1997

The integration of navigational information for a simulated aircraft taxi task

David Scott Tu
San Jose State University

Follow this and additional works at: https://scholarworks.sjsu.edu/etd_theses

Recommended Citation

Tu, David Scott, "The integration of navigational information for a simulated aircraft taxi task" (1997). *Master's Theses*. 1607.
DOI: <https://doi.org/10.31979/etd.728e-92e7>
https://scholarworks.sjsu.edu/etd_theses/1607

This Thesis is brought to you for free and open access by the Master's Theses and Graduate Research at SJSU ScholarWorks. It has been accepted for inclusion in Master's Theses by an authorized administrator of SJSU ScholarWorks. For more information, please contact scholarworks@sjsu.edu.

INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps. Each original is also photographed in one exposure and is included in reduced form at the back of the book.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6" x 9" black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.

UMI

A Bell & Howell Information Company
300 North Zeeb Road, Ann Arbor MI 48106-1346 USA
313/761-4700 800/521-0600

**THE INTEGRATION OF
NAVIGATIONAL INFORMATION
FOR A SIMULATED AIRCRAFT TAXI TASK**

A Thesis

Presented to

The Faculty of the

Human Factors/Ergonomics Program

San Jose State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

David Scott Tu

December 1997

UMI Number: 1388225

**Copyright 1997 by
Tu, David Scott**

All rights reserved.

**UMI Microform 1388225
Copyright 1998, by UMI Company. All rights reserved.**

**This microform edition is protected against unauthorized
copying under Title 17, United States Code.**

UMI
300 North Zeeb Road
Ann Arbor, MI 48103

© 1997

David Tu

ALL RIGHTS RESERVED

APPROVED FOR THE HUMAN FACTORS/ERGONOMICS PROGRAM

Anthony D. Andre, Ph.D., Human Factors & Ergonomics, Chair

Kevin Jordan, Ph.D., Psychology, Member

Del Coates, Art & Design, Member

APPROVED FOR THE UNIVERSITY

ABSTRACT

THE INTEGRATION OF NAVIGATIONAL INFORMATION FOR A SIMULATED AIRCRAFT TAXI TASK

Aircraft ground navigation is a complex task and has become one of the limiting factors for the growing commercial aviation system. This study investigated potential electronic cockpit taxi map features designed to improve the throughput and safety of low-visibility taxi operations. The performance and preference of several map display features were examined. These factors included three-dimensional (3-D) perspective versus two-dimensional (2-D) planar map views, quantitative versus qualitative heading information, constant versus scaled aircraft icon sizes, and graphical route guidance. Usage of a pilot invoked North-up, overview map was also examined.

The results show little difference in performance between the 3-D and the 2-D maps, although the pilots expressed a clear preference for the 3D map. Results from this study also suggest that display appropriateness is dependent on the particular task at hand. For ground taxi navigational tasks, information displays that provide high levels of visual momentum may particularly valuable.

“To be disoriented in space is to be psychotic”

Edward Hall, *The Hidden Dimension*

To those who have helped me find my way.

ACKNOWLEDGMENTS

I would like to thank Dominic Wong for his patience and skill in programming the simulation. I would also like to thank my thesis committee: Dr. Kevin Jordan for the opportunity to participate in research at NASA-Ames Research Center, Del Coates for encouraging me to begin my path (actually paths) in Industrial Design and Human Factors & Ergonomics graduate studies, and finally Dr. Tony Andre for including me in this and many other projects.

TABLE OF CONTENTS

ACKNOWLEDGMENTS.....	vi
LIST OF FIGURES.....	viii
LIST OF TABLES.....	x
INTRODUCTION.....	1
METHOD.....	34
RESULTS.....	66
DISCUSSION.....	90
SUMMARY.....	101
CONCLUSION	103
REFERENCE LIST.....	105
APPENDIX	
A. PILOT INTRODUCTION	109
B. PRE-EXPERIMENT SURVEY	111
C. POST EXPERIMENT SURVEY	112

LIST OF FIGURES

Figure	Page
1. Current cockpit ground navigation technology.....	2
2. The aircraft icon may obscure the map	30
3. Simulation apparatus.....	35
4. The out-the-window display.....	37
5. Wedge display area	41
6. Runway and taxiway labels rotate	43
7. Overview map mode.....	44
8. Two dimensional plan view map mode.....	45
9. Icon display position	46
10. Tethered camera view arrangement used for the 3D view	48
11. Three dimensional perspective used in the study.....	49
12. DATALINK.....	51
13. Electronic taxi map with and without graphical route guidance	52
14. Digital compass heading display	52
15. Graphical rotating compass bars and digital compass	53
16. Scaled icon varies with map zoom levels	54
17. Constant display size icon that does not vary with zoom level	55

18.	Speed control lever and zoom control lever.....	56
19.	The flybox used in this study.....	57
20.	Completion time by map type	68
21.	Completion time by route guidance type	69
22.	Average moving speed by map type	70
23.	Average moving speed as a function of route guidance type.....	71
24.	High speed performance by map type shown as percent time at high speed	72
25.	High speed performance (percent time at high speed) by route guidance type.....	73
26.	Time stopped by map type shown as percent time stopped	74
27.	Percent time stopped by map type and route guidance type	75
28.	Percent time of route by map type	76
29.	Percent time off route by map type	77
30.	Percent time spent at most zoomed in and out by map type	78
31.	Incursion response time by route guidance type	79
32.	Pilot preference by map type.....	80
33.	Percent time of (triggered) overview map usage by map type.....	82
34.	Percent time of overview may usage by route guidance type	83
35.	Pilot preference of heading display type	86

LIST OF TABLES

Table	Page
1. Subjective data concerning graphical route guidance	81
2. Subjective data on overview usage	84
3. Value of the wedge display.....	87
4. Overview map value	87
5. Outside view value	88
6. Best map features	88
7. The worst electronic map features as rated by pilots	89
8. Features wanted by pilots	89

INTRODUCTION

The Problem

Present aircraft cockpit technology and automation allows pilots to routinely take off, navigate thousands of miles, and then land safely even in low visibility conditions. Still, during low visibility conditions there are significant delays in flight schedules since, once on the ground, a pilot has little assistance from this same impressive array of technology to guide the aircraft and its passengers from the runway to the gate and back again (Andre, 1995).

Many current and previous research and design efforts have resulted in providing navigational aids in the cockpit for flight tasks. Specifically, take-offs and landings, and flight management (including, navigation, collision avoidance, and global awareness) have been supported by modern Electronic Horizontal Situation Indicators (EHSI). The goals of these efforts has been to develop and provide technology for delivering aircraft from one airport surface to another.

Although technologies exist both to produce and deliver information to aid a pilot in the task of ground taxi navigation, implementation of those technologies has not yet been accomplished, nor have the potential human factors implications been fully investigated.

To address the disparity between flight navigation and ground taxi navigation, we must first consider the technology pilots currently have, the difficulty imposed by low-visibility, and causes for ground taxi delays.

Current technology. Current ground taxi navigation technologies and information available to pilots, for the most part, consist of verbal instructions from ground control and hand held paper airport maps (Jeppesen charts). From these sources pilots must form a mental model of their ground taxi route (Figure 1). The quality and quantity of this information can influence the difficulty and even the ability of the pilot to perform the task of aircraft control and navigation.

Figure 1. Current cockpit ground navigation technology.

While the needs of control and navigation may seem similar, control and navigation are indeed very different. Manual control of the aircraft, keeping the wheels on the pavement, checking for and avoiding traffic conflicts, maintaining proper separation from other aircraft, vehicles, and objects, is based primarily on the visual “out-the-window” visual cues. Once a pilot determines the position and direction of the aircraft on the airport surface, he or she can then, with verbal instruction from ground control, navigate from there to the destination (usually a gate or runway). Pilots currently determine their position on the airport surface by reconciling the paper map with taxiway markings and signage (Foyle, Andre, McCann, Wenzel, Begault, & Battiste, 1996).

Causes for delays. In a field study based on cockpit observations, pilot interviews, and observations of pilot-controller communications Andre (1995), presented an analysis of current problems experienced by pilots during the taxi operations. He concluded that, “A comprehensive re-design of the current airport surface movement environment, including signs, communication protocols, procedures, and cockpit displays,” would be required to reduce ground taxi delays. Although this study will focus on the cockpit display element of this environment, it is valuable to understand the elements outside the cockpit as well as its context within the overall ground taxi task. Andre identified five classes of concerns related to current taxi operations: (1) The degradation of situational awareness due to the loss of visual cues in low-visibility conditions; (2)

Navigation problems that may arise due to deficiencies in the visual airport surface environment; (3) The inefficient taxi operations that may result from ineffective communications between ground control and the cockpit; (4) The increased workload due to mid-taxi route changes; and (5) The increased complexities due to aircraft taxi sequencing.

Difficulty imposed by low visibility. Typically the task of ground taxi navigation is difficult to begin with since the forward visibility from the cockpit of commercial aircraft is restricted, and the airport may be complex, unfamiliar, and/or congested. The difficulty of the ground taxi task is compounded when low visibility conditions prevail. In fact, NASA's Aviation Safety Reporting System (ASRS) contains numerous incidents triggered by pilots becoming disoriented while taxiing under low-visibility conditions.

The following comments by pilots and conversations between ground control (GC) and the flight crews (FC) were recorded by Andre (1995) regarding taxiing during low-visibility situations:

- ▶ "Low-visibility taxi situations are the hardest."
- ▶ "Taxiing at O'Hare the first time in low-visibility conditions is impossible!"
- ▶ "Under low-visibility conditions I taxi at one-half to one-third the speed of high-visibility conditions."

- ▶ “Delays in taxiing under low visibility conditions are sometimes caused by ground control having to tell you every turn and where you are at a given point in time.”
- ▶ “Recently at SFO, in dense fog, you couldn’t tell where you were. You could only see gate numbers lit up. It took almost one hour from gate to runway.”

It is clear that taxiing in low-visibility conditions is difficult and that some type of aid is needed to compensate for the performance degradation imposed by the poor visibility.

Deficiencies in the airport surface environment. It was noted by Andre (1995) that environment is perhaps the biggest obstacle to safe and efficient ground taxi operations. The following comments by pilots underscore these observations:

- ▶ “SFO is the worst—its like a black hole at night near the ramp areas”
- ▶ “Why can’t they paint the taxiway numbers on the pavement like they do on the runway?”
- ▶ “Some signs are burned out and therefore not visible at night or during poor weather”
- ▶ “All airports should be consistent within themselves and between other airports. For example, why not have it such that A, B, and C are always from North to South, numbers go from low to high from North to South, etc. Why is A sometimes next to K?”

One pilot noted that most of the taxi ways signs were covered by weeds and said, “[I] Only knew where to go using the map”. Andre (1995) also observed during one instance while taxiing at ORD, that pilots got confused at several intersections because they didn’t see signs that indicated which taxiway they were crossing. “The problem was due to the fact that signs are placed a good distance before the intersection (a good feature which provides preview to the pilots) but not repeated at the intersection (a necessary feature which provides confirmation to the pilots). In fact, at a given intersection, the only signs visible are those for the next intersection” (Andre, 1995). These comments by pilots attest to the inadequate and inconsistent nature of the airport surface environment. While efforts to change these factors could (and should) be undertaken, an improved taxi navigational system or process will need to accommodate the deficiencies and the variances encountered in airport surface environments.

Ineffective communications between ground control (GC) and the flight crew (FC). Poor communication was cited as the causal factor in the second largest number of runway incursions and incidents from 1988 to 1992 (Flight Safety International). The following statements were recorded by Andre (1995):

- FC: “We’re lost.” GC: “I can’t hear anything you are saying.”
- GC: “Taxi to gate.” Captain: “He didn’t say which way to go, did he? Then we’ll just go our own way.”
- GC: “Are you ready for takeoff?” FC: “No, we haven’t left the gate yet”

- FC: "Do you still want us to take the inner?" No answer from Ground Control.

These sample conversations highlight the fact that verbal communications alone are not enough to provide adequate route guidance.

Route changes. Andre (1995) noted that one of the most difficult situations faced by pilots is a change of route during the taxi phase and recorded the following statements from pilots:

- "Taxiing to the gate is most difficult when the route is changed in mid-stream. Once you get a mental picture of the route you need to take from the runway to the gate, it's hard to replace it with another route."

This disrupting event occurs fairly often and for a variety of reasons:

- GC: "Can you switch to Runway 1-Right instead?"
- FC: "We need to taxi to test this yaw damper." GC: "Hold on, let me open up the South line for you and put everyone else on the North line."
- GC: "Change to outer at Golf." This new clearance was given due to another aircraft stopped on the Inner just after G. They therefore had to get off the Inner at G (just before the stalled aircraft) and continue on the Outer to their runway.

Taxi sequencing. Andre (1995) also observed that pilots more often know where they need to taxi than when they can taxi as exemplified by the following statements:

- ▶ GC: "Hold and give way to 2 MD-80's and then you can slip right in."
- ▶ GC: "Give way to the 747 up your nose and continue."
- ▶ GC: "At T-10, go behind American 767 to 32L."
- ▶ "Most of the time the clearance is "follow that guy" at O'Hare and other large airports."

The Solution

In summary, the task of ground taxi navigation is indeed a complex and dynamic process. The difficulty of this task is compounded at busy, complex airports especially during low-visibility conditions. Pilots both familiar and unfamiliar with the airport may slow down, stop, deviate from the cleared route, conflict with other aircraft, or get lost especially during conditions of low visibility. Furthermore, when compared to high visibility situations, pilots during low visibility conditions may also spend more time interacting with ground control while they clarify their position and orientation (Andre, 1995). Consequently, overall flight throughput and sequencing is severely constrained during low visibility conditions due to the ground taxi component of aviation operations (McCann, Foyle, Andre, & Battiste, 1996).

Recent advancements in sensor, navigation, database, and computer graphics technologies give us promise that an electronic taxi map may be designed and implemented to provide useful and unambiguous information to aid pilots during ground taxi operations especially during low-visibility conditions (Zimmerman, 1994).

The NASA TAP Program

Recent efforts within the National Aeronautics and Space Administration (NASA), the Federal Aviation Administration (FAA), and the commercial aviation industry have been aimed at developing technologies to reduce runway occupancy times, to improve the efficiency of taxi operations, and to provide the flight deck with integrated surface operations and tower guidance. The present study is part of the Low-Visibility Landing and Surface Operations (LVLASO) element of NASA's Terminal Area Productivity Program (TAP), implemented to provide technology and operating procedures for safely achieving clear-weather capacity in instrument-weather conditions. In particular, the goal is to investigate display components which could support ground taxi operations at levels at or near that of high-visibility conditions. This study was part of a larger series of studies aimed at determining the optimal design of electronic cockpit taxi maps for improving the throughput and safety of low-visibility taxi operations (Mejdal & Andre, 1996; Foyle et al., 1996; McCann et al., 1996).

Potential Solutions: The Electronic Taxi Map Display

In an effort to reduce the incidence of navigational errors and reduce taxi times, especially during low-visibility conditions, it is likely that electronic map displays may soon replace or augment the typical hand held paper map used by today's pilots (Zimmerman, 1994). Andre (1995) recently conducted a study of pilot information requirements for low-visibility taxi by serving as a flight deck observer on over thirty commercial carrier flights. Based on cockpit observations, pilot interviews, and pilot-controller communication analyses, he concluded that based on pilot needs and wants, that electronic taxi map displays could potentially increase the efficiency and safety during low-visibility surface operations.

A study by Mejdal and Andre (1996) indicated that an electronic map display might have the potential to improve low-visibility taxi performance (speed and accuracy) to that of high-visibility taxi performance.

Zimmerman (1994) indicated that more efficient ground taxi operations could also result in fuel savings, better on-time performance, and higher margins of safety since hazardous or closed areas of the airport surface could be easily marked on electronic maps.

Nevertheless, the fact is that recent advances in information display technologies, differential global positioning systems (e.g., DGPS), and digital data communications (DataLink) could be combined to produce a taxi navigation display with potential benefits that far exceed those of stand-alone paper charts

(Batson and Harris, 1994). For these displays to provide invariable assistance to the pilot, a careful, pilot-centered approach to their design and implementation must be undertaken (Andre, 1995). To this end, the criterion for deciding which map design features to implement should lie in whether or not these features increase a pilot's ability to maintain his/her awareness of where they are located on the airport surface (position), where they should be going (route), and where other nearby aircraft are located (conflicts); we refer to this collective knowledge as "navigation awareness" (Andre, Wickens, Moorman, & Boschelli 1991; Aretz, 1991).

The Design of An Electronic Taxi Map

Map design overview. In regard to the design an electronic taxi map we must acknowledge that all maps are distortions of the real world geometry and that there are various design dimensions that must be addressed. The goals of such a map must also be defined. The goals for this project were: (1) a map for low-visibility taxi map is not necessarily a map for zero-visibility, (2) the map should compensate for the lost and degraded local guidance due to low-visibility, (3) there is a need for providing global awareness information, and 4) map information should be provided in a form that is quick and easy for pilots to understand and apply to the task at hand.

Map design: Distortion. All maps are distortions of some sort. It is impossible to translate all of reality exactly to, in this case, an electronic map

display. In fact, we would not want to provide a veridical photographic reproduction even if we could, since the power of a good map is that it symbolically represents only the information that we need or want to know. In other words, much of the value of a map comes from the quality rather than the quantity of the information presented (Semans, 1992). In addition, there are dimensions which can be shown on a map that cannot be readily perceived due to a person's sensory limitations, physical position, or physical orientation. For example, a map can not only tell us what we cannot see but help us focus our attention in a cluttered scene. In the case of a moving map display, the viewer can be provided with information indicating what to look for as well as when to look for it. It is our hope that by providing a map showing what, where, and when to expect targets (taxiway and runway intersections, holds, gate areas, other aircraft, etc.) that the capacity of the pilot to detect and deal with unexpected events (aircraft incursions for example) will be increased.

Map design: Dimensions. An electronic map display envisioned for use in a aircraft cockpit can have many attributes, such as color, perspective, information content, dynamics, icon shape and size, update rate, and scale (McGreevy & Ellis, 1991). Within this infinite set of qualities or attributes we have the potential to provide complementary or supplementary information to the features of the outside environment that are already perceivable by pilots. The challenge for the electronic map display designer is to determine which attributes of the world along with any new attributes to present given the needs of the pilots

and the limitations of current technology. To this end we must begin by defining the goal of such a map by understanding the task of ground taxi navigation and the needs and wants of the pilots who perform this task.

Map design: Low-visibility vs. zero-visibility. To define the functional goals of an electronic map display for low-visibility conditions it is important to first differentiate between low-visibility ground taxi conditions and zero-visibility situations. One of the goals of the NASA TAP/LVLASO program and therefore of this study is to design an electronic map display for use in Category IIIB conditions; That is from three- to seven-hundred feet runway visual range (RVR). In other words, the goal is to enable the pilot to taxi at or near high-visibility performance levels by using a navigation system that can compensate for the cues lost in poor visibility. On the other hand, a very different goal and one which is outside the realm of TAP/LVLASO and this study is one where visibility is virtually absent (0/0 weather conditions) and local guidance information (Aretz, 1991; Lasswell & Wickens, 1995) needed for control must somehow be completely replaced.

Map design: Local guidance. Under low-visibility conditions the out-the-window view can and does provide some local guidance information although it may be incomplete and/or severely degraded. Specifically, the centerline and lights, the taxiway edges, the edge lighting, and taxiway signage are visible out the front and side windows but at reduced brightness and contrast levels (Foyle, Andre, McCann, Wenzel, Begault, & Battiste, 1996). Pilots report that during low-

visibility situations that they need to have more attention out the window in order to compensate for the degraded visual conditions (Andre, 1995).

Map design: Global awareness. Currently, either a paper map and/or a pilot's familiarity with the particular airport surface provides what Lasswell and Wickens (1995) describe as global awareness. In lieu of either of these sources, another goal of an electronic map should be the provision of information in support of global geographic awareness. This is important even for the pilot familiar with the airport surface since during low-visibility conditions major landmarks can be obscured.

Map design: Integration with task. In a previous study, conducted by Mejdal and Andre (1996), an overall performance benefit was found with an electronic map display, although that there was a potential attentional cost of such a display; The cost of drawing attention away from the out-the-window view while attending to the heads-down map display must be considered. Zimmerman (1994) postulated that if an electronic map display could quickly and easily provide positional information to the pilot, the need for voice communications with ground control could be reduced and therefore attentional resources may be available for looking out-the-window. In other words, by providing global awareness information quickly (at a low attentional resource cost) by means of an electronic taxi map, the pilot could have a higher capacity for other local guidance activities. From these past studies it is clear that, while the underlying technologies exist to produce an electronic ground taxi map, we should take care

that the design be compatible and cost effective in terms of attentional resources within the cockpit environment as well as with the task at hand.

The Taxi Task

How pilots taxi: Overview. The pilot's primary task during ground taxi is to maintain control of the aircraft, that is, to keep the aircraft on road and on route, while simultaneously remaining vigilant to potential aircraft incursions and other obstacles out the window (hazard detection). This task is made up of two sub-tasks which are of particular interest: road-guidance, and route-guidance. The different goals as well as the different information requirements distinguish these tasks.

The goals of road-guidance, which refers to the actual task of controlling aircraft speed and steering are to maintain proper separation from other aircraft and other vehicles, keep the wheels on the pavement, and to avoid conflicts on the airport surface. Taxiing an aircraft is similar to the task of driving an automobile even though the operator is much higher off the ground and forward of the vehicle pivot point. Lasswell and Wickens (1995) described the taxi task as one that requires lateral loop closure (e.g. to stay on the road), directional loop closure (to negotiate turns, etc.), and longitudinal loop closure (e.g. to maintain optimal speed, brake for hold markings and other traffic, etc.), information gathering inside and outside the aircraft (e.g. to monitor cockpit instruments and displays, read taxiway signs and markings), and hazard detection (e.g. to

monitor for ground traffic, obstacles). This task may impose a higher demand for aircraft control than actual flight since the tolerance for lateral deviations (keeping the nose-wheel near the centerline) while taxiing is so low. The typical separations between aircraft on the ground in terms of both time and physical distance are much less than in the air.

Adequate aircraft control performance or road-guidance requires a minimum amount and quality of local visual information from the out-the-window scene. Under conditions of high-visibility and to a certain extent low-visibility, judgements of egomotion (Wickens, 1992) are possible which support aircraft control activities including steering, throttle adjustments, and braking. This is due to the available information which is distributed across the visual field. One of the dimensions or *optical invariants*, as defined by Gibson (1979) in Wickens (1992), of this visual information set is optical flow. This refers to the velocity of [visual] points traveling across the display surface (and therefore the retina) as we move through the world. In other words, as long as a pilot can see some visual cues and sense the pavement texture, pavement markings, grass, buildings, etc., judgements of direction and speed can be made. Of course, the latter judgment depends on the quality of the former.

During high-visibility conditions the quality and quantity of these visual cues are at the highest level and can support control. Zero-visibility conditions, by contrast, do not provide these visual components and therefore cannot support these control activities. Between these two visibility conditions lies low-

visibility conditions, where the quantity of visual information is reduced and the quality of that information may be severely degraded. The goal of a taxi map display for these conditions then is to augment these degraded cues.

Route-guidance, in contrast to road guidance, relies on a broader set of information. Wickens (1992) has characterized the acquisition of this type of navigational information using the model proposed by Thorndyke (1980). This model suggested a progression through three stages of geographical learning: Landmark knowledge, route knowledge, and finally survey knowledge.

How pilots taxi: Landmark knowledge. The first stage of Thorndyke's (1980) model is characterized by the ability to orient oneself exclusively by the recognition of salient visual landmarks. These may be, for example, buildings, mountains, light houses, or in the case of Hansel and Gretel, bread crumbs. Landmarks for pilots may include taxiway and runway signs, runway numbers painted on the pavement, and the control tower. These landmarks help provide the answer to the question, "Where am I?". The navigator must first establish these landmarks to provide a frame of reference for which to base the following two stages of navigational learning. All pilots, whether or not they are familiar with a particular airport must, at minimum, have some landmark knowledge of the airport for it provides a common frame of reference on which to base effective interactions with ground control. The success or failure of a pilot's navigation depends on knowing at least the starting point.

How pilots taxi: Route knowledge. Route knowledge is characterized by the ability to navigate from one point to another using the previously established landmark knowledge. Landmarks are used to trigger control decisions such as to stop, to continue on or to deviate from the present course. Taxiway signage on the airport surface can serve to trigger a pilot to make such as turn decision assuming he or she has received route information from ground control. For example, ground control may instruct a pilot to, "Hold short at 34R", or "Go Left at Alpha to Foxtrot." It is also important to note that route knowledge is from a uniquely ego-centered reference frame (ERF).

The strength of route knowledge lies in the fact that the navigator need not be familiar with the environment he or she is traveling in as long as a second agent has, at some point, effectively conveyed route instructions. In terms of the aircraft ground taxi task, this can be limited by either or both factors: 1) The route instructions, and 2) The saliency of relevant landmarks. Another shortcoming of being limited only to route knowledge is the situation where the pilot misses a landmark (taxiway sign hidden in the fog for example) and becomes not only off route but disoriented as well. Recovering from being off-route may be difficult to impossible without a revised set of route instructions or a higher level of geographical knowledge.

How pilots taxi: Survey knowledge. Survey knowledge, on the other hand, is geographical knowledge based on an exocentric or world-centered reference frame (WRF) (Wickens, 1992). Wickens (1992) characterizes survey knowledge

in terms of an internalized “cognitive map” analog to the true physical map described by Tolman (1948). This type of knowledge can eventually be acquired by sufficient navigational experience and allows the navigator to travel a route that he or she has never actually been on before. Other benefits of having survey knowledge lie in the potential to recover from a route deviation and the reduction in the disorientation experienced by going off route.

How pilots taxi: Mental model. How the different levels of acquired navigational knowledge is used depends on the formation of a mental model. The concept of a mental model is described by Wickens (1992) and defined by Carroll and Olson (1987) as, “A rich and elaborate structure, reflecting the user’s understanding of what the system contains, how it works, and why it works that way. It can be conceived as knowledge about the system sufficient to permit the user to mentally try out actions before choosing one to execute.”

Training and experience have provided pilots with knowledge of how and why the “system” (airport surface operations) “works”. On the other hand, the “contents” of this system depend on the pilot’s familiarity with the particular airport as well as the visual conditions. Therefore, the accuracy and completeness of a pilot’s mental model will have an effect on his or her ability to anticipate control inputs, locate visual cues, and in general perform the control and navigational elements of the ground taxi task. Still, the keystone element of the ground taxi navigation task is the acquisition of geographical survey knowledge.

How pilots taxi: Summary. The taxi task for a pilot from a human factors perspective can be summed up to be the formation of an adequate mental model of the airport surface. This mental model, formed by reconciling landmark, route, and survey knowledge of the environment, is then used with the available visual cues and route clearance instructions from ground control to navigate the aircraft along that route to the destination. The design goals of an electronic map should therefore be to support the accurate formation of this mental model in a way that does not preclude the gathering of the existing out the windows cues.

Map design features: Local guidance vs. Global awareness

At a different level, the ground taxi task can be described in terms of local guidance and global awareness. The different stages of navigational knowledge support different aspects of local guidance and global awareness. Route knowledge, or the information needed to navigate from point to point, generally supports local guidance activities while survey knowledge contributes to global awareness. Wickens and Prevett (1995) characterize successful navigation as involving local guidance (keeping the aircraft on route and on the road) as well as global awareness (incursion detection). The many possible dimensions alluded to earlier for a map display have implications in terms of the tasks they are intended to support.

Display perspective, two-dimensional vs. three-dimensional. Wickens and Prevett (1995) contend that information supporting local guidance should be

presented in an ecological ego-referenced frame (ERF), emphasizing the forward field of view and should be in perspective where foreground elements are depicted in greater detail than those in the background. In other words, "Such displays tend to be optimal if they mimic characteristics of natural vision; that is, they present close-in three-dimensional representation of the "cone" of vision ahead of the aircraft," (Wickens, 1995). In contrast, a two-dimensional world referenced frame map representation has been suggested as a better choice for supporting global awareness.

Frame of reference. North-up vs track-up. The ERF local guidance information display should faithfully represent the feedback given to the operator from the forward visual scene (Wickens, 1995). As the pilot makes inputs for vehicle control, the display should match the features of the outside environment." This would indicate a need for a track-up moving map display where the "tracking" direction was always indicated by the "top" of the map. In other words, a map that rotated about the aircraft icon so that the aircraft was oriented toward the top of the display area. In contrast, Wickens and Prevett (1995) indicate that displays supporting global awareness need to provide information about the environment from a world referenced frame (WRF). This type of view would suggest a North-up map display, where North was always oriented towards the "top" of the map. In this case the aircraft icon would rotate as well as change position on a static map display.

A study by Mejdal and Andre (1996) allowed pilots to choose between track-up and North-up electronic map displays. They indicated that there was no need for a North-up map based on the relative infrequency of North-up use. The fact that some pilots did invoke the North-up map at times may indicate that there are still some situations in which it is a useful frame of reference.

Field of view. Recommendations for a global awareness display by Wickens and Prevett (1995) indicate the need for a broader view of the environment. In other words, a more “zoomed out” view (wider field of view) or an “overview” view showing aircraft position and orientation within a broader geographical context. On the other hand, a more “zoomed in view” (narrower field of view) has been suggested to support local guidance since in this case there is a greater need for detail.

Heading information. In the context of the taxi task, voice communication with ground control provides much of the global awareness to the cockpit. For this communication to be effective a common reference frame must be used since the reference frames of these two agents are different. For example, communications between ground control and a pilot may utilize a common (polar) coordinate system such as that provided by a digital heading display. While this type of information WRF information may best support global awareness, ERF information such as right, left, or straight ahead may best support local guidance activities.

The Present Study

Clearly there may be performance and preference implications of display perspective, frame of reference, field of view, and heading information as applied to the task of a simulated ground taxi navigation task during low visibility conditions. Studies by Lasswell and Wickens (1995) and Mejdal and Andre (1996) have indicated that while the overall taxi task includes both local guidance and global awareness requirements, there is an unequal distribution between these requirements. Additionally, this distribution may vary during the actual taxi path as certain sub-tasks arise. In this study we investigate pilot performance and preference differences while comparing two-dimensional vs three-dimensional display map display formats, track-up vs. North-up maps, different zoom levels, digital vs. analog heading displays, and conformal vs non-conformal scaling icons.

So far we have established the information requirements for current taxi operations, the degradations imposed on that information by the presence of low-visibility weather conditions, and research on the two main modes of pilot navigation (local vs. global). In the following sections, the taxi map display dimensions examined in the present study will be discussed. Specifically for each of the dimensions of interest, we contrast two methods of providing information towards supporting various aspects of the ground taxi task.

Display dimensionality, two-dimensional vs. three-dimensional. Studies by Andre, Wickens, Moorman, and Boschelli (1991), Haskell and Wickens (1993),

Rate and Wickens (1993), and Wickens et al. (1994) suggest that 3-D displays can support local guidance if they represent the environment from a fully egocentric reference frame. However, Lasswell and Wickens (1995) point out the potential costs of three-dimensional displays: (1) 3-D displays introduce a degree of ambiguity regarding the precise location of points along the line of sight (see Wickens, Todd, and Seidler, 1989 for discussion of use of depth cues to reduce this ambiguity); (2) 3-D displays will present true distances at various (and therefore inconsistent) levels of resolution; and (3) a fully egocentric 3-D display will support only limited global awareness due to its limited field of view. While it is true that the 3-D displays suffer from line of sight ambiguity (depth perception) and has an inconsistent horizontal scale within the display, the impact this has on the two-dimensional task of ground navigation remains to be seen.

On the other hand, 3-D perspective displays have the advantage of presenting information at various map scales. For example, elements in the foreground are viewed in greater detail than those seen in the background and more elements in the far-ground can be viewed, although at reduced levels of detail. This could be an advantage if these dimensions, detail quality and detail quantity, are compatible with the information needs of a taxiing pilot. A study by Wickens, Liang, Prevett, and Olmos (1994) dealt with display dimensionality for flight tasks. Performance costs were identified for 3-D displays that had to do with vertical flight control but not necessarily for horizontal tracking. This should not rule out 3-D displays for ground taxi operations since taxiing can be thought

of as a 2-D navigation task since neither the perception nor control of the vertical axis applies.

Two-dimensional maps provide consistently-scaled geographic information about the entire map area. This may allow for better judgement of distances in the horizontal plane. A 2-D planar map display may certainly be a more expected or usual map presentation for most people even though few humans have really seen the earth from the same “bird’s eye” perspective depicted by a typical two-dimensional maps. On the other hand, we humans experience the world on a daily basis from a three-dimensional perspective rather than from an overhead or two-dimensional plan-view.

Wickens, Schreiber, and Renner (1994) experimented with planar rotation. Their results indicated that three-dimensional mental rotation did have a role in image comparison between the simulated out-the-window view and the map display, that three-dimensional maps had an advantage over plan-view maps by minimizing the disparity in view angle between the out-the-window view and the map display, and that there were no substantial costs when small disparities between the two views existed. In this study we examine two-dimensional vs. three-dimensional map perspectives as applied to the particular task of aircraft ground taxi navigation.

Frame of reference. North-up vs track-up. Batson and Harris (1994) have indicated that local guidance during a taxi task is best supported by a rotating or track-up map where the top of the map (“up”) conforms to the direction of travel

rather than a North-up (fixed-map) display. It was also found that the track-up map was also the preferred display orientation by the pilots. Studies by Aretz (1991), Aretz and Wickens (1992), Wickens, Liang, Prevett, and Olmos (1994) support this notion by also finding that track-up maps eliminate the need to perform the transformations required to make ego to world or world to ego reference frame correlations. Clearly track-up map displays have advantages when used for local guidance.

Lasswell and Wickens (1995) noted that these findings may not be without costs in terms of reduced global awareness. A North-up map display can be thought of as supporting global awareness since it utilizes a fixed frame of reference. Mejdal and Andre (1996) found, in a study where pilots were given the choice to use either a North-up or a track-up display, that while the track-up display was chosen most of the time, the North-up display was still used some of the time. This behavior may be an indication of the degree to which pilots performing a ground taxi navigation task need or want WRF information. This may further indicate that the task of taxiing an aircraft is mostly, but still not entirely, a local guidance task. In other words, there may be instances where a North-up map would be advantageous to better provide global awareness.

Field of view. The field of view varies inversely with the zoom level, that is, a higher zoom level displays a narrower field of view (at the same virtual camera position). Thus the FOV or zoom level of a particular map is determines the amount of visual geographic information available to the navigator. A large field

of view (FOV) (zoomed-out), provides more information but at a lower resolution than can be seen at a smaller field of view (zoomed-in) (Lasswell & Wickens, 1995). Global awareness is supported by a larger FOV while local guidance is better supported to FOVs. A map display that has changeable FOV or zoom levels may support both global awareness as well as local guidance.

Heading information. Pilots require different types of directional information depending on the task at hand. During flight the pilot needs precise heading information which is provided in numerical form by a digital compass display. While performing a ground taxi task there is evidence that the pilot's directional information needs are somewhat different. Directional status information needs tend to be more qualitative than quantitative (Andre, 1996). In other words, ground control may communicate an instruction in terms of the cardinal compass directions North, South, East, West, North-West etc.. For example a pilot's mental model of an area may also be formed in terms of cardinal compass directions such as, "Make a right turn and go out North side if you can get around company", "United 2063, go behind American that's going South, hold short of 34R at Quebec", and " Go round the North side, taxi to parking." Clearly there is a need for both qualitative as well as quantitative compass information in the cockpit at different time or for different situations.

When provided only a digital compass display, the pilot is required to mentally transform the numerical bearing information into actual compass direction. For example, a pilot might be told to exit the South side of the ramp

area. A heading of 220 degrees indicates a generally South-West direction. Due to experience, pilots may perform in this situation quickly and accurately, but there is a cognitive cost that they must pay (Dror, 1992). Additionally, there is also the cost of integrating compass directions with the out the window view and the left-turn vs. right-turn decision making process.

In this study two types of heading displays were presented: a digital quantitative compass display located at the top center of the map indicating current bearing and a qualitative moving “compass bar” display. The compass bar consisted of a four colored bars arranged end-to-end around the perimeter of the map display. Each bar represented one of the four cardinal compass directions (N, S, E, W). The color of each bar remained constant: grey for North, green for South, blue for East, and orange for West. These colors were also consistent with a similar display element used by Andre, Wickens, Moorman, and Boschelli (1991). The orientation of these bars was varied with that of the map as it rotated to denote the current orientation of the aircraft in the track-up map conditions. The bars were presented with the track-up map only since, by definition, the North-up map already indicates cardinal compass direction (North at the top. etc.).

The compass bar may incur the cost of adding to the complexity of map since more graphic elements can impose a workload on the viewer and due to its movement, may attract attention away from the map and it requires some display area. This cost must be weighed against the potential benefits of a total

reduction of transformations from numerical representation to compass direction and then to right-left decision-making. Again this feature was intended to contribute to a more optimal level of integration between the map and the clearance instructions through providing visual momentum.

Icon size. From a previous study by Mejdal and Andre (1996) it was noted that some pilots had trouble finding the aircraft icon especially when the map zoomed out. For those cases, the icon, whose size scaled with respect to the map scale, became very small and potentially difficult to find. The obvious solution would be to make the icon bigger, but may impose a cost of potentially obscuring other map elements especially when zoomed in (see Figure 2).

Figure 2. The aircraft icon may obscure the map.

An alternative solution may be to display a fixed size icon when the map zoom level is changed. By retaining a constant absolute display icon size, there may be an advantage of not “losing” the icon when zoomed out. This may come at the cost of obscuring other map elements when zoomed out. To help understand the trade-offs involved in designing the icon scale behavior the aircraft icon was presented in one of two ways: (1) at a constant display size, and (2) at a constant scale with respect to the map. The constant display size icon remained the same absolute size relative to the display at all zoom levels. The scaled aircraft icon varied in display size as the map scale (zoom level) was changed.

Route guidance. Currently available DataLink technology allows a stream of text based information to be transmitted to the cockpit from ground control. Using this technology, text can be delivered from ground control via digital radio transmission and displayed within the cockpit. How this information actually gets entered into the system is beyond the scope of this study. Currently voice recognition technology is being studied as a possible solution to this challenge.

Graphical route guidance was provided in half of the trials through the addition of an overlying magenta line on the map display, approximately the width of a runway, connecting the starting point to the destination via the desired route. The route information displayed graphically by the route guidance line was consistent with that of the route defined by the text clearance window. Based on a previous study using a similar simulation (Mejdal & Andre, 1996), it was

expected that pilots would complete the routes faster and more accurately when provided with graphical route guidance. The magenta color was chosen to retain consistency with the route color of existing flight displays. Mejdal and Andre (1996) note that overall benefits of route guidance may be a “mixed blessing.” There is a question of whether the presentation of this feature actually draws the pilots’ attention into the cockpit more rather than out the window where they could be (and should) be watching for unexpected incursions.

Andre (1996) noted that foreign pilots, especially those who are not proficient with the language of the country they are landing in, may benefit from an automated taxi map that provided non-text based navigational information. Specifically, qualitative graphical compass and route information could provide helpful redundant navigational information.

The present study: Summary. There are trade-offs that must be taken into account when designing an electronic taxi map such as whether or not to display a map North-up or track-up. What if the pilot was presented with the map type that supports his or her needs most of the time, as the default, and could activate, on demand, a display that would address occasional additional needs? As stated previously it has been shown that track-up maps support local guidance better while North-up maps support global awareness better. In the present study we examined three map modes: (1) an “overview map” that was a two-dimensional, planar, North-up, moving-icon, fixed-map, (2) a “two-dimensional map” that was a two-dimensional, planar, track-up, fixed-icon

moving map, and (3) a “three-dimensional map”, that was a three-dimensional, perspective, track-up, fixed-icon, moving map. For last two modes, the pilots were allowed to toggle to the overview map mode. In addition, the following dimensions were also examined: heading type, icon scaling, and route guidance type.

METHOD

Design

Four independent variables were manipulated within subjects: map type (two-dimensional track-up vs. three-dimensional track-up vs. North-up (overview)), icon size (conformal scaling vs. non-conformal scaling icons), compass heading display type (digital only vs. digital + compass bar), and route guidance type (text only vs. text + graphical). Map type and route information type were completely factorialized while the compass heading displays and icon type were manipulated only within the two-dimensional and three-dimensional track-up map types.

Apparatus

The hardware used for the experiment consisted of a Silicon Graphics Indigo 2 Extreme workstation, a Silicon Graphics Iris Indigo Elan workstation, two 21-inch color video monitors, a BG systems flybox containing a 2-axis joystick for directional control, a trigger on the joystick to toggle to an overview map, and two 1-axis control levers to manipulate aircraft speed and map zoom level. The monitors were situated one over the other so that the upper monitor displayed the out-the-window view while the lower monitor presented the electronic map display. The flybox was situated in front of the participant so that the joystick as well as the speed and zoom levers could be easily manipulated. The apparatus as presented to the participants is shown in Figure 3.

Figure 3. Simulation apparatus including the out-the-window view (upper monitor), electronic taxi map (lower monitor), and flybox with speed control and zoom level controls (levers on left), and joystick with overview map trigger.

Simulation

Out-the-window-view. The upper video monitor displayed a simulated aircraft cockpit out-the-window view of San Francisco International airport. This scene was modeled using the approximate characteristics and dynamics of a typical narrow-body commercial passenger aircraft. In particular, the pilot eye point, acceleration, braking, and turning characteristics of a Boeing 737 were mimicked. The view was updated at 25Hz and represented the position and orientation of the aircraft on the airport surface. The scene was complete with all operational runways, taxiways, taxiway and runway signs, gate markers, buildings, and other landmarks. Daytime low visibility (fog) conditions were simulated to approximate Category IIB (RVR 1000 ft.) conditions. A sample of the out-the-window view is shown in Figure 4.

Figure 4. The out-the-window display.

Map type: Overview. The Overview map mode presented a fixed area North-up view of the entire airport surface in plan-view. This condition was provided as a simulation of the typical airport paper chart, which is the only current navigational aid available to pilots when taxiing (Andre, 1995). During this condition the map appeared stationary while the aircraft icon changed position and orientation on the map display as the pilot taxied. Pilots were presented this map during one third of the trials.

Map type: Track-up. For the other two thirds of trials for each pilot, two track-up map displays (two-dimensional and three-dimensional) were presented. For these conditions, the aircraft icon remained in a stationary display position (one third up from the bottom centered) and used a track-up orientation while the

map translated, rotated, and scaled to reflect the position and orientation of the aircraft as well as map field of view.

Under the track-up conditions, the pilot could control the level of detail by changing the field of view (zoom level) of the map as he or she felt necessary to perform the task. Also, by depressing and holding the trigger switch on the joystick, the pilot could, at any time, access the Overview map described earlier.

Map type: Two-dimensional. During one third of the trials (half of the track-up trials), the pilots were presented with a two-dimensional (plan-view) track-up map with zoom capabilities and the option to toggle to the Overview map.

Map type: Three-dimensional. For the remaining third of the trials each pilot experienced a three-dimensional (or perspective) track-up map. This view is basically a plan-view map viewed at an angle 40 degrees below horizontal so that it appears in three-dimensional perspective. Map features in the foreground are magnified and shown in greater detail than those map features in the far ground (Lasswell & Wickens, 1995). This viewpoint could also be thought of as showing a greater slice of far ground real estate compared to that of the foreground. This view was programed to provide a two-point perspective view with two vanishing points. A true three-dimensional rendering of the map features (with three vanishing points) would show the height of the buildings and any other rises, dips, or slopes on the airport surface. However, this display presented a view of a totally flat airport surface. The benefit of this kind of perspective display is that the buildings and other features with vertical

dimensions do not obscure map information as would a true three-dimensional rendering of buildings.

Route guidance. Two types of route guidance information were provided. A simulated DataLink display contained text-based route instructions similar in content to that which is currently provided by voice communication. This display remained visible during the entirety of each trial since we were not interested in the pilot's ability to memorize a route sequence. Graphical route guidance was provided during half of the trials as a second method of providing route information. This consisted of a magenta line overlying the route on the electronic map.

Compass heading. Two types of compass heading displays were presented. During half of the trials a quantitative heading display consisting of a digital heading indicator located at the top center of the map display. During the other half of the trials, a qualitative heading display was presented. This consisted of a four color border around the electronic map that rotated to reflect changes in aircraft orientation.

Icon type. Two types of icon displays were presented. During half of the trials the display size (the actual number of pixels displayed on the monitor) of the icon varied with changes in zoom level (conformal), while during the other half of the trials the icon remained a consistent display size regardless of zoom level (non-conformal).

Zoom levels. Both the two-dimensional and three-dimensional map displays incorporated a variable zoom feature which could be controlled by the pilot at any time. This feature was provided so the pilot could manipulate the field of view (the amount of airport surface shown on the map) by changing the magnification level of the map "camera". The map zoom level was controlled by using a lever to toggle between six discrete zoom levels. The incremental changes between each zoom level were designed to be small enough to appear to vary continuously. It was thought that smaller "jumps" in zoom level would be more ecological and less disturbing to the viewer.

Electronic Map Display: General factors

Overview. The lower video monitor, tilted at approximately 15 degrees from vertical, displayed a 6.4" square (~9" diagonal) electronic moving map display. This size, position, and orientation of the glass display is similar to the electronic horizontal situation indicator (EHSI) currently used in the Boeing 747-400.

Colors. Pavement on the map was depicted in grey, buildings were depicted in blue, and other pavement areas (grass) were shaded green. Runway and taxiway labels, and terminal gates were labeled with yellow text.

Wedge. Following the work of Aretz (1991) and Mejdal and Andre (1996), a wedge was presented at all times on the map display. The wedge (see Figure

In other words, the left and right legs of this triangle represented the limits of the pilot's left and right field of view out the front window.

The wedge was originally implemented to provide what Aretz (1991) called "visual momentum" when using North-up displays. It is thought that the wedge display feature would allow easier, faster, and more accurate transformation between the ERF and WRF when using a north-up map by providing cues linking the orientation of the aircraft as well as a graphic description of the pilot's field of view. This was especially important when traveling south while using a North-up map. For this study the wedge was presented at all times even during the track-up map conditions. A study by Mejdal and Andre (1996) showed no detrimental costs to providing the wedge during track-up conditions, in fact it may have may have had the unintended benefit of providing a location cue for the aircraft icon when the map was zoomed out.

Labels. The use of computer generated graphics allows certain features not available with a conventional paper map. In particular, the runway, taxiway, and gate labels can be automatically rotated in place to remain right-side-up as the map in track-up mode rotated. In other words the labels were always presented right-side-up to the pilots as shown in Figure 6.

Figure 6. Runway and taxiway labels rotate to remain upright as the map rotates.

Electronic Map Display: Map Type

Three distinct map modes were presented: Overview (North-up), two-dimensional track-up, and three-dimensional track-up.

Overview map. The “Overview” map mode is shown in [Figure 7](#). The goal of this map display was to show the entire airport surface in a North-up orientation similar to that provided by a conventional hand-held paper map. This map mode differs from the other two modes in that it is a fixed rather than moving map. The aircraft icon moves about a fixed map reflecting the current own-ship position and orientation. It also differs in that the scale of the map is fixed as well, that is, it does not have a changeable field of view (zoom level). It is thought that this kind of map presentation might be most useful in providing global awareness given its WRF and view of the entire airport. This benefit is not without cost since the pilot must perform rotational transformation to align the

environment with the orientation of the aircraft icon. In other words, the map information must be mentally “tilted” to conform to the real world view.

Figure 7. Overview map mode — North-up, fixed-map, moving icon, fixed full view of airport surface

Two-dimensional map. The “two-dimensional” map mode is shown in Figure 8. This two-dimensional, planar view map display has the advantage of consistent scale over the entire map area since the longitudinal and lateral

horizontal distances are represented in a linear, to-scale manner. A track-up, fixed-icon, moving-map configuration was used to display the two-dimensional map.

Figure 8. Two-dimensional plan-view map mode

A virtual overhead camera position was used so that the upper two-thirds of the map display represented an area ahead of the aircraft icon (see [Figure 9](#)). Laterally the aircraft icon was framed in the center of the map display area. In

this map mode, as well as in the three-dimensional perspective mode, the position and orientation of the icon remained fixed on the display screen while the map changes or moves to reflect changes in aircraft position and orientation. It is thought that this type of map display would be good at supporting local guidance. The cognitive cost to the pilot of a planar map such as this, is mental transformation required to rotate the map about the lateral axis to coincide with the environment.

Figure 9. Icon display position.

Three-dimensional map. Three-dimensional perspective displays have the advantage of being more ecological by integrating the three Euclidean dimensions into a single display. On the other hand, viewers of three-dimensional perspective displays must tolerate a certain amount of foreshortening of the axis orthogonal to the viewing plane. We can think of a three-dimensional perspective display as the view through a virtual camera with parameters such as position (horizontal and vertical), orientation relative to the aircraft, field of view, and magnification or zoom level. The display designer is faced with a infinite number of ways to “set” this camera. The orientation of this “camera” should be chosen so that costs of planar rotation are minimized. The difficulty of this mental transformation could be minimized by simulating a viewpoint direction that would coincide with that of the pilot. This would be considered the ego-referenced viewpoint. This view, while having the potential to declutter the pilot's view by reducing the number of elements in that view, has the limitation of showing no more of the world than the pilot already has available by looking out the window. For this reason, and because we have established that pilots performing ground taxi navigation need and want a certain degree of world-referenced information, we have created an exocentric, three-dimensional, perspective, tethered view. A tethered view is one in which the virtual camera remains a fixed distance behind and above the aircraft position along its center axis and oriented in the same direction as the aircraft as shown in Figure 10.

Figure 10. Tethered camera view arrangement used for three-dimensional perspective view

For this study a downward camera angle of 40 degrees was used with a longitudinal offset that allowed the upper two-thirds of the map display to represent an area ahead of the aircraft. Wickens' (1990) review of previous studies suggested that a camera angle of between 30-45 degrees may provide the optimum three-dimensional map view for a flight task. This study did not specifically address determining the optimum camera angle, rather it endeavored to provide insight into whether a reasonable perspective three-dimensional view would have speed or accuracy benefits when applied to a two-dimensional task such as ground taxi aircraft navigation.

One of the problems associated with three-dimensional, perspective displays is that the objects can be obscured in the background by objects in the foreground. Rather than represent objects on the airport surface with height as three-dimensional objects on the map display, we represented them as differentially colored flat object areas (for example, blue buildings). In other

words, the three-dimensional, perspective map appeared as a plan-view map that was tilted about a horizontal axis parallel to the view plane. See [Figure 11](#).

[Figure 11](#). Three-dimensional perspective used in the study

Electronic Map Display: Route Guidance

Text-based route guidance. A box containing taxi clearance in text form similar in format to the vocal clearances familiar to pilots, was presented during

each trial above the out-the-window view. This display element would presumably be transmitted by the airport air traffic control (ATC) via DataLink (see Figure 12). Each pilot was told that they did not have to, nor should they attempt to, memorize the taxi route clearance since it would remain visible throughout the duration of each trial for reference. The position of the route information, as well as the digital ground speed indicator (top center of the out-the-window display), were chosen so that looking at these displays would not come at the cost of looking away from the out-the-window view. This was designed so that the only reason for not looking away from the upper monitor (the out-the-window view) would be to look down at the electronic map display. The textual information display was provided for all of the experimental trials.

Figure 12. DATALINK (upper left corner)

Text and graphical route guidance. A second method of conveying route information was presented during half of the trials for each pilot. In addition to the text-based route display, a magenta line, roughly the width of a roadway on the map, was displayed graphically indicating the route from the starting point to the destination gate or runway (see [Figure 13](#)). The magenta color was chosen to retain consistency with the route color of existing flight displays. Each participant was assured by the experimenter that the route represented by the route text was in fact analogous to the route shown by the graphical route guidance and that there was no need to spend time or cognitive resources comparing the two.

Figure 13. Electronic taxi map without graphical route guidance (left) and with graphical route guidance (right).

Electronic Map Display: Compass Heading

Digital. A digital compass heading display (see [Figure 14](#)) was shown during all the trials. This display consisted of white text on a black background located on the top-center of the electronic map display. This was intended to mimic the digital compass heading display currently provided in typical commercial aircraft.

Figure 14. Digital compass heading display

Digital + compass bars. During the other half of the each participant's trials, a qualitative heading display (Andre et al., 1991) was presented in addition to the digital heading display. This qualitative display consisted of four colored bars arranged end-to-end around the perimeter of the map display. Each bar represented one of the four cardinal compass directions (N, S, E, W). The color of each bar remained constant: grey for North, green for South, blue for East, and orange for West. The orientation of these bars was varied with that of the map as it rotated to accommodate the current orientation of the aircraft in the track-up map conditions (see [Figure 15](#)). The bars were presented with the track-up map only since by definition the North-up map already indicates cardinal compass direction.

Figure 15. Graphical rotating compass bars and digital compass. Headings 212 and 192 shown on displays on the left and right respectively.

Electronic Map Display: Icon Size

Conformal scaling icon size. Half of the trials had an aircraft icon that scaled in size with changes in zoom level as shown in Figure 16. In other words, the icon scale varied with the map scale.

Figure 16. Scaled icon varies with map zoom levels. Zoomed-out and zoomed-in maps shown on left and right respectively.

Non-conformal scaling icon. The other half of the trials had an aircraft icon that remained a constant display size regardless of zoom level. The icon size for these trials was roughly equivalent to the display size of the scaled icon at the mid-zoom level as shown in Figure 17.

Figure 17. Constant display size icon does not vary with map zoom level. Zoomed-out and zoomed-in displays shown on left and right respectively.

Electronic Map Display: Controls

Speed. The speed of the aircraft was controlled by moving a one-axis lever fore or aft. Pushing the lever all the way forward produced a maximum speed of 32 knots while pulling the lever all the way back brought the aircraft speed to zero (as if brakes were applied). The approximate braking and acceleration characteristics of a Boeing 737 were factored into the simulator dynamics to provide speed control lag due to aircraft momentum. The speed control lever is shown in Figure 18. This manipulation of icon scale was included

in response to comments from pilots during a previous study that indicated that at the aircraft icon was difficult to see at the lower zoom levels.

Figure 18. Speed control lever (left) and zoom control lever (right)

Zoom levels. Map display field of view (scale) was controlled by the pilots by utilizing a lever similar to and next to the speed control. Six zoom levels were provided and labeled on the flybox. The highest level of map magnification (zoomed in all the way) was invoked by pushing the lever all the way forward, while pulling back all the way in the lever produced the least magnified (zoomed out) map view.

Steering. Deviating the joystick from side to side controlled the nose gear of the aircraft. The flybox which housed the speed and zoom controls as well as the joystick is shown in Figure 19.

Figure 19. The flybox used in this study.

Overview trigger. In the two-dimensional and three-dimensional track up map modes, holding the joystick trigger down the pilots could at any time access the Overview map.

Procedure

Pre-experiment survey. Participants were asked to read a two page introduction (see Appendix A) to the study and fill out a short pre-experiment survey (see Appendix B). The survey included questions about the participants pilot rating, flight hours, flight experiences at SFO, previous map type and usage, and experience with flight related video games.

Introduction and practice period. The participant was then seated in a sound-proof experiment booth and allowed to adjust the seat and table height so that the controls and displays were comfortable and easily accessible. A thirty- to forty-minute introduction to the controls and display elements was given. The participants were encouraged to manipulate the controls to learn the system “hands-on” as the experimenter described each element and instruction.

Each participant was told to perform as though they were the pilot of a narrow body commercial aircraft, similar to a Boeing 737, taxiing at SFO with passengers on board. They were asked to perform arrival and departure taxi navigation tasks while optimizing speed and accuracy so that accuracy was not compromised by speed. In other words, each participant was asked to perform the task as fast as they could do so accurately. In this context, “accuracy” was defined as the ability to keep the wheels of the aircraft on the pavement (on-road) and to remain on-route.

During the initial practice period each pilot was encouraged to experiment as they taxied on a runway or taxiway, made turns, and changed speeds, in an

effort to become accustomed to steering with the joystick and using the speed control lever. They were told that they would not be able to make 90 degree turns at full speed and to keep in mind that they are sitting forward of the nose gear and at a height of ten feet.

Each participant was made aware that what would happen out the window was being measured and recorded and that what happened out-the-window was a consequence of how they used the controls and map display. It was also explained that they as individuals were not being tested, but rather that they as a group of pilots were aiding us in testing the quality of the various display elements in relation to a pilot's ability to quickly and accurately taxi. The participants were reminded throughout the instruction period that the map display was to be used as an navigational aid rather than a control aid. In other words they were asked to taxi aircraft by means of the out-the-window view rather than taxi the aircraft icon on the map.

Due to the nature of this simulation the participants were asked to accept several differences between the real world and the experimental situation. In particular, route sign location, seat position, joystick steering control, and aircraft turning behavior were different than found in an actual aircraft. It was assumed that these differences would not impact the study of the navigational qualities of this particular map display.

Only a forward out-the-window view was provided by the upper monitor, that is, no side view was available to the pilot.

To compensate for this, route signs (taxiway and runway) appeared in the middle of the roadways. The participants were instructed that it was okay to taxi over (run over) these signs while taxiing.

The participants were told to act as if they were sitting in the center of the cockpit rather than off to one side so that there would not be any compensation effect on the pilot's part to center the aircraft on the roadway from an off-center seating position.

After the out-the-window visibility level was lowered to approximately 1000' RVR, each participant was shown each of the manipulated display factors. First the three map modes were explained and demonstrated: 1) two-dimensional, plan-view, track-up, with zoom control, and available toggle to the North-up overview map 2) three-dimensional, perspective view, track-up, with zoom and available toggle to the north-up overview map, and finally 3) the north-up overview with fixed zoom level. The participants were told that each map mode would be used for one third of the trials. Again the participant was reminded that the map is meant only as a navigational aid and that one of their primary goals is to keep the aircraft on the pavement. It was reemphasized that the map was not to be used as a control aid.

It was explained that the wedge elements were an indication of the forward as well as left and right limits of out-the-window field of view. The two icon scaling manipulations, to scale and constant display size, were

demonstrated. The participants were informed that half of trials would use the scaled icon and half of the trials would use a constant displayed size icon.

The ATC clearance text terminology was explained and the pilots were shown a sample ATC text box. It was emphasized that the routes were workable, correct, and that the text would remain visible during the entire taxi trial. It was explained that at the beginning of each trial the aircraft would initially be positioned and oriented correctly to perform the cleared taxi route. The participants were reminded that since each trial was timed that they should not, nor should they need to, verify the initial aircraft position or the initial aircraft orientation. They were also reminded that they should not, nor should they need to, memorize the route, verify the entire route before beginning their initial aircraft movement, or for any reason doubt the rational of the route. Each pilot was instructed to taxi the cleared route and only that route. Since they were cleared for each route they were told that they were not required to slow or stop before entering any intersection. It was also explained that routes were not necessarily the most direct way to get from that particular starting point to destination. In case the participant found him or her self off the designated route the instructions were to stop, rotate the aircraft 180 degrees, and go back to the point on the route where navigational error occurred before proceeding toward the destination. The runways in this simulation of San Francisco were renamed with non-directional names (Y1, Y2, A1, and Z2) and without the usual compass bearing information imbedded in these names (i.e. 28R or 10L).

It was explained that since this study was not about the pilot's ability to park the aircraft gently at the terminal but rather to investigate the efficacy of potential taxi navigational aids, it was not necessary or were they encouraged to slow down just before reaching the taxi destination for reasons other than for navigational purposes.

The route guidance feature of the map was toggled on and explained to be exactly same route described in the ATC text box displayed on the upper monitor. The route guidance line was described as if someone had traced the route on the map with a magenta marker. The participants were reminded that they were being timed and that they should not nor should they need to spend time making sure that the two sources of route information were analogous. Again, the participants were reminded that the map was intended to be used as a navigational aid and not as a control display to "drive" the icon on the map. Each participant was told that the route guidance lines would be displayed during half of the trials.

The digital compass heading indicator was pointed out on the top center of the map display. It was explained that it would always be visible on the display. The second method of providing compass information, the rotating compass-bar, was demonstrated and explained for each participant during the instruction period. The participant was informed that the colors for the compass-bar would always be the same each time it appeared. Each participant was told that the compass-bar would be displayed during half of the trials. Each

participant was reminded that the compass-bar would not appear in the North-up overview map mode condition, but that cardinal compass direction was implied by this type of map. A second sample of ATC text was shown which included an instruction to turn South on a taxiway. This was provided to show how this form of qualitative compass indicator may be useful.

Recall that the participants were instructed not to stop or slow before entering an intersection. However, they were instructed that it was mandatory to come to a stop if one of two situations arose. The first condition was the appearance of another aircraft out the window. The second condition which required an immediate stop was the appearance of a red hold bar, also seen out the window. A sample out-the-window view of these conditions was demonstrated to the pilots. In either of these cases, the participant was instructed to come to a full and immediate stop as soon as either of these situations was presented. When the participant's ground speed indicator indicated a full stop, the incursion aircraft or hold bar would disappear in the out-the-window view. At that point the participant was instructed to resume with the taxi task as before. The participants were specifically told not to roll up to the hold bar or incursion aircraft, but rather to stop immediately. They were told that their reaction time would be measured and recorded. The participants were told that they may or may not experience either of the stop situations.

The last bit of information given to each participant was that the map may display some but not all of the hold bar locations. The participants were also

reminded that they did not have to stop unless they saw another aircraft or a hold bar out the window. Again each participant was reminded that the map was intended to be a navigational aid, that they were, as the pilot, responsible for well being of the aircraft and its passengers, keeping the aircraft on pavement, staying on route, and to try to accomplish all of the former as quickly as possible.

Practice trials. Each participant was given twelve practice trials after the initial introduction and practice time. Each of the three blocks of four trials presented a different map mode. The trials alternated between arrival and departure scenarios. Participants were encouraged to experiment with the speed and steering controls as well as the map controls available for that particular condition during the practice trials. They were told to use this time to develop their own methodology for accomplishing the taxi tasks since these trials were just like the experimental trials except that the actual routes were different. Each participant was exposed to the same map conditions in the reverse order in which they would be presented in the experimental trials. During the practice trials the experimenter would check periodically to make sure the participant did not have any new or lingering questions about the operating procedure.

After completing the twelve practice trials (about an hour for most), the participant was encouraged to get up and stretch, drink and/or eat, and use the rest room if necessary before starting the twelve experimental trials.

Experimental trials. Before starting the experimental trials, each participant was reminded of the basic goals of their taxi task, in particular that

they should stay on pavement, stay on route, and do the former goals as quickly as possible. It was emphasized that the study was about how fast the task could be done accurately. Any last questions if any were answered before the experimental trials were initiated. The participants were also reminded that during the experimental trials times would be measured and recorded and that they were essentially the same as the practice trials except that actual routes would be different. Each of the three blocks of four trials presented a different map mode. The trials alternated between arrival and departure scenarios. During the experimental trials the subject was for the most part left alone. After the initial “welcome” screen was initiated by the experimenter, the following trials were self-initiated by the participant. The participants were given the opportunity to take a break if needed after each block of four trials.

Post-experiment survey. After the twelve practice and twelve experimental trials the participants were given a survey questionnaire (see Appendix C). Questions concerning preference and perceived performance using the various map types and map features were given. Open ended questions were also asked concerning when and how the various map elements were beneficial.

Participants

Twenty-four licensed general aviation pilots who did not have experience taxiing at San Francisco International Airport were paid to participate in this study.

RESULTS

Data Analysis

The data were analyzed in five separate analyses. The first analysis was performed on data that represented performance only when the overview trigger was not engaged in the two-dimensional and three-dimensional map conditions. This allowed an analysis of the differences between the map types (two-dimensional vs. three-dimensional vs. overview) in addition to the effects of the graphical route guidance.

The second analysis was performed on data that represented performance only when the overview trigger was engaged in the two-dimensional and three-dimensional map conditions. This allowed us to analyze differences between usage of the overview trigger as a function of map type (two-dimensional vs. three-dimensional) and route guidance.

The third analysis was performed on data that represented performance over trials in which either the two-dimensional and three-dimensional map was used. This allowed us to analyze differences between the icon type conditions (constant vs. scaled).

The fourth analysis attempted to analyze differences between the compass heading conditions (digital vs. digital+bars). This analysis was performed on the two-dimensional and three-dimensional trials, since the overview map condition only utilized the digital heading display. Further, this analysis was conducted only on the six trials in which heading references were

provided (e.g., “turn south onto Taxiway D”). The analysis was carried out manually in the following manner. For each trial that a heading-specific reference was provided, the experimenter viewed a replay of the out-the-window view during the trial (without knowledge of the compass condition) and noted if a wrong turn was made at the intersection in question.

Finally, the results of the post-experiment subjective survey are presented.

Analysis 1: Map Type x Route Guidance

Completion time: Map type. The ANOVA revealed a significant effect of Map Type on route Completion Time, $F(2,46)=11.17$, $p<.05$. The two-dimensional, track-up and three-dimensional track-up maps resulted in faster completion times (221.1s and 224.6s, respectively) than the overview, North-up map (238.3s) as shown in Figure 20.

Figure 20. Completion time by map type.

Completion time: Route guidance type. The ANOVA revealed a significant effect of Route Guidance on Route Completion Time, $F(1,23)=5.47$, $p<.05$. Pilots completed the routes faster with graphical route guidance (223.2s) than without (232.7s) as shown in **Figure 21**.

Figure 21. Completion time by route guidance type.

Average moving speed: Map type. Not surprising, the results of the average moving speed analysis mirrored that of the completion time analysis and revealed a significant effect of Map Type, $F(2,46)=9.80$, $p<.05$. The two-dimensional and three-dimensional maps resulted in faster average moving

speeds (26.4 Kts and 26.2 Kts, respectively) than the overview map (25.5 Kts) as shown in Figure 22.

Figure 22. Average moving speed by map type.

Average moving speed: Route guidance type. An ANOVA revealed a significant effect of Route Guidance on Average Moving Speed, $F(1,23)=17.92$, $p<.05$. Pilots taxied at a faster average moving speed with route guidance (26.4 Kts) than without (25.7 Kts) as shown in Figure 23.

Figure 23. Average moving speed as a function of route guidance type.

High speed performance: Map type. The percentage of time spent at speeds greater than 24 Kts (this was considered high-speed) was significantly effected by map type, $F(2.46)=8.37$, $p<.05$. Again, the two-dimensional and three-dimensional maps resulted in a greater percentage of time taxiing at high speeds (67.8% and 66.7%, respectively) than the overview map (62.3%) as shown in Figure 24.

Figure 24. High speed performance by map type shown as percent time at high speed.

High speed performance: Route guidance type. The percentage of time spent at speeds greater than 24 Kts (we consider this high-speed) was significantly affected by Route Guidance, $F(1,23)=17.19$, $p<.05$. Pilots taxied at speeds greater than 24 Kts a greater percentage of time with route guidance (67.4%) than without (63.8%) as shown in Figure 25.

Figure 25. High speed performance (percent time at high speed) by route guidance type.

Time stopped: Map type. The percentage of time the aircraft was stopped during the route was significantly effected by map type, $F(2,46)=3.20$, $p<.05$. Pilots spent less time stopped while using the two-dimensional (2.6%) and

three-dimensional maps (2.6 %) compared to the overview map (3.5%) as shown in Figure 26.

Figure 26. Time stopped by map type shown as percent time stopped.

Time off road: Map type. This measure reflects the percentage of time the wheels of the aircraft went off the road. Thus, this is a measure of inaccurate or unstable steering. A significant effect of Map Type was not observed ($p=.50$).

Time off road: Route guidance type. This measure reflects the percentage of time the wheels of the aircraft went off the road. Thus, this is a measure of inaccurate or unstable steering. A significant effect of Route Guidance was not observed ($p=.56$).

Time stopped: Map type x route guidance type. There was no main effect of Time Stopped observed for Route Guidance ($p > .10$), but there was a significant interaction, $F(2,46)=3.86$, $p < .05$, between Map Type and Route Guidance.

This interaction revealed that with the Overview map, more time was spent stopped with route guidance (3.7%) than without route guidance (3.3%), while with the three-dimensional map, more time was spent stopped without route guidance (3.5%) than with route guidance (1.7%). Finally, the two-dimensional map showed an equal percentage of time stopped with and without route guidance (2.6%) as shown in Figure 27.

Figure 27. Percent time stopped by map type and route guidance type.

Off route: Map type. No statistical analysis were done since the data was captured as an average across trials rather than by individual trials. The averaged values indicated that pilots strayed off route 0.93% of the overall time with the overview map, 0.85% with the two-dimensional, and 0.86% with the three-dimensional map as shown in Figure 28.

Figure 28. Percent time off route by map type.

Off route: Route guidance type. No statistical analysis were done since the captured data was the average of subjects and not provided by trial. The averaged values indicated that pilots strayed off route slightly more without route guidance (0.97%) than with route guidance (0.79%) as shown in Figure 29.

Figure 29. Percent time off route by map type.

Zoom level usage: Map type. The averaged data from only the two-dimensional and three-dimensional map trials indicated that pilots spent 51.3% of the time at the highest zoom level (zoomed in) when using the three-dimensional display and 12.5% when using the two-dimensional display. Pilots used the largest field of view (zoomed out) 4.3% of the time when presented with

the two-dimensional map and 1.9% of the time when presented with the three-dimensional map. This is shown in Figure 30.

Figure 30. Percent time spent at most zoomed in and most zoomed out by map type.

Incursion detection: Map type. There were no significant effects of Map Type for any of the incursion events.

Incursion detection: Route guidance. There were no significant effects of Route Guidance for any of the incursion events, save for one marginally significant finding. The response time to unexpected aircraft incursions was faster with route guidance (.8 s) than without route guidance (1.1 s), $F(1,23)=12.93$, $p=.069$) as shown in Figure 31.

Figure 31. Incursion response time by route guidance type.

Pilot preference: Map type. Sixty-seven percent (16/24) of the pilots preferred the three-dimensional map the most, twenty-five percent (6/24) preferred the two-dimensional map the most and only two pilots (8%) preferred the overview map the most. Eighty-three percent (20/24) of the pilots reported

that they toggled on the overview map at some time while using the two-dimensional or three-dimensional maps as shown in Figure 32.

Figure 32. Pilot preference by map type.

Pilot preference: Route guidance. All of the pilots (24/24) felt that the display of graphical route guidance was helpful. Other comments regarding graphical route guidance are shown in Table 1.

Table 1. Subjective data concerning graphical route guidance.

100%	"The display of graphical route guidance was helpful."
50%	"It was easier to follow the route."
33%	"It helped to keep the speed up."
25%	"I didn't have to decide which way to turn."
13%	"It provided redundancy with text route display."
13%	"It helped with route accuracy."
8%	"It gave instant overview."
8%	"It enables the pilot to look out the window."
4%	"It was helpful for complex taxis"
4%	"You can start right away"
4%	"It replaces the text display"

Pilot perception: Map performance. In terms of perceived performance, sixty-three percent (15/24) of the pilots ranked the 3-D map highest while eighty-eight percent (21/24) ranked the overview the lowest.

Pilot perception: Route guidance performance. Ninety-two percent (22/24) of the pilots felt that their taxi performance was better when route guidance was displayed.

Analysis 2: Map Type x Overview Usage

Overview usage: Map type. Pilots referred to the overview map more while using the three-dimensional map (2.5%) compared to the two-dimensional map (.8%) as shown in Figure 33.

Figure 33. Percent time of (triggered) overview map usage by map type.

Overview usage: Route guidance type. Pilots referred to the overview map more without route guidance (2.1%) than with route guidance (1.2%) as shown in Figure 34.

Figure 34. Percent time of (triggered) overview map usage by route guidance type.

Subjective data on overview usage. Table 2 shows the responses from pilots indicating the reasons the overview map was activated by the joystick trigger.

Table 2. Subjective data on overview usage.

21%	"Wanted to see the entire airport surface at first for learning the global layout."
21%	"Wanted to have North/South direction reference."
13%	"Wanted to see destination that was not on the current map view."
8%	"Wanted to see an overview of the route."
4%	"Wanted to see a destination that was not in view and found it easier to use the trigger than to use the zoom lever."
4%	"Wanted to see destination which was difficult from a distance when using the three-dimensional map."
4%	"Wanted to cross check for redundancy."
4%	"I was just experimenting."

Subjective data on overview non-usage. The overview map was not toggled to because, "It seemed redundant", "I didn't really need it", "I used it only as a back-up", "The overview [map] made it difficult to keep eyes out the window.", and "I didn't really need it as long as I could zoom in and out".

Analysis 3: Icon Size

A significant effect of Icon Size was not observed for any of the dependent measures. However, a significant Icon Size x Route Guidance interaction was observed for route completion time, $F(1,23)=21.62$, $p<.05$. With

route guidance present, pilots completed the routes faster with the constant sized icon, but with route guidance absent, pilots completed the routes faster with the scaled icon size.

Pilot preference: Icon type. Sixty-seven percent (16/24) indicated a preference for aircraft icon displayed to scale.

Pilot perception: Icon scale performance. Seventy-five percent (18/24) of the pilots felt they performed better with the aircraft icon display to scale.

Analysis 4: Compass Heading Display

There were no wrong turns made at intersections where heading-specific references were provided. Thus, a statistical analysis of these data was not carried out.

Pilot preference. Seventy-one percent of the pilots (17/24) preferred the quantitative combined with qualitative heading display(digital+bars) over the quantitative heading display along (digital only). Eight percent (2/24) indicated no preference for either heading display. This is shown in Figure 35.

Figure 35. Pilot preference of heading display type.

Analysis 5: Additional Subjective Data

Compass bar display performance. Sixty-seven percent (16/24) of the pilots felt that their performance was better with the compass-bars.

Pilot perception: Wedge display. Seventy-one (17/24) percent of the pilots indicated that the wedge display was helpful while twenty-nine percent (7/24) felt that the wedge display was not helpful.

Value of wedge display. Table 3 shows the how pilots responded to the question concerning the value of the wedge display.

Table 3. Value of the wedge display.

46%	provided quick aircraft orientation/direction
17%	provided a reference to FOV of aircraft
4%	easier to distinguish depth perception and it highlighted the most important forward area.

Overall electronic map value. Table 4 shows the how pilots responded to the question concerning the value of an electronic map.

Table 4. Overview map value.

25%	determining overall position or direction of travel
21%	when beginning a taxi and wanting an overview
8%	when determining turn direction
8%	when beginning a taxi at a gate and wanting an overview
4%	when lost
4%	as a cross reference with the window view

Outside view value. Table 5 shows the how pilots responded to the question concerning the value of the out-the-window view.

Table 5. Outside view value.

71%	centering/driving the aircraft
13%	avoiding traffic
29%	spotting hold bars
17%	turning
13%	finding gates
8%	avoiding obstacles
4%	when given only the overview map

Best map features. Table 6 shows the how pilots responded to the question concerning the best features of an electronic map.

Table 6. Best electronic map features as rated by the pilots.

63%	graphical route guidance
17%	rotating map labels
17%	quick orientation of own-ship and airport surface
13%	three-dimensional view
4%	zoom control
4%	compass bars
4%	the two-dimensional track-up display

Worst map features. Table 7 shows the how pilots responded to the question concerning the worst features of an electronic map.

Table 7. The worst electronic map features as rated by the pilots.

21%	overview only map conditions
21%	label letters that were too small when zoomed out
8%	the lack of gate area detail
8%	attention drawn in the cockpit rather than out the window
8%	the digital-only compass
8%	the overview without zoom feature
4%	the buildings not clear or accurate on the map
4%	the map clutter
4%	inaccuracy of the map
4%	the constant sized icon
4%	the scaled icon

The features pilots wanted. The pilots were asked which of the map features they would want to have on their own taxi map. Responses are shown in Table 8.

Table 8. Features wanted by pilots.

100%	graphical route guidance
79%	wedge display
58%	aircraft icon that scales with the different zoom levels
46%	two-dimensional, three-dimensional, and the overview maps (all three)
29%	constant display size icon
17%	only the three-dimensional map
13%	only the two-dimensional map
4%	only the overview map

DISCUSSION

Aretz (1991) describes the term “navigational awareness” as the operator’s knowledge of the current vehicle position and orientation. A pilot derives navigational awareness by integrating environmental cues with his or her mental model of the world. At an unfamiliar airport a pilot must rely on some sort of map for formation of this mental model. This kind of integration inevitably involves the comparison of both the ego-centered reference frame (ERF), the out the window view, and the exocentric or world-centered reference frame (WRF), the automated map display. The utility of a map varies with the ability of the pilot to connect the navigational information it provides with his or her knowledge of the airport surface.

Successful map display design is a balance of many factors including appropriate display perspective, viewpoint, orientation, symbology, and display behavior. The cost of integrating the display as a whole with the real world and the task at hand must be considered as well. To this end we borrow the concept of visual momentum from the art of film making. Woods (1984) elaborated on Hochberg and Brooks’ (1978) definition of visual momentum as, “...a measure of the user’s ability to extract and integrate information across displays...” Wood’s explanation of visual momentum states that,

When the viewer looks to a new display there is a mental reset time; that is, it takes time for the viewer to establish the context for the new scene. The amount of visual momentum supported by a display system is inversely proportional to the mental effort required to place a new display into the context of the total data base and the user’s information needs. When visual momentum is high, there

is an impetus or continuity across successive views which supports the rapid comprehension of data following the transition to a new display. It is analogous to a good cut from one scene or view to another in film editing. Low visual momentum is like a bad cut in film editing—one that confuses the viewer or delays comprehension (Woods, 1984).

This study investigated several factors in order to understand how taxi maps may be designed to provide information in a form which can be easily and quickly integrated with the pilot's existing out-the-window view. The display elements or combination of display elements that demonstrate performance benefits are those with the highest degree of visual momentum.

Map Perspective

When the pilots were provided only the overview map, they taxied at the lowest average moving speed (average speed when not stopped), taxied the least at high speed (over 24 knots), spent the most time stopped, and spent the most time off route when compared to being presented with either the 2D and 3D map. It is no surprise that when using only the North-up, fixed, overview map the pilots completed the taxi routes with the highest average completion times. It is clear that on these measures the 2D and 3D map modes are advantageous for a majority of this low visibility taxi task measures.

In terms of taxi performance as a function of map type, the results suggests that the 2D and 3D maps may provide a higher degree of visual momentum than the overview map. This may be partially explained by the fact that the 2D and 3D maps were both of the track-up type which has been shown

to support local navigation tasks (Aretz 1991; Andre and Koonce, 1991; Mejdal 1995). At similar field of view (FOV) levels, the overview (North-up) map and the 2D and 3D (track-up) maps have approximately the same quantity of information. However, the visual momentum of a display is determined by the quality of that information. In the context of aircraft taxi displays, the manner in which the information is presented (North-up vs. track-up, plan-view vs. perspective) clearly has a significant impact on the ability of a pilot to integrate and utilize that information.

In terms of overall completion time there was little difference between the 2D and 3D map mode track-up conditions. The 2D map fostered slightly higher average moving speeds and, as expected, a slightly higher percentage of time spent at high speed. In addition, the results indicate equal periods of time spent stopped in 2D and 3D modes, and a slightly lower time spent off route in 2D map mode than in 3D. However, it is noteworthy that these results conflict with the results of the subjective questionnaires, which demonstrate a clear preference for the 3D map.

The pilot questionnaires show that over 90% of the subjects preferred either the 2D or 3D map to the overview only map. Two-thirds of the pilots stated a preference for the 3D map. These subjective results are encouraging because pilots preferred to use the display designs that tended to affect the best performance. In real world use, a demonstrated preference may be highly meaningful; Despite possible performance gains, users may be resistant to

employ a new design for reasons including aesthetics, novelty, familiarity, ease of use, or tradition (Wickens & Andre, 1994).

A difference between the 2D and 3D track-up modes is revealed when comparing the amount of time spent at the highest and lowest zoom levels. As a whole, the pilots spent slightly over half of the time at the highest zoom (smallest field of view) level while using the 3D map view. This contrasts with only about one eighth of the time fully zoomed in when using the 2D map. This may have been a result of the 3D map view having the perspective feature of being both “zoomed-in” in the foreground, and “zoomed-out” in the background, decreasing the need to change map zoom levels. Because of this perspective feature, the 3D map has the advantage of cultivating a higher level of global navigational awareness than the 2D display. It would be interesting to further investigate whether a single optimized (or compromised) 3D view could be used, eliminating the need or desire for a zoom feature and its associated costs.

Route Guidance

The results of the measures regarding graphical route guidance are consistent with and reinforce the findings of the previous study by Mejdal and Andre (1996). When compared to trials without it, the display of graphical route guidance resulted in shorter overall route completion times, faster average moving speeds, higher percentages of time at high speed, less time off route, and faster incursion response times. Not only were performance benefits

demonstrated for this feature, it was also preferred by all (24 of 24) of the pilots in the study. The most common subjective comment regarding the value of graphical route guidance was that it made it easier to decide which way to turn. The second most frequently heard comment was that graphical route guidance helped pilots maintain a higher speed. The provision of graphical route guidance made it easier for the pilots to place the map information into the context of the environment (the out-the-window view) and the task.

The utility of graphical route guidance seems to increase as the map view becomes more egocentric, such as in the 3D maps. While navigating with 3D maps, graphical route guidance provides immediate indication of the correct turn direction (left is left, right is right, and so on). Because of the high level of qualitative mapping between the two “scenes” we would expect this situation to have a high degree of visual momentum. This is supported by the results of this study; The inclusion of graphical route guidance had the effect of reducing the time stopped by half while in the 3D map mode and little or no effect on the percentage of time stopped in 2D mode trials. The percentage of time stopped actually increased in trials where graphical route guidance was present in the overview map mode.

Recall that the overview map was a North-up design while the 2D and 3D maps were of the track-up type. Aretz (1988) proposed that the cognitive process of interpreting electronic map information is a three stage process: “1) the perceptual encoding of the information presented on the display, 2) the mental

transformation of the information into alignment with the perceptual view out of the cockpit, and 3) a decision process comparing the mental image to the real world." This model is consistent with results from another study by Aretz (1989) as well as the results of the present experiment. Like the overview map it is displayed with, the graphical route information requires this mental transformation of alignment before being a useful tool. Because the degree of visual momentum is a function of the qualitative mapping between the out-the-window scene and the map-view scene, it follows that the amount of required mental transformation, and therefore performance, varies inversely with the level of visual momentum.

Overview Usage for 2D and 3D Modes

The overview map mode was activated by pressing the joystick trigger while using either the 2D or 3D track-up map modes. There appears to be some qualitative difference between the 3D and 2D maps which pilots attempt to compensate for by referring to the overview map. It was observed that pilots spent over three times more time (2.5% of the time) with the overview map toggled on while in the 3D mode than when using the 2D map (0.8% of the time). The subjective data regarding the overview usage may shed some light on this observation. When asked why they toggled to the overview map, the greatest number of responses cited the need for exocentric or world-centered navigational information. This suggests that the task of ground navigation

involves different subtasks where either egocentric or exocentric information are most advantageous. This is a similar result to findings reported by Wickens (1995) for navigation in 3D space (aircraft flight) which indicated a need for a compromise between purely exocentric and egocentric display information.

Wickens (1995) also suggested a model of human navigation in 3D space based on a continuum of display perspectives ranging from highly egocentric to highly exocentric. For any given situation, the optimal display is the one that can provide the pilot the optimal amounts of ego- and exocentric information for the task at hand. Finding the ideal proportion to be used for a single map type display will often involve some compromise since egocentric and exocentric informational needs vary within the overall task. By providing a primary display that best suits the most frequent needs of the task (the 2D or 3D map) at a local level and a secondary display (the trigger activated overview map) that can provide lesser used but nonetheless important information for global awareness and planning, the overall task performance can be optimized.

Let us now relate the issue of exo- and egocentric information to the context of navigation aids for taxiing under low visibility conditions. The results of this study demonstrate that pilots perform a low visibility taxi task better when the out-the-window view is supplemented by the 2D or 3D moving maps than the window view plus the overview map alone (highly exocentric). Likewise, it seems safe to conclude that performance would also be worse with the out-the-window view alone and no map (completely egocentric) than with the 2D or 3D moving

maps plus the window view. Performance analysis of the map types supports Wickens (1995) model of human navigation in 2D space in which the informational needs of the pilot lie somewhere on the egocentric to exocentric display continuum. Given the assumptions that: (1) the overview map mode is more exocentric than the 2D map and that, (2) the 2D map is more exocentric than the 3D map, we can view the overview map usage data as an indication of the need for supplemental exocentric information when using the 2D and 3D map types. To that end, users of the 3D type map are in slightly greater need of additional exocentric information than those using the 2D type map. From the perspective of the map designer, the question becomes which combination of map perspectives (overview, 2D, and/or 3D) to provide rather than which individual perspective to provide.

Overview Usage With/Without Graphical Route Guidance

When the pilots were presented a map with graphical route guidance, they activated the overview map less than when graphical route guidance was absent. While the toggle allowed the pilot access to a more exocentric map, this study provided no means for a pilot to toggle to a more egocentric map to obtain more local guidance information. Thus, we cannot be sure whether the data showing more overview usage represents attempts to specifically obtain more exocentric information, or simply attempts to obtain more overall navigational information. However, the data does suggest that providing graphical route

guidance has the effect of reducing the need for additional exocentric navigational information. Also, graphical route guidance gives preview and prediction of where a pilot will be going. Without it, the pilot will need to refer to a zoomed out or overview map to plan a route.

Icon Scale

Recall that the icon scaling behavior was investigated to compare the costs and benefits of providing an aircraft symbol that conformed to the map scale versus one that retained the same absolute display size regardless of the map scale level. Icon size alone did not have significant effects on any of the dependent measures although there was an interaction between icon size with route guidance on route completion times. Pilots completed the taxi routes more quickly with the constant-size aircraft icon when graphical route guidance was displayed and with the scaled aircraft icon when the graphical route guidance wasn't displayed. Two-thirds of the pilots preferred the aircraft icon that scaled with the changes in zoom level.

The unscaled icon had a greater tendency to obscure map features such as the runway and taxiway labels than the scaled icon. It seems that when the graphical route guidance is displayed the map can be interpreted more qualitatively by following the magenta path instead of reading the labels. On the other hand, when graphical route guidance was not displayed, clear legibility of the map labels played a greater role in taxi performance. Thus, the importance of

the map labels is reduced when graphical route guidance is displayed. Even when the icon obscures those labels, the cost in overall map utility is insignificant. We should keep in mind that the lack of effect for the constant size display may be due to how it was implemented.

Compass Heading

No turn errors were observed at intersections where heading-specific references were provided by the textual route information, indicating that there were no detrimental effects to displaying graphical compass information. Additionally, over two-thirds of the pilots indicated a preference for having the compass bars displayed on the map. While this display element imposes a cost on overall display area and potentially to display clutter, no significant negative impact was observed. The offsetting benefit of the rotating compass bars display may be the directional frame of reference, otherwise missing in the track-up 2D and 3D map modes.

Hooper and Coury (1994) reported in a study of submarine periscope designs that when participants used a track-up display, the compass quadrant points were critical reference points when orientation judgements were needed. These observations are similar to findings of Andre, Wickens, Moorman, and Boschelli (1991), who performed studies involving similar color-coded rotating compass bars for three-dimensional navigational tasks. The 2D and 3D map modes in this experiment were track-up, moving map displays with fixed size

icons and zoom capabilities. The first two characteristics have many benefits but are not without costs in that they create a display without reference points or reference directions to the world reference frame. The rotating compass bar may offset these costs by providing the user with a directional “anchor” and a link to the external reference frame. Thus, the compass bars may provide the visual momentum the pilot needs to connect the map with the out the window view. This connection is especially important in the context of the aircraft taxi task because communication to and from the world outside the cockpit is generally in terms of the exocentric rather than the egocentric navigational reference frame of activities within the cockpit.

SUMMARY

A successful map display for ground taxi navigation should provide quick and unambiguous navigational information without competing significantly with the attention that could and should be spent elsewhere such as out the window. In addition, benefits to lateral and longitudinal loop closures and vigilance to other expected and unexpected events should ideally come from the reduced cognitive workload required to perform the taxi navigation task.

This goal can be achieved by recognizing that the quality of the information is at least as important, if not more, than the quantity of information presented. A qualitative measure of this property is the amount of visual momentum supported by the display(s). In other words, the utility of the automated map display is a function of the pilots' ability to quickly and accurately integrate the information from all of the available sources in the "scene".

Clearly there are many benefits of a computer generated automated map display. These benefits are not without costs though. While there are advantages in terms of the information content and form of the 2D and 3D maps used in this study (track-up, moving-map, fixed-icon, maps with user changeable field-of-view or zoom levels), there are also costs. The costs are the uncertainties caused by the information not provided by such maps. The 2D and 3D maps studied here vary in terms of levels of egocentricity and clearly have many qualities pilots want and need in a navigational map. The maps also vary in the level in which

pilots can integrate the various types of information, that is, they vary in the levels of visual momentum provided.

The information provided by the overview map, while not accessed much in terms of time, is both necessary and complimentary to that provided by the track-up maps. It seems clear that different types of navigational information are needed and wanted at different times during a taxi task and it is important that pilots be able to have control over it. Harwood (1989) and Harwood and Wickens (1991) in a study involving helicopter flight, concluded that a pilot selectable-map display (between track-up and north-up) would be advisable given that each map may better support different tasks. It is interesting to note that for the task of helicopter flight, unlike aircraft ground taxi navigation, the north-up map should be configured as the primary map display. This is a strong reminder that display appropriateness is a function of the particular task or set of tasks.

CONCLUSION

The present study examined several critical design dimensions of electronic taxi map displays, each of which underlies an established human factors concept or principle (e.g., visual momentum, navigation learning, map exocentricity) . The following conclusions can be drawn from the results of this study: (1) pilots taxi better with, and prefer, track-up display formats; (2) pilots prefer a perspective map format, and this format creates a higher degree of visual momentum with the out-the-window view; (3) pilots benefit from also having dynamic access to North-up, full-scale maps (overview) for planning purposes, while navigating primarily with the zoomed, track-up display; (4) graphical route guidance information allows pilots to perform the taxi task faster, and with greater accuracy; (5) more research needs to be performed to determine the difference, if any, between scaled and constant-size ownship icons; (6) qualitative heading information is beneficial for establishing a reference to cardinal compass directions, which are often part of taxi clearances (Andre, 1995).

This study demonstrated that design research should, and can, be driven from human factors guidelines and principles, and that the combination of performance data and behavioral data provides for more informative decisions about the utility of various design features. Aircraft taxi is an overlooked, but essential factor in the overall efficiency of the National Airspace System.

Through the development of advanced, taxi map displays that are based on established human factors principles and valid design research, we are confident that this bottleneck will be alleviated in the near future.

REFERENCES

- Andre, A.D. (1995). *Operational issues during low-visibility taxi operations: A field study*. Submitted to Flight Management and Human Factors Division NASA Ames Research Center.
- Andre, A.D. (1996). *Directional clearances recorded during jump seat rides* unpublished.
- Andre, A.D., & Koonce, J. (1991). Spatial orientation and wayfinding in airport passenger terminals: Implications for environmental design. In *Proceedings of the Human Factors Society 35th Annual Meeting* (pp. 561-565). Santa Monica, California: Human Factors Society.
- Andre, A.D., Wickens, C.D., Moorman, L., & Boschelli, M.M. (1991). Display formatting techniques for improving situation awareness in the aircraft cockpit. *International Journal of Aviation Psychology*, 1(3), 205-218.
- Aretz, A. (1988). A model of electronic map interpretation. In *Proceedings of the Human Factors Society 32nd Annual Meeting* (pp.130-134). Santa Monica, California: Human Factors Society.
- Aretz, A. (1989). Spatial cognition and navigation. In *Proceedings of the Human Factors Society 33rd Annual Meeting* (pp. 8-12). Santa Monica, California: Human Factors Society.
- Aretz, A. (1991). The design of electronic map displays. *Human Factors*, 33, 85-101.
- Aretz, A. & Wickens C.D. (1992). The mental rotation of map displays. *Human Performance*, 5, 303-328.
- Batson, V.M., Harris, R.L., & Hunt, P.J. (1994). Navigating the airport surface: Electronic vs. paper maps. In *Proceedings of the 13th Digital Avionics Systems Conference* (pp. 1-6). Phoenix, Arizona.
- Carroll, J.M., & Olson, J. (eds.). (1987). *Mental models in human-computer interaction: Research issues about what the user of software knows*. Washington, D.C.: National Academy Press.

Dooling, D. (1996). Technology 1996: Transportation. *IEE Spectrum*, 2-4.

Dror, I. (1992). Visual mental rotation: Different processes used by pilots. In *Proceedings of the Human Factors Society 36th Annual Meeting*, Santa Monica, California: Human Factors Society.

Federal Aviation Administration. (1994). *1995 Federal aviation administration plan for research, engineering and development*. Washington, D.C.: DOT/FAA.

Flight Safety Foundation (1993). Runway incursions and incidents remain safety issues. *Airport Operations*, 19 (4), 1-4.

Foyle, D.C., Andre, A.D., McCann, R.S., Wenzel, E.M., Begault, D.R., & Battiste, V. (1996). Taxiway navigation and situation awareness (T-NASA) system: Problem, design philosophy, and description of an integrated display suite for low-visibility airport surface operations. In *Proceedings of the SAE/AIAA World Aviation Congress* (Paper 965551). Washington D.C.: American Institute of Aeronautics and Astronautics.

Harwood, K. (1989). Cognitive perspectives on map displays for helicopter flight. In *Proceedings of the Human Factors Society 33rd Annual Meeting* (pp. 13-17). Santa Monica, California: Human Factors Society.

Harwood, K. & Wickens, C.D. (1991). Frames of reference for helicopter electronic maps: The relevance of spatial cognition and componential analysis. *The International Journal of Aviation Psychology*, 1, 5-23.

Haskell, I. D. & Wickens, C.D. (1993). Two- and three-dimensional displays for aviation: A theoretical empirical comparison. *International Journal of Aviation Psychology*, 3(2), 87-109.

Hochberg, J., & Brooks, V. (1978). Film cutting and visual momentum. In J.W. Senders, D.F. Fisher, & R.A. Monty (eds.), *Eye movements and higher psychological functions* (pp. 293-313). Hillsdale, New Jersey: Lawrence Erlbaum Associates, Inc..

Hooper, E.Y., & Coury, B. (1994). Graphical displays for orientation information. *Human Factors*, 36, 62-78.

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

- McCann, R.S., Foyle, D.C., Andre, A.D., & Battiste, V. (1996). Advanced navigation aids in the flight deck: Effects on ground taxi performance under low visibility conditions. In *Proceedings of the SAE/AIAA World Congress* (Paper 965552). Washington D.C.: American Institute of Aeronautics and Astronautics.
- McGreevy, M.W., & Ellis, S. (1991). *Format and basic geometry of a perspective display of air traffic for the cockpit*. (NASA Technical Memorandum 86680). Moffett Field, California: National Aeronautics and Space Administration, Ames Research Center.
- Mejdal, S. & Andre, A. D. (1996). An evaluation of electronic map display features for aircraft ground navigation. In *Proceedings of the Silicon Valley Ergonomics Conference & Exposition* (pp. 43-52). San Jose, California: Silicon Valley Ergonomics Institute.
- Rate, C.R. & Wickens, C.D. (1993). *Map dimensionality and frame of reference for terminal area navigation displays: Where do we go from here?* (Technical Report Number. ARL-93-5/NASA-93-1). Savoy, Illinois: University of Illinois, Aviation Research Laboratory, Institute of Aviation.
- Schuffel, H. (1998). Some effects of radar and outside view on ships' controllability. In D.J. Osborne & J.A. Levis (eds.), *Human Factors in Transport Research* (pp. 40-48). London: Academic Press, Inc..
- Semans, C. (1992). Paper worlds: Maps vs. reality. In Cole, K. C. (eds.) *Finding Your Way: Navigation Essays From the Exploratorium* (pp. 10-14). San Francisco, California: Exploratorium.
- Steenblick, J.W. (1996). TWA Flight 427: Runway incursion. *Air Line Pilot*, 01, 20-24.
- Spoerri, A. (1993). Novel route guidance displays. In *Proceedings of the Vehicle Navigation and Information System Conference*. Society of Automotive Engineers, International.
- Thorndyke, P.W. (1980). *Performance models for spatial and locational cognition* (Technical Report R-2676-ONR). Washington, D.C.: Rand.
- Tolman, E.C. (1948). Cognitive maps in rats and men. *Psychological Review*, 55, 189-208.
- Wickens, C.D. (1990). Navigational ergonomics. *Contemporary Ergonomics*, 1990. 16-29. London: Taylor and Francis.

Wickens, C.D. (1992). *Engineering psychology and human performance*. New York, New York: HarperCollins Publishers Inc..

Wickens, C.D. (1995). *Integration of navigational information for flight*. (Technical Report Number. ARL-95-11/NASA-95-5). Savoy, Illinois: University of Illinois, Aviation Research Laboratory, Institute of Aviation.

Wickens, C.D., & Andre, A.D. (1994). Performance-preference dissociations. *1994 SID Digest*, Palisades Institute for Research Services, New York.

Wickens, C.D., Liang, C-C, Prevett, T.T., & Olmos, O. (1994). Egocentric and exocentric displays for terminal area navigation. University of Illinois Institute of Aviation Technical Report (ARL-94-1/NASA-94-1). Aviation Research Laboratory, Savoy, Illinois.

Wickens, C.D. & Prevett, T.T. (1995). Exploring the dimensions of egocentricity in aircraft navigation displays: Influences on local guidance and global situation awareness. *Journal of Experimental Psychology: Applied*, 1, 110-135.

Wickens, C.D., Schreiber, B., & Renner, G. (1994). *3D navigational checking: A conceptual model and an experiment*. (Technical Report Number. ARL-94/NASA-NAWC-94-1). Savoy, Illinois: University of Illinois, Aviation Research Laboratory, Institute of Aviation.

Wickens, C.D., Todd, S., & Seidler, K. (1989). *Three-dimensional displays: Perception, implementation, and applications*. (Technical Report Number. ARL-89-11/CSERIAC-89-1). Savoy, Illinois: University of Illinois, Aviation Research Laboratory, Institute of Aviation.

Woods, D.D. (1984). Visual momentum: A concept to improve the cognitive coupling of person and computer. *International Journal of Man-Machine Studies*, 21, 229-244.

Zimmerman, S.L. (1994). *Development and test of a pilot display for surface operations*. Warrendale, Pennsylvania: SAE.

APPENDIX A

PILOT INTRODUCTION

MapView² Participant Introduction

Hello and thanks in advance for participating in this study!

The purpose of this study is to aid in the development of future ground (airport taxi) navigation displays for transport aircraft.

You will be seated in front of two computer monitors with various controls at hand. Presented on the upper monitor will be an out-the-window view of San Francisco Airport (SFO). On the lower monitor you will be provided with a moving map display. The display will consist of various features, some of which will change between experimental trials. Your task is to taxi the aircraft from the gate to the runway and visa-versa. Don't worry about the details now...you will be introduced to the specifics of your task and given practice in performing the task in a few minutes.

The aircraft dynamics and geometry are that of a narrow-body commercial jet, so there will be a few differences in the out-the-window view angle as well as the turning methods relative to your normal (general aviation) experience. In addition, some aspects of the taxi routes and procedures you will be introduced

to are somewhat artificial. For example, the runways have a single identification at both ends and are not given the same names as they exist at SFO. In addition, you will be asked to taxi at speeds faster than you are used to.

Again, thanks for participating! Please feel free to ask questions at any time during your session. We will now start your training and practice trials.

APPENDIX B
PRE-EXPERIMENT SURVEY

MAPVIEW²
PARTICIPANT PRE-EXPERIMENT SURVEY

Participant #_____Date_____Experimenter:_____

What is your current pilot rating?_____

How many flight hours have you accumulated to date?_____

Have you ever flown out of San Francisco Airport?_____

Do you typically use a hand-held map when taxiing your aircraft?_____

Have you ever used an electronic moving map during taxi or flight?_____

APPENDIX C

POST-EXPERIMENT SURVEY

MapView² Participant Post-Experiment Survey

Participant # _____ Date: _____ Experimenter: _____

Please answer the following questions based on your experiences during the experimental trials only:

- 1) Please rank order the maps in terms of which you PREFER.
1=prefer most, 3=prefer least

_____ 2D
_____ 3D
_____ Overview
_____ Neither

- 2) Please order the maps in terms of PERFORMANCE.
1=best performance, 3=worst performance

_____ 2D
_____ 3D
_____ Overview

- 3) In the 2D and 3D map conditions, did you ever user the overview display (using the trigger)? _____ (yes or no)

Why?

- 4) Which compass display did you PREFER?

_____ Digital only
_____ Compass Bars + digital
_____ Neither

- 5) Which compass display did you PERFORM best with?

_____ Digital only
_____ Compass Bars + digital

- 6) Which icon size manipulation do you PREFER?

☐ To-scale
☐ Constant size
☐ Neither

7) Which icon size manipulation did you PERFORM best with?

☐ To-scale
☐ Constant size

8) Was the route guidance (pink lines) helpful? _____ (yes or no)
 If yes, how so?

9) Did you perform better or worse with the route guidance? _____

10) Was the wedge helpful? _____ (yes or no)

11) What percentage of the time did you look at the map display versus the outside view?

Map _____% Outside view _____% (total of both should equal 100%)

12) When was the MAP display most help?

13) When was the OUTSIDE view most helpful?

14) Please rate your performance on a scale of 1 (poor) to 10 (excellent) for the following items:

Route following _____
 Centerline accuracy _____
 Route completion time _____
 Hold bar reaction time _____
 Incursion reaction time _____

15) What was the best feature of the map display?

16) What was the worst feature of the map display?

17) For the following items put a check next to those that you would want on your taxi map display:

Only the 2D map _____
 Only the 3D map _____
 Only the overview map _____
 Only 2 maps _____

All 3 maps_____

Wedge_____

Route guidance_____

To-scale icon_____

Constant size icon_____

Other?_____

- 18) Finally, what other features or information would you like to see on an aircraft taxi map display?

Thank you very much for your participation!!!!