encourage the use of the EMM as a secondary display for general navigational awareness information only, and not primary control of the aircraft. Developing and adhering to a design philosophy helped ensure that T-NASA did not succumb to feature creep , a common tendency to add components to the display based on subjective comments of test users or subject matter experts.

The human-centered design process led to the development of the T-NASA prototype suite of displays shown in Figure 1. The design philosophy determined the information and functions that would be supported by the T-NASA displays. Subsequently, the format and interface design of the displays was determined using an iterative process incorporating both existing literature of similar systems and T-NASA-specific human-in-the-loop research.

MULTI-METHOD, MULTI-DIMENSIONAL EVALUATIONS

The T-NASA system underwent a system evaluation process in which over 300 pilots participated in focus groups, part-task simulations, full-mission simulations, and operational flight tests. These studies led to iterations on the design of the T-NASA system and provided an estimation of the benefits (and limitations) of T-NASA both in simulation and actual-use environments. To accomplish this, a variety of research methodologies and evaluation dimensions were used. It is important to note that the emphasis of these evaluations was on human performance and interaction with the displays. In parallel to the research efforts presented here, evaluations of technology performance (such as system latency, update rate, integrity, and accuracy) were also conducted (for more information on these evaluations, see Jones & Young, 1998; Young, 1998).

EVALUATION METHODS

Several research methods were employed including part-task simulations, full-mission simulation, and flight test. Each method possesses unique advantages and disadvantages, as reviewed below.

Part-Task Simulations - Part-task simulations vary from desk-top simulators to low- and medium-fidelity mock-ups of a cockpit with simplified aircraft controls and displays. Most of the T-NASA part-task studies were conducted in a fixed-based, single-crew, part-task taxi simulator, with a single front screen measuring 2.43 m wide by 1.83 m high, providing approximately 53 deg of horizontal visual angle. Two visual databases (Chicago O’Hare and Dallas Fort Worth airport) are available, each with accurate signage, paint, and markings on the airport surface. The simulator offers the capability to present clear-day, low-visibility and night conditions as well as the depiction of other aircraft and ground vehicles. Limited ATC communications (i.e., taxi clearance delivery) are available via microphone and headset. Scenario generation software was developed to control the movement of other traffic on the airport surface.

This test environment allowed experimenters to manipulate display, environment, and simulation conditions that were critical to derive data upon which to base design decisions. Given the relative low costs of this simulation compared to other evaluation methods, many scenarios and display design options could be tested with minimal integration efforts — many more that would have been feasible in either full-mission simulation or flight tests.

Full-Mission Simulations - NASA Ames Advanced Concept Flight Simulator (ACFS) is a two-crew cockpit, similar to a Boeing 767, that offers a full six degree of freedom motion, 180 degree cross-cockpit viewing, and high-fidelity visuals of Chicago O'Hare airport including airport lighting, signage and markings. Compared to the part-task simulator, the ACFS offers greater visual and physical fidelity, and the ability to evaluate interactions within a two-crew cockpit. The ACFS is also connected with an ATC simulation laboratory that provided real-time ATC controller interactions and pseudo-pilots who emulated the communications between other aircraft on the airport surface and ATC. Scenario generation software was developed to control the movement of traffic, orchestrate ATC and pseudo-pilot agent roles, and control the transmission of navigation and route information on the T-NASA displays.

The full-mission simulation environment also allowed for control of experimental conditions, but at the same time increased operational realism over and beyond the part-task simulation, particularly by enhancing the realism of the cockpit procedural operations, ATC interactions, and traffic interactions. Perhaps most importantly, the full-mission simulation allowed for controlled, scripted, off-nominal events that either occur infrequently or are unsafe to test in a real-world environment. Events such as near incursions could be inserted into the simulation in a manner that allowed for complete repeatability across trials. These types of events may be experienced in flight tests, either by design or circumstance, but often are not repeatable across pilots or test sessions.

Operational Flight Tests - Flight tests were conducted at Atlanta Hartsfield International Airport during normal (evening) operations. The T-NASA HUD and EMM were integrated into NASA s Boeing 757 aircraft. Commercial pilots participated as test subjects and NASA test-pilots served as first-officers and safety pilots. Pilots communicated with actual ATC at the airport, who provided verbal taxi clearances to the pilots which were simultaneously converted to route depictions on the T-NASA HUD and EMM using voice recognition software. Pilots completed arrival and departure taxi operations with and without the T-NASA displays.

The main purpose of the flight tests was not to answer specific research questions, but rather to determine if the technology could be successfully utilized in the actual context for which it is intended and to learn about the potential usability and integration problems. From this flight test, it was clear that operational conditions vary markedly from normative procedures, and also vary by time of day (traffic flow), controller, and other dynamic circumstances on the airport surface. The flight test was a valuable test to evaluate the robustness of the T-NASA system.

EVALUATION DIMENSIONS

In a parallel, iterative manner, part-task studies, full-mission simulations and a flight test were conducted to evaluate the T-NASA system. A thorough evaluation of the T-NASA system required assessment of several performance dimensions. The evaluation dimensions included:

display design elements, taxi performance, user acceptance, crew roles and procedures, and system robustness.

Display Design Elements

A human-centered design process was used to determine the functionality of the system and the information that should be displayed. However, there are several ways in which any given function or piece of information could be depicted on the HUD and/or EMM. Thus, empirical evaluations were conducted in NASA s part-task taxi simulator to drive display design decisions. A complete list of these studies is presented in Table 1. Successful display elements were then incorporated into the T-NASA design, and included in subsequent full-mission simulations and/or the flight test. As the design and evaluation process was iterative, the full-mission simulations and flight-tests also provided opportunities in which problems with the displays were identified, either by test subjects or experimenters. These elements were then modified and investigated in the controlled part-task simulation environment.

Table 1. Summary of T-NASA Display Element Evaluations

Display	Research Method	Specific Research Issues	Reference
EMM	Part-task	North-up vs. track up Route guidance	Mejdal & Andre (1995)
EMM	Part-task	2D vs. 3D formats Route guidance Heading indicator Icon scaling	Tu & Andre (1996)
EMM	Part-task	Traffic coding Overview inset Clearance text Map size	Andre & Graeber (1997)
EMM	Part-task	Visual allocation Route and hold bar Heading bars EMM training	Graeber & Andre (1999)
HUD	Part-task	Turn symbology formats	Atkins, Foyle, Hooey & McCann (1999)
EMM	Part-task	Visual & auditory call-outs Visual scan patterns	Purcell & Andre (2001)
HUD	Part-task	Situation awareness Cognitive capture	Foyle, Hooey, Wilson & Johnson (2002)

Taxi Performance

After the development and initial validation of the T-NASA prototype displays, and still early in the evaluation cycle, several evaluations were conducted to assess taxi performance with the T-NASA system. The primary goal of these studies was to ensure that the T-NASA technologies would meet the intended goal of increasing both the efficiency and safety of surface operations. Multiple research methods were utilized to assess the system benefits including part-task simulations, full-mission simulations, and the flight tests. Each of these studies, employed several measures to assess both efficiency and safety (see Table 2).

Table 2. Summary of Taxi Performance Evaluation

Research Method	Reference
Part-task	McCann, Foyle, Andre, Battiste (1996)
Part-task	McCann, Andre, Begault, Foyle, Wenzel (1997)
Flight-Test	Andre, Hooey, Foyle & McCann (1998)
Full-Mission	McCann, Hooey, Parke, Foyle, Andre & Kanki (1998)
Full-Mission	Hooey, Foyle, Andre & Parke (2000)

Performance Dimension	Performance Measures
Taxi Efficiency	Taxi speed Total taxi time Time and number of stops Route planning time Runway occupancy time
Safety	Navigation errors Hold short conformance Incursion detection Head-down time
Workload	Subjective ratings (NASA TLX)
Situation Awareness (SA)	Subjective ratings Objective SA probes

All studies showed that T-NASA increased taxi speed by approximately 16%, and eliminated navigation errors (compared to an error rate of about 17% without T-NASA) and hold short errors (compared to an error rate of about 25% without T-NASA). Also, it was important to assess pilots workload and situation awareness with the T-NASA system as they serve as indirect measures of performance. Workload was rated lower by the pilots when taxiing with T-NASA than without it. This lowered workload may have contributed to pilots ability to taxi faster and minimize time stopped on the airport surface. Situation awareness, as assessed by subjective pilot ratings and objective situation awareness probes, was increased with the T-NASA system. Increased situation awareness likely contributed to the elimination of navigation errors, and increased detection of incursions.

User Acceptance

The above objective measures of performance were important to demonstrate that the system can achieve its intended goals. However, user acceptance of the system is another facet of evaluation that must not be overlooked. A system that increases performance in simulation tests, but does not meet pilots approval will ultimately fail once fielded. There are many examples of systems that are either ignored, or turned off altogether by the pilots (i.e., early versions of Traffic Alert and Collision Avoidance System; TCAS, and Ground Proximity Warning System; GPWS), because they are considered by the users to be annoying or even unsafe (Wickens, Mavor & McGee, 1997). Early versions of both TCAS and GPWS emitted too many false alarms and this ultimately reduced pilots trust in the system. Another factor that may limit user acceptance is perceived workload (Riley, 1996), particularly transient spikes in workload levels. A good example is seen in the use of the Flight Management System (FMS) which in general reduces workload, except when it must be reprogrammed at a time-critical phase, such as is required because of a runway change during final approach (Wickens, Mavor & McGee, 1997).

Analyses of user acceptance of the T- NASA system were conducted after each study (see list of studies in Table 2 above) and included subjective ratings of workload, situation awareness, trust in the system, confidence while using the system, as well as ratings of utility and ease of use. Across all studies, there is strong evidence that pilots value the efficiency and safety benefits of the T-NASA system and there is minimal risk of failure of acceptance if implemented in the manner tested.

Crew Roles and Procedures

The human-centered evaluation process does not end with a well-designed interface, nor is it sufficient to demonstrate the anticipated safety and efficiency benefits. While both are important, it is also necessary to address how pilots use the system, and how it changes the nature of their task. Crew roles and procedures were explored in full-mission simulation with and without the T-NASA system (Parke, Kanki, McCann & Hooey, 1999; Parke, Kanki, Munro, Patankar, Renfroe, Hooey & Foyle, 2001). Post-hoc videotape analyses were conducted to explore changes in the quality and quantity of communications between captain and first officer, and between pilots and ATC. Also, real-time assessments of tasks, roles, and responsibilities were conducted by a trained airline captain, who viewed the experimental trials from the simulator cockpit. T-NASA effectively enhanced crew communication and minimized uncertainty and confusion between crew members and ATC. These observational analysis techniques supplemented the objective performance data and subjective ratings and provided a richer picture of the impact of the T-NASA displays on crew operations.

Robustness

For T-NASA to be successfully fielded, it must withstand a wide range of operating conditions. As such, T-NASA was subjected to robustness testing that included evaluating performance (using metrics identified in Table 2) under a variety of visibility conditions, dynamic taxi operations, and current-day and potential future national airspace operations. A summary of the conditions that were tested in full-mission simulation (McCann et al., 1998; Hooey, Foyle, Andre & Parke, 2000) and flight tests (Andre, Hooey, Foyle & McCann, 1998) are provided in Table 3 below.

Table 3. Summary of Robustness Testing Conditions

Robustness Considerations	Conditions Tested
Visibility Conditions	Day Visual Meteorological Conditions (VMC) Instrument Meteorological Conditions (IMC; 0 to 1000 ft) Night Visual Meteorological Conditions (VMC)
Dynamic Taxi Conditions	Hold short Land and hold short operations (LAHSO) Route amendments Runway crossings Missed runway turnoff Taxi clearance styles (traffic sequences, taxiway names, cardinal heading)
National Airspace Operations	ATC voice-issued taxi clearances and amendments Datalink-issued taxi clearances and amendments Airborne taxi clearances

The full-mission simulations allowed for manipulation of variables that were not possible in the operational flight tests - in particular visibility and future national airspace operations (such as airborne taxi clearances). The flight tests, on the other hand, allowed for examination of T-NASA under actual operational conditions. Several examples of deviations from normative operating procedures were identified during the flight tests. For example, in actual operations, ATC used a variety of taxi clearance methods that deviated from the normative phraseology of Taxi to Concourse C, via taxiway Alpha, Bravo, Charlie . Instead, clearances were issued to follow traffic sequences (i.e., Follow company to gate) or to taxi using cardinal headings (i.e., Continue taxiing north on Alpha until further notice). Also, problems that exist at operational airports, such as radio frequency congestion and radio communications being stepped-on by other pilots sharing the radio frequency, were revealed in the flight test, but not the simulation environment.

As a result of the robustness testing, several design changes and enhancements were made to the EMM and the HUD. The EMM, for example, was modified to include cardinal heading bars and traffic labels to accommodate the range of taxi clearance styles issued in the operational setting. The HUD was modified to include hold bars and preview of the cleared route beyond the hold to accommodate the multiple and sometimes lengthy hold instructions. Further, when Atlanta ATC instructed pilots to hold their position while mid-turn, it was revealed that the HUD turn symbology was not sufficient to support the pilots task of continuing through the turn after receiving instructions to proceed. In this example, the flight test revealed an operational condition that occurs on a daily basis, but that was not discovered in the simulation studies. This observation resulted in the redesign and empirical evaluation of a new turn symbology format (see Atkins, Foyle, Hooey & McCann, 1999) which was subsequently incorporated into the HUD design. Ensuring that T-NASA will enhance performance in all visibility conditions, as well as accommodate the dynamic taxi conditions of current-day and potential future national airspace operations, was important to ensure the robustness, and therefore acceptance of the T-NASA system once fielded.

In summary, each of the research methods possesses unique characteristics, advantages, and disadvantages. The research team was able to select the best method to answer the research questions of interest. In general, the medium-fidelity, part-task simulator was most effective to answer display design research questions. Higher fidelity, full-mission simulations were required to examine crew interactions and crew-ATC interactions with higher degrees of realism. The operational field-tests provided an opportunity for validation and proof of technology of the T-NASA system, but was less effective for answering specific research questions.

PROCEDURAL INTEGRATION ISSUES

In addition to the evaluation process described above, empirical and analytical research efforts were conducted to investigate the procedural integration of the T-NASA system. (A parallel effort was also conducted to explore physical integration and retrofit issues; see Cotton, Schwirzke, Hennessy & Johnson, 1999). The goal of this procedural integration effort was to identify potential problems that could occur with the introduction of the T-NASA technology and identify solutions to mitigate their effects, and maximize the probability of successful integration of the T-NASA system.

To identify potential integration issues, nine focus group sessions were conducted with two to four participants in each session (Hooey et al., 1999). Sixteen airline pilots from six different airlines, and eight experienced air traffic controllers participated in the sessions. Following an introduction and training period, the focus group moderator, a retired airline captain, led the group through scenario-based discussions. Participants were asked to consider how the introduction of T-NASA would alter taxi procedures. The focus groups raised a large number of issues. In order to achieve a better understanding of the consensus of the issues, a summary of the focus group issues was compiled and distributed to participants in the form of a questionnaire. Participants were asked to rate their level of agreement with each issue (on a five-point Likert scale) as well as the degree of criticality of each issue (on a three-point scale).

Four of the issues, summarized in Table 4 and described below, were perceived to be potentially serious problems that could limit the success of T-NASA, and received high ratings for both criticality and agreement from the focus group participants. These issues were subsequently examined in full-mission simulation (Hooey, Foyle & Andre, 2000), by incorporating off-nominal events into the experimental design that simulated the potential problems identified by the focus group participants. The controlled, yet realistic environment of the full-mission simulation proved to be an excellent testing ground for these issues. These anomalies are often difficult to implement in flight tests, and often are not repeatable due to changes in environmental conditions and operational requirements.

Table 4. T-NASA Integration Issues

Focus Group Issue	Simulation Scenario
EMM / Surveillance Failure	Near-incursion with incurring traffic not depicted on EMM
HUD Induced Complacency	HUD depicted incorrect route
Mixed-equipped Fleets	Redundant voice and T-NASA clearances vs. T-NASA alone
ATC-Pilot Interactions	ATC taxi clearance error

EMM / Traffic Surveillance Failure - Focus group participants were concerned that if the EMM failed to depict an aircraft on the airport surface, perhaps due to a failure of traffic surveillance equipment, there could be severe safety consequences. To address this issue, a near-incursion was inserted into a full-mission simulation to assess the degree to which the EMM guided pilots visual attention to the out-the-window environment and the resulting effect on situational awareness when the EMM traffic surveillance information fails. Crew responses to a near-incursion when all but the intruding aircraft appeared on the EMM was compared to when crews had no EMM. The braking response time data revealed that pilots were slower to detect and respond to the incurring aircraft when they had T-NASA, but the aircraft failed to appear on the EMM, than if they didn t have T-NASA at all (see Hooey, Foyle & Andre, 2000). This result pointed to the need for interface modifications that depict radar or sensor uncertainty, crew training requirements to calibrate crew to the accuracy and reliability of the technology, and EMM usage procedures to ensure effective scan patterns that include both the out-the-window scene and the EMM.

HUD Induced Complacency - Participants were concerned that a single-HUD available only to the captain, and not viewable by the first officer, could limit cross-checking abilities and crew communication. This could cause the captain to complacently follow the HUD and the first officer to be out-of-the-loop . In a full-mission simulation (Hooey, Foyle & Andre, 2000), a HUD route error was inserted into the final scenario to assess the degree to which the HUD minimized cross-checking and communication. Results revealed that 39% of the eighteen crews avoided the error all together. This was attributed to their effective crew-coordination and communication procedures in which the First Officer used the EMM to call out up-coming turn and navigation information to the Captain on an on-going basis. Another 28% of the crews were able to use the EMM as a cross-check during navigation to detect the error immediately and recover quickly. The final 33% of the crews exhibited less effective cross-checking and communication procedures resulting in the Captain erroneously following the HUD symbology to the incorrect gate. By observing crews that successfully detected and responded to the HUD error, recommendations for effective crew procedures and communications were developed.

Mixed-Equipped Fleets - Focus group participants also raised concerns about the near-term integration of T-NASA. Specifically, they were concerned that some aircraft may have T-NASA and some might not, and the subsequent effect on pilots who rely on the party-line radio communications to gather situation awareness of traffic on the airport surface. Pilots suggested that to ensure safety in the near-term, all ATC-Pilot communications would need to be issued by voice, even if they are also communicated by datalink, and on the T-NASA displays. This integration strategy was implemented in a full-mission simulation and compared to both current-day operations, and potential far-term operations in which all aircraft were equipped with datalink and T-NASA (Hooey, Foyle, Andre & Parke, 2000). The study revealed that in the far-term implementation approach, T-NASA would provide efficiency benefits above and beyond increased taxi speed and reduced time stopped on the airport surface. The far-term approach also allowed for reduced radio transmissions and congestion, and improved efficiency of the initial taxi clearance and communication of mid-route taxi instructions. However, these additional efficiency benefits were not realized during the near-term integration stage due to the required redundancy of voice communications and T-NASA clearances. Based on these and other results, suggestions for near-term and far-term integration of surface operations displays and technologies were developed (see Hooey, Foyle, Andre & Parke, 2000; Parke, Kanki, Munro, Patankar, Renfroe, Hooey & Foyle, 2001).

ATC-Pilot Interactions - Focus group pilots expressed concerns about integrating the T-NASA displays into their taxi procedures, specifically while interacting with ATC. Concerns were raised about issues of authority, information availability, and new requirements to cross-check ATC clearance information with the T-NASA displays. To assess these issues, an intentional ATC clearance error was inserted in a full-mission simulation scenario (i.e., ATC cleared pilots to Taxi to Concourse Alpha via taxiway Charlie, Bravo, Foxtrot, Concourse Lima). The pilots ability to detect that the final concourse in the clearance (Concourse Lima) did not match their actual destination concourse (Alpha) was assessed both with and without T-NASA. Results revealed that the ATC error was not better detected with T-NASA, even though the clearance was presented by voice, as well as textually and graphically on the EMM (see Hooey, Foyle & Andre, 2000). It was concluded that pilots were not effectively integrating the technologies into their standard operating procedures for taxi clearance communications, and therefore were not realizing all of the potential benefits offered by T-NASA. The need for developing clearance cross-checking procedures using the T-NASA technologies was identified.

In summary, the insertion of any technology or automation into the cockpit has the potential to introduce new or unanticipated problems. Problems can arise from unanticipated interactions between technology, the operator, and the environment. Often these are not problems inherent to the technologies themselves, but due to interactions within the larger, complex and distributed system (Woods, 1993). A system that is tested in relative isolation in the laboratory may fail once fielded because important interactions and procedural integration issues were overlooked or ignored. Therefore it was important to anticipate the potential problems that may be introduced along with T-NASA and determine solutions such as design modifications, training requirements, and standard operating procedures, to ensure successful integration once fielded to the operational environment.

CONCLUSION

A three-stage human factors design, evaluation, and integration process was used in the development of the Taxiway Navigation and Situation Awareness (T-NASA) system. The human-centered design process began with an assessment of the pilots' task and environment, the constraints and limitations imposed by technology, and the information required by pilots for successful taxi in low-visibility conditions. A set of system requirements and a design philosophy was developed that was strictly adhered to throughout the design process. The prototype displays were then subject to a human-factors evaluation process that included over 300 pilots who participated in part-task studies, full-mission simulations, and flight tests. It is clear that no single evaluation methodology would have been sufficient to fully evaluate the T-NASA displays system. Further, a multitude of measures and metrics were used to evaluate the T-NASA system. The combination of objective, subjective, and observational data measures was useful to provide a rich data set from which to draw conclusions and inferences about the T-NASA system. Finally, potential procedural integration issues and problems were identified by subject matter experts in focus group discussions. These were subsequently examined in a full-mission simulation study using off-nominal events that simulated potential system failures and human errors. These analyses identified required display modifications, and contributed to the development of training requirements and standard operating procedures to ensure effective integration of the technologies into the cockpit and the national aviation system.

The result of this three-phased process is a human-centered display that has been shown to meet the intended goal of increased taxi efficiency and safety during low-visibility taxi operations without introducing excessive demands or new problems into the cockpit. In summary, it is hoped that lessons learned from the T-NASA development process may prove useful for the design and evaluation of other enhanced and synthetic visions systems — all of which will need to demonstrate good design principles, enhanced performance, and effective integration strategies to ensure their success and acceptance.

REFERENCES

Andre, A. D. (1995). Information requirements for low-visibility taxi operations: What pilots say. In R. S. Jensen and L. A. Rakovan (Eds.), *Proceedings of the Eighth International Symposium on Aviation Psychology*, 484-488. Columbus, OH: The Ohio State University.

Andre, A. D., Hooey, B. L., Foyle, D. C. & McCann, R. S. (1998). Field evaluation of T-NASA: Taxiway navigation and situation awareness system.˚ *Proceedings of the AIAA/IEEE/SAE 17th Digital Avionics System Conference*, 47:1 - 47:8, Seattle: WA.

Andre, A. D. & Graeber, D. A. (1997). Unpublished manuscript.

Atkins, M. L., Foyle, D. C., Hooey, B. L. & McCann, R. S. (1999). Head-up display symbology for surface operations: Comparisons among scene-linked symbology sets for optimum turn navigation. In R. S. Jensen, B. Cox, J. D. Callister & R. Lavis (Eds.), *Proceedings of the Tenth Symposium on Aviation Psychology*, 784-790. Columbus, OH: The Ohio State University.

Cotton, J., Schwirzke, M. F. J., Hennessy, R. T. & Johnson, W. A. (1999). *Issues in the Physical Integration of Terminal Area Productivity (TAP) System and Displays into Commercial Aircraft.* (Technical Report MTI 99-940506-36-2).

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

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

Foyle, D. C., Hooey, B. L., Wilson, J. R. & Johnson. W. A. (2002). HUD Symbology for Surface Operations: Command Guidance vs. Situation Guidance Formats. *To appear in Proceedings of SAE World Aviation Congress (Paper Number 2002-01-3006),* Phoenix, AZ.

Graeber, D. A. & Andre, A. D. (1999). Assessing visual attention of pilots while using electronic moving maps for taxiing. In R. S. Jensen, B. Cox, J. D. Callister & R. Lavis (Eds.), *Proceedings of the Tenth Internationa Symposium on Aviation Psychology*, 791-796. Columbus, OH: The Ohio State University.

Hooey, B. L. & Foyle, D. C. (2001). A post-hoc analysis of navigation errors during surface operations: Identification of contributing factors and mitigating solutions. *Proceedings of the Eleventh International Symposium on Aviation Psychology*. Columbus, OH: The Ohio State University.

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

Hooey, B. L., Foyle, D. C., Andre, A. D. & Parke, B. (2000). Integrating datalink and cockpit display technologies into current and future taxi operations. *Proceedings of the AIAA/IEEE/SAE 19th Digital Avionics System Conference*, *7.D.2-1 - 7.D.2-8*. Philadelphia, PA.

Hooey, B. L., Schwirzke, M. F. J., McCauley, M. E., Renfroe, D., Purcell, K. & Andre, A. D. (1999). Issues in the procedural implementation of low-visibility landing and surface operation displays. In R. S. Jensen, B. Cox, J. D. Callister & R. Lavis (Eds.), *Proceedings of the Tenth International Symposium on Aviation Psychology*, 797 - 803. Columbus, Ohio: Ohio State University.

Jones, D. R. & Young, S. D. (1998). Airport surface movement technologies - Atlanta demonstration overview. *Proceedings of the AIAA/IEEE/SAE 17th Digital Avionics System Conference.* Seattle, WA.

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

Lasswell, J. W. & Wickens, C. D. (1995). *The effects of display location and dimensionality on taxi-way navigation* (Tech. Report ARL-95-5/NASA-95-2). Savoy, IL: University of Illinois Aviation Research Laboratory.

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 Human Factors and Ergonomics Society*, 37-41. Santa Monica, CA: Human Factors and Ergonomics Society.

McCann, R. S. & Foyle, D. C. (1995). Scene-linked symbology to improve situation awareness. *AGARD Conference Proceedings, No. 555, Aerospace Medical Panel Conference on Situation Awareness*, 16:1 - 16:11.

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.

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.

McCann, R., Foyle, D. C., Hooey, B. L. & Andre, A. D. (1999). Pilot Interactions with an Electronic Display Suite to Support Low-Visibility Taxi. In *Countering the Directed Energy Threat: Are Closed Cockpits the Ultimate Answer? 3rd Symposium of the Human Factors & Medicine Panel*. RTA:NATO, 17:1-17:13.

Mejdal, S. & Andre, A. D. (1996). An evaluation of electronic map display features for aircraft ground navigation. *Proceedings of the Silicon Valley Ergonomics Conference and Exposition*, 43-52. San Jose, CA: Silicon Valley Ergonomics Institute.

Parke, B., Kanki, B., McCann, R. S. & Hooey, B. L. (1999). The effects of advanced navigation aids on crew roles and communication in ground taxi. In R. S. Jensen, B. Cox, J. D. Callister & R. Lavis (Eds.), *Proceedings of the Tenth Symposium on Aviation Psychology,* 804-809. Columbus, Ohio: Ohio State University.

Parke, B., Kanki, B. G., Munro, P. A., Patankar, K., Renfroe, D. F., Hooey, B. L. & Foyle, D. C. (2001). The effects of advanced navigation aids and different ATC environments on task-management and communication in low visibility landing and taxi. In *Proceedings of the 11th International Symposium on Aviation Psychology*, Columbus, OH: Ohio State University

Purcell, K. P. & Andre, A. D. (2001). The influence of callouts on pilot visual attention to an electronic moving map. In R. S. Jensen, L. Chang & K. Singleton (Eds.), Proceedings of the Eleventh International Symposium on Aviation Psychology. Columbus, Ohio: Ohio State University.

Riley, V. (1996). Operator reliance on automation: Theory and data. In R. Parasuraman and M. Mouloua (Eds.) Automation and human performance: Theory and applications. Hillsdale, N.J.: Erlbaum.

Tu, D. S. & Andre, A. D. (1996). Integration of navigational information for aircraft ground navigation, In *Proceedings of the Silicon Valley Ergonomics Conference and Exposition*, 218-221. San Jose, CA: Silicon Valley Ergonomics Institute.

Wickens, C. D., Mavor, A. S. & McGee, J. P. (Eds.). (1997). *Flight to the Future: Human factors in Air Traffic Control*. Washington D.C.: National Academy Press.

Woods, D. D. (1993). The price of flexibility in intelligent interfaces. *Knowledge-Based Systems*, 6:1-8.

Young, S. D. (1998). Comparison of A-SMGCS requirements with observed performance of an integrated airport CNS System. *Proceedings of the AIAA/IEEE/SAE 17th Digital Avionics System Conference*, Seattle: WA.

ACKNOWLEDGEMENTS

The development of the T-NASA prototype displays was funded by NASA's Terminal Area Productivity program and funding for this paper was provided by the Airspace Operations Systems (AOS) Project of NASA's Airspace Systems Program. The T-NASA displays have since been successfully transferred to NASA s Aviation Safety Program and transfer to industry partners is in progress.

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