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An evaluation of electronic map display features for aircraft ground navigation

Sig Mejdal
San Jose State University

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AN EVALUATION OF ELECTRONIC MAP
DISPLAY FEATURES FOR AIRCRAFT
GROUND NAVIGATION

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
Sig Mejdal
November 1995

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APPROVED FOR THE HUMAN FACTORS/ERGONOMICS PROGRAM

A handwritten signature in cursive script, appearing to read 'Lou Freund', written over a horizontal line.

Dr. Lou Freund

A handwritten signature in cursive script, appearing to read 'Anthony Andre', written over a horizontal line.

Dr. Anthony Andre

A handwritten signature in cursive script, appearing to read 'Connie Goddard', written over a horizontal line.

Ms. Connie Goddard

APPROVED FOR THE UNIVERSITY

A handwritten signature in cursive script, appearing to read 'Serene K. Stanford', written over a horizontal line.

ABSTRACT

AN EVALUATION OF ELECTRONIC MAP DISPLAY FEATURES FOR AIRCRAFT GROUND NAVIGATION

by Sig Mejdal

This thesis addresses the human factors issues associated with aircraft taxi map displays, and describes an experiment that examined different map display options. Performance and behavioral differences due to the map's reference frame, visual momentum wedge, route guidance, and zoom were examined under 2 visibility conditions. Twenty-four pilots navigated around a simulated airport. Each performed half the trials with and without the Wedge and Route Guidance. Visibility was varied between pilots while the map's reference frame and zoom were varied at the pilots' discretion.

The results showed that the map display improved performance in the low-visibility conditions to a level equal to that of the high-visibility conditions. With Route Guidance, the pilots completed the trials in less time and with fewer errors. However, complacency concerns when using this feature were brought up, as was the need for further research on the design of aircraft taxi map displays.

To the Loughhead brothers

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I would like to thank Dominic Wong and David Tu for their assistance in programming and running the experiment, respectively, and Dr. Anthony Andre for his guidance and assistance throughout the entire project. Thanks also to Dr. Lou Freund and Connie Goddard for serving on my thesis committee.

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INTRODUCTION

As air traffic has increased in recent years, the airport surface has become increasingly more congested. This has affected the difficulty of navigating and taxiing between airport gates and runways—especially in large, complex airports. The difficulty of this task is magnified when operating under low-visibility conditions, such as at night, in fog, or during inclement weather. Under these conditions, the pilot's forward view is severely restricted, making it difficult to determine where the aircraft is, and where it should be going.

Low-visibility conditions often lead to slowdowns and delays for two reasons: First, pilots who are familiar with the airport surface must taxi at a slower speed to ensure that they are aware of the immediate surroundings of the aircraft and to guard against collisions with other aircraft. Second, pilots who are not familiar with the airport surface often get lost, have to slow down, or come to a complete stop while they clarify their position and direction with ground control. The difficulty in quickly getting aircraft to the gate or runway has limited the number of flights that an airport can schedule, for it is not only the air delays, but also the ground delays which determine the number of flights an airport can process. Thus, if the navigational tasks of the pilots could be facilitated, then ground delays would be reduced and overall aircraft throughput would be increased.

There are many ways in which a designer could assist the pilot in the task of ground navigation during both high and low-visibility conditions.

One such way is to provide additional information about the visual environment to the pilot through an on-board electronic map display. While the use of maps seems a likely candidate for increasing ground throughput during low-visibility conditions, the wide range of human factors problems associated with maps and navigation should be evident to anyone who has encountered the following circumstances:

(1) driving through a complicated series of intersections, heading in a generally southerly direction while navigating from a conventional road map; (2) following a list of instructions on how to get somewhere and missing a turn; and (3) having carefully studied the map of a strange place and then suddenly becoming unable to locate one's position within the region depicted by the map because the surrounding landmarks are all unfamiliar (Wickens, 1992, p.145).

To understand why these problems occur requires that we first understand how one acquires navigational knowledge about an environment (Wickens, 1992).

Navigational Knowledge

Thorndyke (1980) has proposed that as we become increasingly familiar with a new environment, the nature of our knowledge undergoes both qualitative and quantitative changes. The qualitative changes are seen as we progress through three different levels of navigational knowledge.

The first of these stages is termed *landmark knowledge*. In this stage, travelers are able to orient themselves exclusively through the use of visible landmarks such as statues, tall buildings, water towers, and mountains. The travelers may not be able to navigate from one spot to another, but are able to orient themselves by direct visual access to these landmarks. At this point, a skeletal framework has been created (Wickens, 1992).

The second stage is termed *route knowledge*. With this level of navigational knowledge, one is able to navigate from point to point using landmarks or features as guides. These structures trigger the decisions to turn left, turn right, or continue straight. The important point is that the visual observation of these landmarks or features actually triggers the desired actions. The navigator does not know the proper direction he should travel until they see the landmark or, in some cases, recall a mental image of the landmark. In the latter case, one is able to give directions to another unfamiliar traveler ("turn right at the water tower") without actually being in front of the water tower. Often though, they are in the situation in which they can navigate themselves but can not describe the steps they took to get there beforehand ("I can take you there, but I can't explain how to get there") (Wickens, 1992). This route knowledge is expressed in an ego-centered (personal) frame of reference. That is, "turn left" and "turn right" commands are used as opposed to more world-centered descriptions like "the school is 3 miles northwest of the tower."

With more experience, the acquisition of navigational information progresses to *survey knowledge*. At this point the navigator has an internalized cognitive map analogous to the true physical world (Wickens, 1992). With the acquisition of survey knowledge, the navigator has a general picture of an entire space, including Euclidean relationships among objects in that space (Antin, 1992). For example, they have acquired the ability to describe the relative location of landmarks even though they have not traveled the route that connects them. The navigational experience that they have acquired has gradually turned the route knowledge into survey

knowledge by filling in the skeletal framework of the cognitive map that was earlier developed through landmark knowledge.

Some pilots do not yet have enough experience within a particular airport environment to have advanced navigational knowledge of that environment. Clearly, pilots at different stages of knowledge will have varying success at navigating the airport environment. Those unfamiliar with the airport, or with only landmark knowledge, will need to rely more on a paper map or the help of ground controllers to direct them to the proper gate or runway via ego-referenced directions ("Turn right on runway 13 and left onto Delta"). Those with route knowledge will use a map and ground controller help relatively less frequently, and finally, those with survey knowledge may use a map only on rare occasions of disorientation. Under low-visibility conditions, however, many pilots, even those with survey knowledge, require some guidance information to aid in orientation and way finding. The following sections discuss various issues related to one way that pilots do obtain guidance information—through the use of maps.

Maps

A map supplying information about the environment can be thought of as a tool used to acquire survey knowledge and, more immediately, a tool used to facilitate navigational awareness (Andre, Wickens, Moorman, and Boschelli, 1991), especially when the quality of information gained from the forward visual scene is diminished.

Paper maps. Like our cognitive map, a paper map is a representation of the physical environment. In this case it is a 2-D, simplified version of a 3-D

environment. The paper map has the purpose of representing spatial distances and relationships of the environment to the user. These representations are a shortcut to obtaining survey knowledge (Wickens, 1992). Thorndyke and Hayes-Roth (1978) compared the performance between those trained through navigation (route knowledge) and those trained through map study (survey knowledge). At moderate levels of training those who trained through map study showed better estimates of Euclidean distances and better judgments of object localization. In this case, the subjects had used the map as a shortcut to survey knowledge. Repeated navigations were not needed in order to produce the survey knowledge required to perform the tasks optimally. In contrast, the group initially trained through navigation required further navigations to develop survey knowledge and perform as well as the map-learning subjects. Clearly, the map extended the user beyond his or her immediate surroundings by linking "here" and "there" together (Harwood, 1989). This finding is also consistent with Thorndyke's (1980) model of navigational knowledge acquisition.

Currently, the only type of map available to pilots are paper maps. Clearly, these maps are great navigational tools, but they offer little help in low-visibility conditions when the pilots do not know where they are and therefore, are unable to "place" themselves on the map. In these situations, the use of electronic maps may be helpful.

Electronic maps. Recent advances in display technology have allowed the merging of an electronic airport map with aircraft position data. Differential Global Positioning System (DGPS) can generate very accurate aircraft position data, enabling the precise placement of an aircraft symbol on

a taxi map, while faster graphics capability enables the drawing of airport details in real-time. Also, Datalink technology has enabled the placement of ATC-cleared ground routes on the taxi map. This produces a system with benefits that far exceed those of stand alone paper charts (Batson and Hunt, 1994). However, along with advancements, new concerns arise. For example, new designs may be more powerful and have more features, but they are also more complex, and thus the question of whether these additions should be incorporated into the cockpit needs to be addressed. The driving force as to which map design features to implement should lie in whether or not these features tend to increase "navigational awareness" and safety.

In the following sections, the 4 map display design features that are examined in this study will be discussed. These features include: 1) map frame of reference, 2) Visual Momentum, 3) Route Guidance, and 4) zoom level.

Frame of Reference

The forward field of view (FFV) is the navigator's personal view of the world, and simply reflects what the pilot sees through the windshield glass. Since this "personal", inside-out view is unique to that particular spatial location, orientation, and particular point of time, it is known as an egocentric reference frame (ERF) (Aretz, 1988).

The second frame of reference is a world-centered reference frame (WRF) (Aretz, 1988). It is an outside-in reference frame in which the environment is normally stationary and the vehicle moves within this environment. For the pilot, this reference is realized and maintained by a

visually present map or by a mental representation of the area derived from experience or map study. The pilot will view a map or visualize the environment and then superimpose the moving vehicle on the "map." This map has a canonical representation that is "north-up." That is, the most favored or most natural way in which it is aligned, is with the northerly direction upwards (Wickens, 1990).

When using a map under good visual conditions, proper navigation demands cognitive coupling between the two reference frames. In other words, in order for a pilot to properly navigate the aircraft, the current view of the world—the egocentric reference frame (ERF)—and the pilots perceived location and orientation in the environment—the world reference frame (WRF)—must agree. Thus, the navigator must answer the question, "Am I (based on the ERF) where I should be (in the WRF)?" (Aretz, 1991).

When using a paper map, a user has the option of either orienting the map with the northerly direction upwards (north-up map) or rotating the map in such a way as to constantly align the direction of travel upwards (track-up map). Similarly, electronic displays afford the option of navigating with either a north-up or a track-up map, as shown in Fig. 1 and 2, respectively. Note that the bottom center of the screen contains the map display. In Fig. 1, the north-up map display, the aircraft rotates while the environment is fixed. While, in Fig. 2, it is the environment which rotates about the fixed aircraft.

Fig. 1. Experimental screen with a north-up map display.

Fig. 2. Experimental screen with a track-up map display.

There are arguments in support of track-up and north-up maps. The most obvious support for the track-up map is realized when the navigator is traveling south while using a north-up map (notice that the pilot in Fig. 2 is traveling almost due south while using a north-up map display). In this case, the forward field of view and the north-up map do not correspond and therefore a mental rotation of one of these frames is needed, because what appears as a left turn on the map is really a right turn in the environment (Aretz, 1988).

Shepard and Metzler (1971) published the first experiment demonstrating mental rotation and found that the time required to mentally rotate images into alignment was linearly dependent on the angle of disparity between the two images. That is, the more rotation needed to align two images for the sake of comparison, the longer it takes. Aretz (1988) later showed that the same effect also takes place with the rotation of map displays. As the angle of rotation needed to bring the map into a track-up orientation is increased, so does the time to complete this mental rotation.

With the track-up map, there is a clear benefit in terms of reduced mental rotation because of the congruence between left-right distinctions on the map and the forward view. Since the map is already aligned with the forward field of view, there is no need to mentally rotate the map in order to maintain navigational awareness. Aretz (1991) conducted an experiment investigating the merits of a north-up and a track-up display in a simulated low altitude helicopter mission. In this study, subjects were given "fly-to" commands on their screens that commanded them to navigate to different

locations in the environment. This environment was scattered with various colored landmarks. Also, when an enemy aircraft flew across the screen, the subjects were instructed to halt their travel to the checkpoint, and subsequently chase the enemy aircraft. After the enemy aircraft led the subject to a part of the world that was previously out of view, a localization task was conducted in which the subject was asked to determine if the map was aligned with the view out the window. Further, at the completion of a mission (15 checkpoints flown to in a particular world), the subjects were asked to provide a rough sketch of the world in which they had just flown in.

Aretz (1991) found out that the subjects initiated a turn in the correct direction to a new checkpoint significantly faster while using a track-up map relative to a north-up map. Further, the localization task results indicated that it was easier to determine the congruence between the WRF and the ERF while using the track-up map.

In discussing his results, Aretz (1991) also cited 4 cognitive operations that are required to achieve navigational awareness: Triangulation establishes the geometries of the ERF and the WRF, mental rotation aligns the WRF and the ERF, image comparison confirms the WRF and ERF alignment, and translation monitors the position of the ERF as it proceeds through the WRF. Clearly, with the elimination of one of these operations—the need to mentally rotate the reference frames with the track-up display—the navigational task demands are reduced.

Thus, the fundamental advantage of a track-up display is that left on the map is always left of the vehicle (and therefore the pilot's line of sight), regardless of the direction of travel (Antin, 1992). Moreover, this format also

follows the traditional design principle of "pictorial realism" in that it represents a view that is analogous to the real world view out the window (Roscoe, Corl, and Jensen, 1981).

In studies of "you are here" maps in shopping malls and airport passenger terminals, Levine (1982) and Andre and Koonce (1991) also found that people had greater difficulty establishing their position in the environment when the map was oriented in a north-up fashion. That is, difficulties arose when the forward field of view did not correspond with "up" on the map. Also, Batson, Harris, and Hunt (1994) reported on a taxi simulation study in which pilots were allowed to choose the map frame of reference; the track-up mode was chosen almost 100 percent of the time.

Note, however, that while it may appear that track-up maps are categorically more advantageous and preferred over north-up maps, research studies have not consistently shown clear benefits for the former over the latter for all navigational tasks. For example, in the Aretz (1991) study described earlier, the results showed that in a map reconstruction task in which the subjects were asked to reconstruct the "world" in which they had just flown through, those using a north-up map excelled over those using the track-up map. Thus, it would seem that they were better able to demonstrate an acquisition of what Thorndyke (1980) calls survey knowledge. That is, they had a better ability to describe the location of, and the relationship between, relevant landmarks in the world.

Andre, Wickens, Moorman, and Boschelli (1991) manipulated display reference frames in a fixed-wing aircraft instrument-flight simulation. The primary task was to reach as many waypoint stations as possible in a given

amount of time. A description of the specific point the subjects were to fly to appeared on the screen and the subjects would initiate a turn, direction, and altitude change as soon as they had ascertained their relative bearings. When the pilots reached their waypoint, another waypoint description would appear on the screen. The pilots had directional display indicators, and compass displays that were either egocentric (track-up) or world-centered (north-up). Unlike the present study, however, the pilot had no forward field of view—i.e., there was no windshield to look through.

The results of this study showed that the north-up display was significantly superior for the waypoint navigation task. That is, those subjects using the north-up display were able to reach more waypoints than those using the track-up displays. This study also included a task in which pilot "re-orienting" ability was measured. On random occasions, the screen would blank and the subject's aircraft would be thrown into an unpredictable bank, pitch angle, altitude, and heading. Upon reappearance of the screen, they would then have to reorient themselves as rapidly as possible. Here, the north-up display was again found to support better performance than the track-up display.

Harwood (1989) carried out a helicopter simulation study that also compared the two types of map displays. For a landmark orientation task in which subjects were given a description of a particular landmark and then had to fly to it, the north-up map was also found superior to the track-up map.

Collectively, these empirical studies and others (e.g., Baty, Wempe, and Huff, 1974; Marshak, Kuperman, Ramsay, and Wilson, 1987) do not reveal a

consensus for one map reference frame over the other. Interestingly, surveys of pilots' preferences also reveal somewhat of a split between orienting their paper maps north-up or track-up (Wickens, 1992). A reason for these ambivalent conclusions may be that some types of navigational tasks are performed better with one type of display, while other tasks are performed better with the other type of display. In other words, the advantage of the display may be task-dependent (Wickens, 1992). The question is then, "Which tasks are benefited by which display?"

Harwood (1989) concluded that a north-up map helped in the search of specific landmarks. North-up displays were also found to be superior for pilot communication with other aircraft (Aretz, 1991). Not surprisingly, both of these tasks are best served by a consistent location of landmarks (a stationary world), that is afforded by the north-up map. Wickens (1993) has described these types of tasks as "global situation awareness" tasks. These are duties which require the pilot to know "where I am with regard to features and landmarks on the ground and in a much broader volume of airspace" (Wickens, 1993, p.2).

On the other hand, local guidance tasks seem to be performed best with the track-up display. These are tasks in which the pilot needs to know "when I must turn, climb, descend, accelerate or decelerate to follow the appropriate flight path" (Wickens, 1993, p.1).

In summary, the north-up display seems to be "better" for "global awareness tasks" while the track-up display seems to be "better" for "local guidance tasks." Clearly, then, there is no single map design that will be optimal for all tasks. As such, Wickens (1992) proposed two options for map

display design. The first is to give the user the option to switch between the displays at their discretion. However, both the task of switching and the "reorientation" required when the display is switched may require cognitive resources that outweigh the obvious benefits of switching.

The present study examines this issue by allowing the pilots to easily switch between the track-up and north-up displays, while performing a realistic airport surface navigation task. This manipulation will allow us to determine which format pilots prefer. Alternatively, if pilots develop a strategy which utilizes both displays, we can begin to conclude exactly which tasks are better served with which display. Further, by analyzing which map type subjects preferred for each task, we may better be able to describe the terms "global" and "local" task, or we may develop better task descriptors.

The second approach suggested by Wickens (1992) to the frame of reference problem is to only use a north-up display, but "within it provide a very salient representation of the forward field of view of the navigator" (p.153). This solution relies on the concept of visual momentum (Woods, 1984).

Visual Momentum

Visual momentum is a concept that was borrowed from the cinematographic world by Woods (1984). Hochberg and Brooks (1978) originally coined the term to refer to what sustains and initiates "looking behavior." In film making, "cuts" are used to guide or assist the viewers understanding and perception of a particular scene. For example, a scene from a movie is viewed in which a pilot is seen taking off. He checks his instruments and reaches for

the clipboard, a panicked expression is seen on his face; then a scene of the "ready-room" at the airport is shown and we see a set of maps lying on a table (Harwood, 1989). The cut that shows the pilot's expression provides the visual momentum relating the two scenes (pilot in cockpit and the ready-room) together. Similarly, there can be characteristics of a display that can provide visual momentum to the viewer relating two "scenes" (informational sources) together. In this case the two scenes are the ERF obtained through the windshield view, and the WRF obtained from a north-up map.

Harwood's (1989) helicopter experiment attempted to provide visual momentum in the navigational display by including color coding on both the map and the forward field of view. This color coding was based on the four main compass directions (N-W-S-E). In the study, electronic mountains framed the borders of the map display. The northern range appeared white on the map; the western range green; the southern range red; and the eastern range blue. When the helicopter was heading north, white mountains were projected on the windshield; red when heading west; green when heading south; and blue when heading east. The use of this color coding provided the pilots with an immediate anchor for orienting the map with the view out the windshield. Harwood found that the presence of the color aided some tasks by creating visual momentum between the map display and the forward field of view. In other words, the use of color "tied" together these two different displays. In effect, there was a common framework (the colors) between these two displays that seemed to facilitate the cognitive coupling of them.

Andre et al. (1991) also used directional color to create visual

momentum between displays. Depending on which direction the aircraft was traveling, portions of the frame of each display were color coded. Like Harwood (1989), Andre also found out that the use of color aided in the cognitive coupling of the inconsistent displays, thereby improving performance significantly.

Aretz (1991) provided visual momentum in a different manner. He implemented a "wedge" display (similar to our wedge shown in Fig. 3) on a north-up map that outlined the range of the forward field of view. The wedge rotated within the north-up map display, thus providing track-up (ERF) information in a north-up display. Again, the information of one display (the forward field of view) was presented in the context of the other (the north-up map) in order to "maintain a cognitive representation of the system" (Aretz, 1991, p.88). Aretz (1991) found that this visual momentum technique captured the benefits of both display types.

In the present experiment, we adopt the Wedge display concept used by Aretz (1991) as a method for creating visual momentum between the ERF and WRF. To this end, we will examine how the performance and behavioral differences between the visibility conditions varies with the presence or absence of the visual momentum wedge.

Fig. 3. Experimental screen with Wedge in effect.

Route Guidance

Near future technology will be able to allow the air traffic controller to communicate clearances to the pilot directly via the map display. The controller will not only be able to make textual clearances appear on the pilot's display, but can also create an outline of the desired route on the map (see Fig. 4). That is, the desired route, from gate to runway (or vice versa), will actually appear on the map in the form of a colored or highlighted outline along the taxiways and runways. This feature may have an effect on the utility of other map features previously described. In the Batson, Harris, and Hunt (1994) taxi simulation, an electronic map with Route Guidance and

data-linked ATC-clearances was compared to the traditional paper map in both good and poor visibility conditions. Taxi times, centerline deviation, and navigation errors were measured. The results showed that the pilots were not only enthusiastic in their acceptance of the electronic map but also performed better with it. Under both good and poor visibility, taxi times, centerline deviation, and errors were all reduced with the electronic map. In the present study, half of the trials were run with Route Guidance and the other half were run without the outline. We examined whether the differences between Visibility, frame-of-reference, and the visual momentum Wedge change as a function of visual Route Guidance, as well as its performance advantages over the "no Route Guidance" condition.

Fig. 4. Experimental screen with Route Guidance in effect.

Map Zoom Level

In the present study, we also examined the pilots' preference for, and performance with, different zoom levels of the map field of view. The Batson, Harris, and Hunt (1994) experiment also allowed pilots to choose and change their zoom level at anytime. The results showed a tendency for pilots to zoom to a closer level in the poor visibility condition as compared to the good visibility condition. Also, pilots exercised scale changes, primarily in order to allow them to see the next turn on the path. Fig. 5 through 8 show the various map zoom levels used in the present study.

Fig. 5. Experimental screen zoomed in to closest level.

Fig. 6. Experimental screen zoomed in to second closest level.

Fig. 7. Experimental screen zoomed out to second furthest level.

Fig. 8. Experimental screen zoomed out to furthest level.

Visibility

The usefulness of the map display grows substantially during situations of low visibility. It is during these times that the map display must provide the pilot with the information that is normally available in the window view (Zimmerman, 1994). An effective map display would allow pilots to taxi under low-visibility conditions in order to realize the benefits of low visibility landing systems included on modern aircraft. Quite simply, the capability to takeoff and land in low visibility is not very useful if the aircraft can not subsequently navigate the airport surface in a timely and safe manner (Zimmerman, 1994). In the present study, the 4 map display features described above were examined under conditions of low and high visibility. Fig. 9 and 10 both show airport scenes, but Fig. 10 is with the low-visibility.

Fig. 9. Experimental screen in high-visibility condition.

Fig 10. Experimental screen in low-visibility condition

METHOD

Design

In this study 3 independent variables were manipulated : (a) Visibility (high vs. low), (b) visual momentum (Wedge vs. no Wedge), and (c) Route Guidance (highlighted route vs. no route). Visibility was varied between subjects, while Visual Momentum and Route Guidance were varied within subjects. All subjects were allowed to switch between track-up and north-up map displays, and all zoom levels at any time.

Apparatus

The hardware used for the experiment consisted of a Silicon Graphics Indigo 2 Extreme workstation with a 19 inch color monitor, a BG systems flybox containing a 2-axis joystick for directional control, toggle levers for speed control and map zoom control, and a joystick trigger for selection of display reference frame.

Simulation

The majority of the experimental screen consisted of a view of the San Francisco International airport surface environment. This view is a limited view of what the pilot would see out the cockpit window of a typical narrow-body jet aircraft. The view was complete with all relevant runways, taxiways, signs, gate markers and other landmarks. Fig. 11 shows the entire experimental screen along with labels of the various areas.

Fig. 11. Experimental screen with areas labeled.

Reference Frame. The map display was located at the bottom center of the screen. This display could be toggled between a north-up or a track-up map display. An aircraft icon was superimposed on the display. For the track-up display, this icon was 1/4 of the way up on the display, remained stationary, and constantly pointed straight up on the screen. The surrounding airport environment would rotate around the aircraft. In the north-up display, the aircraft icon was in the center of the map display, did not translate, but rotated as the aircraft changed directions. In both cases, as the aircraft moved through the airport surface, the map translated beneath the aircraft symbol in order to maintain the aircraft icon position in the center of the screen and one-fourth the way up on the screen.

Map Zoom. The view of the airport could be zoomed in or out over 4

different levels of magnitude. The furthest level gave a view of 19000 ft. by 23000 ft. that encompassed the entire airport. The other zoom levels gave views of 6200 ft. by 7800 ft., 3100 ft. by 3900 ft., and 2000 ft. by 2600 ft.

Visual Momentum. One half of the trials included a 60 degree wedge that extended from the nose of the aircraft icon to the edge of the map display. This represented the outside field of view of the upper window. The wedge would also rotate with the aircraft icon.

Route Guidance. One half of the trials included a visual representation of the desired route. This would be accomplished through the addition of a red line, roughly the width of a runway, connecting the starting point to the destination via the desired route.

Taxi Clearance Window. At the bottom left of the screen was a taxi clearance window. Text directions to the desired runway or gate would appear—much the same as vocal clearances are currently given to the pilot. These directions were similar to those used in the real environment, such as, "Taxi to runway 28R via A,B,D".

Feedback Window. At the bottom right of the screen was a window that gave the status of the chosen map zoom level, and the current map frame of reference (north-up or track-up).

Controls. The speed of the aircraft was controlled by moving a toggle lever fore and aft—the further forward, the faster the aircraft traveled. In addition to a zero velocity condition (toggle at aft most position), the subject could travel at 8, 16, 24, 32, 40, or 48 knots, respectively.

A second toggle lever was used to control the zoom level of the map display. There were 4 different zoom levels. Pulling the lever back gave a

higher level view (zoomed out), while moving the lever forward gave a lower level view (zoomed in).

The joystick controlled the front wheels of the aircraft thus enabling the pilot to turn. The pilot could turn while moving forward or could turn while stopped as if using a tiller control. The joystick also featured a "trigger" that was used to initiate a new route and to switch between map displays.

Procedure

One half of the subjects were put into a "low-visibility" group in which the view out the cockpit window was severely limited due to simulated fog. The taxiways were difficult to distinguish from the grass and signs were unreadable until approximately 250 ft. The other group performed under high visibility conditions.

Practice Session. The subjects were first given a practice session prior to the actual experimental trials. The subjects were given directions on how the controls worked. After this, they were allowed 10 minutes to familiarize themselves with these controls by freely taxiing around the airport. They were introduced to all the map features and were encouraged to experiment with the different zoom levels and map displays.

This was then followed by 12 practice trials. They were first given the instructions that their primary task was to navigate as accurately and as quickly as possible through the simulated airport environment. They were instructed to avoid making wrong turns, veering from the center of the taxiway, or driving off of the taxiway and onto the grass. At the same time they were instructed to maximize the speed at which they taxied. Each practice

trial would begin when directions to a particular gate or runway appeared in the clearance text field. The subjects would then navigate through the SFO environment to the desired point. Upon arrival, the screen would blank and a message telling the subject that this particular trial was completed would appear on the screen. When the subject was ready to start the next trial, they would hit the trigger button on the joystick. At this time, the aircraft reappeared at a different runway or gate, new directions appeared in the text field, and the subject would again navigate to the gate or runway.

For the first 3 trials, the subjects were forced to use one of the map display formats (north-up or track-up). For the next 3 trials, they were forced to use the other type of display. The map display for the final 6 trials was under the selection of the pilot—as it would be for the rest of the experiment. For instance, to switch from the north-up map display to the track-up map display simply required the pilot to press the trigger button. For these final 6 trials and for all of the experimental trials, the map display presented for each new trial would be the same display that was in use at the completion of the last trial. The map display for the very first practice trial was varied since there was no previous trial to reference.

Within the 12 practice trials, the Wedge and Route Guidance were crossed so that 1/4 of the trials had only the Wedge, only the Route Guidance, neither or both. The trials would alternate between travel from a gate to a runway and travel from a runway to a gate. Upon completion of the practice trials, the subjects were given a 5 minute break before starting the experimental trials.

Experimental Session. The routes introduced in the experimental

session were a bit more intricate than those in the practice session. The procedure was still very similar to that of the practice session, however. Directions would appear in the text window, and the subject would navigate to the desired point. Upon arrival, the subject would get a message and, when ready, would hit the trigger to start the next trial. For the very first experimental trial, the map display was started in the state that it was in when the subject completed the last practice trial.

The combination of gates and runways were varied in order to give a wide sampling of routes without repetition. The trials would alternate between going to a runway and going to a gate. Each subject went through the same routes in the same order. Only the existence of the Wedge and Route Guidance were varied between subjects.

The existence of Route Guidance and the Wedge were varied such that 1/4 of the trials had only the Wedge, 1/4 had only Route Guidance, 1/4 had both and 1/4 had neither aid. These conditions (Wedge, Route Guidance, neither, or both) were introduced in blocks of 5 trials and were counter balanced between subjects in order to minimize any learning or fatigue effects. There were mandatory 2 minute breaks after every 8 trials and a 5 minute break after completion of the 20th trial.

Post-test survey. At the end of the series of 40 trials, the subjects were given a survey questionnaire. Questions concerning their preference between map displays and the navigational aids were given. They were asked to describe when and why each map type and feature was helpful to them.

Dependent variables. Position data, velocity data, zoom level, map choice, and whether or not the aircraft was on the correct path were all

recorded every half second throughout the simulation.

Subjects

Twenty-four pilots were paid to participate in the study. There were 10 participants with a commercial license, 11 with only a private pilot's license, and 3 student pilots. The pilots flight experience ranged from 20 to 3000 hours, with an average of 670 hours. Only 4 pilots had ever flown out of SFO. Also, 4 pilots had some experience with electronic maps and 5 pilots reported that they typically used a hand-held map while taxiing. Twelve pilots were assigned to each of the 2 visibility groups (high and low). The high visibility group averaged 600 hours of flight, included 3 of the 4 pilots with experience at SFO, 3 of the 4 with electronic map experience, and 3 of the 5 who typically used a hand-held map. The low-visibility group averaged 750 hours of flight time.

RESULTS

Table 1 shows the averages and variations of the dependent variables. While Table 2 shows the effect (or lack of effect) of the independent variables on the various dependent variables.

Dependent Variable	Average	Std. Dev.
Performance variables		
route planning time	8.3 sec.	6.2 sec.
route completion time	191.3 sec.	16.8 sec.
average moving speed	44.3 knots	2.3 knots
% time at maximum speed	74.7	15.4
% time stopped	6.2	3.4
navigation errors per route	.12	.08
% time off route	3.1	1.9
incursion detection success	88%	30%
incursion detection time	2.0 sec.	.3 sec
Choice variables		
% time track-up map	95.8	6.1
% time "furthest" zoom level	1.0	1.1
% time "far" zoom level	27.6	16.4
% time "close" zoom level	34.4	22.6
% time "closest" zoom level	36.9	25.8
Survey variables		
track-up map rating	9.0	1.5
north-up map rating	3.1	2.5

Table 1. Averages and standard deviations for dependent variables.

	planning time (sec)	avg. moving speed (sec)	% time at max. speed	# nav. errors per route	% time stopped	% time off route	
High visibility	9.5	194	44.1	73	6.4	.117	3.1
Low visibility	7.2	189	44.5	77	5.5	.127	2.5
Track-up map	na	na	45.1	75	9.6	na	4.5
North-up map	na	na	44.6	76	6.5	na	3.2
Wedge on	8.2	190	44.2	75	5.9	.119	2.5
Wedge off	8.5	192	44.5	76	6.1	.125	3.2
Guidance on	4.1	178	45.2	82	2.9	.052	0.6
Guidance off	12.6	205	43.5	68	9.0	.192	5.1

Table 2. Effect of the independent variables on the dependent variables.

The following sections discuss the effects of the independent variables studied on the objective and subjective dependent measures. The independent variables are Visibility, Wedge, and Route Guidance. Recall that Visibility was varied between participants while Wedge and Route Guidance were varied within participants. The dependent variables that were analyzed were broken down into three "types" of measures—performance, choice, and survey. The performance measures include route planning time, route completion time, average moving speed, time at maximum speed (48 knots), time stopped, number of navigation errors, time off route, success rate at detecting the aircraft incursions, and time to detect the aircraft incursions. The choice measures include frame of reference choice and zoom level choice. The survey measures include the responses to a variety of rating and

open-ended questions.

In the following sections, the independent variables, the choice measures, and the open-ended survey questions are analyzed. The first independent variable analyzed is Visibility. This is followed by the two choice variables—Frame of Reference and Zoom level. The next analysis is of the two independent variables varied within subjects—Wedge and Route Guidance. And finally the results of the open-ended survey questions are described.

In order to further clarify, the presentation of the results of a particular variable will begin with a bold heading of the variable. This is followed by a discussion of any significant effects found in the performance dependent variables, the choice dependent variables, and finally, the survey dependent variables. For example:

Independent variable

Performance. (A discussion of any significant performance effects is included here.)

Choice. (A discussion of any significant choice effects is included here.)

Survey. (A discussion of any significant survey effects is included here.)

Since Frame of Reference choice and zoom level choice were dynamically nested in this study and thus not factorially manipulated like the independent variables, separate ANOVA tests were run on these data, whereas a MANOVA was conducted on the independent variables of Visibility, Wedge, and Route Guidance. When the overall MANOVA was significant for a given factor, univariate F-tests were then analyzed in order to

find significant effects on specific dependent variables. It should be noted that, as expected, some of the dependent variables correlate highly with one another. For example, average moving speed and route completion time are highly correlated for the obvious reason that the faster the aircraft travels the faster the route is completed. Thus it would be expected that if an independent variable has a significant effect on one of these dependent variables, it will also have a significant effect on the other. Table 3 shows the correlation matrix for the dependent variables. Absolute values of the correlation constant greater than .40 are significant at the .05 level. Absolute values greater than .50 are significant at the .01 level.

	planning time	completion time	avg. moving speed	time at max. speed	time stopped	# nav. errors	time off route	map orientation
planning time	1	.80	-.55	-.77	.89	.34	.35	-.13
completion time		1	-.85	-.93	.76	.51	.58	-.11
avg. moving speed			1	.93	-.40	-.22	-.24	.18
time at max. speed				1	-.62	-.33	-.36	.18
time stopped					1	.54	.55	.01
# nav. errors						1	.83	-.08
time off route							1	.02
map orientation								1

Table 3. Pearson Correlation constants for dependent variables.

Visibility

Performance. Fig. 12 shows the significant effect of Visibility on incursion detection accuracy, $F(1,23)=4.7$, $p<.05$. Pilots in the high-visibility

condition detected 100% of the incursion trials while pilots in the low-visibility condition detected only 75% of the trials. There was also a significant effect on incursion detection response time as a result of the Visibility condition, $F(1,23)=22.3$, $p<.01$. For trials in which the incursion was detected, participants in the high-visibility condition responded almost twice as fast as those in the low-visibility condition (1.4 to 2.7 seconds). In summary, the pilots failed to detect more incursions, and responded more slowly when they did detect them in the low-visibility condition relative to the high-visibility condition.

There were no other significant effects of Visibility on taxi performance.

Fig. 12. Effects of Visibility on incursion detection and time.

Choice. There were no significant effects of Visibility on map Orientation or zoom level choice.

Survey. There were no survey questions directed at the Visibility manipulation.

Frame of Reference

Choice. Throughout the experiment the pilots had the ability to choose between north-up and track-up map orientations. As shown in Fig. 13, pilots chose to use the track-up orientation a significantly greater amount of time (96%) than the north-up orientation (4%), $F(1,23)=1256$, $p<.01$.

Fig. 13. Map orientation choice.

Survey. The post-experimental survey indicated that pilots preferred the track-up orientation because: a) there was "no need to mentally juggle left/right," b) it was "harder to drive 'upside-down' or south with the north-up map," and c) the track-up map made it "easier to orient oneself, especially when given left and right directions." Additionally, in the pilots' preference rating portion of the survey, the track-up map was given a higher score of acceptance relative to the north-up orientation (a 9 out of 10 and a 3 out of 10, respectively).

Although all pilots stated that they preferred the track-up orientation, 74% of the pilots reported that they used the north-up orientation as well

during some portions of the trials. (Performance data revealed that actually, 79% of the pilots used the north-up map at some time during the study.) Fig. 14 shows that the vast majority of these pilots (all but 2) used the north-up orientation only out of curiosity. The 2 pilots that reported using the north-up orientation for more than just satisfying their curiosity, stated that the north-up map "better gave the big geographical picture" or simply "gave a better view."

Fig. 14. "Did you ever use the north-up display? If yes, why?"

Performance. Having established that the pilots preferred the track-up orientation, a performance analysis between the two orientations was conducted, but no significant effects were found. Note that this analysis is severely limited due to the large sampling differences between the conditions (recall that pilots used the north-up orientation only 4% of the time). Because

of this sample disparity, we can not make conclusions concerning performance differences between the two map orientations.

Zoom level

Choice. Fig. 15 shows a significant difference in the percentage of time that each zoom level was chosen, $F(3,69)=13.4$, $p<.01$. A multiple comparison difference of means test using the Scheffe technique was conducted and showed that the three closest zoom levels did not differ significantly from each other but did all differ significantly from the farthest zoom level, which was used only 1% of the time ($p<.01$).

Fig. 15. Percentage of taxi time that a particular zoom level was used across all pilots.

Survey. It is of interest to examine individual pilot zoom preferences by tallying each of their most-used zoom levels over the course of the study. Notice that their actual zoom level preferences, shown in Fig. 16, corresponded very well with their post-study responses, shown in Fig. 17. Although Fig. 15 revealed that the "far" zoom level was used about as much as the two closer levels, it was rarely the most preferred zoom level for a given pilot (only 3 out of the 24 pilots).

Fig. 16. Most often chosen zoom levels.

Fig. 17. "What zoom level did you use most often?"

Performance. Having established that the pilots preferred all but the farthest zoom level, a performance analysis between the zoom levels was conducted. The only significant performance difference found was with the percentage of time off-route, $F(3,92)=3.1$, $p<.05$. A multiple comparison difference of means test, using the Scheffé technique, was conducted but no individual zoom level was found to differ significantly from any other zoom level.

Wedge

Performance. The Wedge showed a significant effect on incursion response time. The response time to incursion events when the Wedge was present was slower than when it was absent (2.6 s to 1.5 s), $F(1,23)=15.9$, $p<.01$. The MANOVA did not show a significant effect of the Wedge for any other

performance measures.

Choice. Although the MANOVA did not show a significant effect of the Wedge, $F(7,16)=1.5$, $p=.22$, the results of one univariate F-test still is of interest. The effect of the Wedge on the percentage of time that pilots chose the north-up orientation was found to be marginally significant, $F(1,23)=3.2$, $p=.09$. Fig. 18 shows that the pilots were more likely to use the north-up orientation when the wedge was present. Recall that the visual momentum wedge is designed to tie together both track-up and north-up views (Aretz, 1991). Thus, in accord with previous research (e.g., Andre et al., 1991; Aretz, 1991), there is more of an advantage to using the Wedge, that portrays track information, when the map is oriented north-up, an orientation not normally in alignment with the forward field of view.

Fig. 18. Effect of the Wedge on the percentage of time that the north-up map display was chosen.

Survey. In the survey, 52% of the pilots reported that the Wedge was helpful. The majority of those that found it helpful reported that the Wedge was "helpful in planning turns, and in knowing when to expect a taxiway or terminal to appear (in the forward field of view)."

Route Guidance

Performance. Route Guidance was found to have a significant effect, $F(7,16)=12.8$, $p<.01$. Fig. 19 reveals a significant reduction in planning time—the time between the start of the trial and the aircraft's first movement—as a result of the Route Guidance, $F(1,23)=33.4$, $p<.01$. Without Route Guidance, participants took longer to orient themselves and plan their initial portion of the route than with Route Guidance (12 and 4 seconds, respectively).

Fig. 19. Effect of Route Guidance on planning time.

Fig. 20 shows a significant reduction in the average route completion time with Route Guidance, $F(1,23)=35.6$, $p<.01$. On average, 26 seconds—

which is more than 12% of the total completion time for a particular route—were saved with the introduction of the Route Guidance. Thus, Route Guidance enabled the pilots to excel at the primary task of navigating to the destination as quickly as possible.

Fig. 20. Effect of Route Guidance on completion time.

Average moving speed is highly correlated with completion time ($-.97$), so as expected, there is also a significant gain in average moving speed when the Route Guidance is present, $F(1,23)=22.3$, $p<.01$. As shown in Fig. 21, pilots traveled, on average, more than 1.5 knots faster with Route Guidance present.

Fig. 21. Effect of Route Guidance on the average moving speed of the aircraft.

The percentage of time at maximum speed also correlates highly (.93) with average moving speed. Accordingly, Fig. 22 shows a significant difference in the percentage of time at maximum speed, $F(1,23)=63.2$, $p<.01$. With Route Guidance pilots were at maximum speed 80% of the time, compared to 68% without Route Guidance.

Fig. 22. Effect of Route Guidance on percentage of time at maximum speed.

Fig. 23 shows a significant difference in the time that the pilots had the aircraft stopped as a result of the Route Guidance, $F(1,23)=57.5$, $p<.01$. The pilots were stopped more than 3 times longer without Route Guidance than with Route Guidance.

Fig. 23. Effect of Route Guidance on percentage of time aircraft stopped.

There is also a high correlation (-.83) between the number of navigation errors and the time spent off of the correct route. Fig. 24 shows a significant decline in navigation errors per route as a result of the Route Guidance, $F(1,23)=26.6$, $p<.01$, while Fig. 25 shows the percentage of time off route as a function of the Route Guidance, $F(1,23)=44.1$, $p<.01$. With Route Guidance, navigation errors were decreased by more than 3.5 times and the time off of the route was reduced by more than a factor of 8. Thus, not only were the pilots able to complete the route in less time, but they also made fewer navigational errors along the way.

Fig. 24. Effect of Route Guidance on number of navigation errors per route.

Fig. 25. Effect of Route Guidance on percentage of time off the correct route.

The presence of Route Guidance had no effect on the incursion detection accuracy. That is, the success rate of the pilots in the task of detecting the other aircraft in the runway. However, reaction times to incursion events were significantly slower with Route Guidance (2.5 seconds) than without Route Guidance (1.6 seconds), $F(1,23)=10.6$, $p<.01$.

Choice. Fig. 26 shows a significant difference in the use of the north-up orientation as a function of Route Guidance, $F(1,23)=5.8$, $p<.05$. With Route Guidance, the pilots opted to use the north-up orientation 6% of the time relative to 2.5% of the time without Route Guidance. Although the total usage of the north-up orientation is very low in either case, clearly the navigation information provided by the Route Guidance prompted some of the pilots to experiment more with this less-preferred orientation.

Fig. 26. Effect of Route Guidance on the percentage of north-up use.

Fig. 27 shows a significant Wedge $\times$ Route Guidance interaction for map orientation choice, $F(1,23)=6.6$, $p<.05$. Clearly, the major influence on the orientation choice was the combined effect of Route Guidance and Wedge. In this condition, north-up was used 9% of the time as compared to 2-4% in the other conditions.

Fig. 27. Effects of Wedge and Route Guidance on percentage of north-up use.

Fig. 28 shows a significant interaction between zoom level choice and the Route Guidance, $F(3,69)=20.7$, $p<.01$. With the Route Guidance present, pilots zoomed in closer than without the guidance. In fact, the pilots spent more than twice as much time at the closest zoom level when the Route Guidance was on than when it was off. Clearly, with Route Guidance, there is less need to look at the map and plan the route, so there is less need for the larger, planning view afforded by the further zoom levels.

Fig. 28. Effect of Route Guidance on the zoom level choice.

Survey. In the survey, all of the pilots described the Route Guidance as helpful. They were "able to look outside the cockpit more" and thus "spend more time looking for obstacles" and less time looking at the map display and planning the route. There was however some concern about complacency generated as a result of the Route Guidance. Pilots reported that it was "easier to get relaxed with this crutch (Route Guidance)," that it made them "lazy when it came to watching their progress" and as a result they, "missed a turn once or twice."

Open-Ended Survey

Fig. 29 shows that the reported "best" feature of the map display was clearly the Route Guidance. Fig. 30 shows that the tendency for the pilots to spend less time looking outside the cockpit window when using the map

display, and the inability of the map display to legibly show all the taxiways in a single view were mentioned as the "worst" features of the display.

Fig. 29. "What is the best display feature of the map display?"

Fig. 30. "What is the worst display feature of the map display?"

The pilots were also asked to report which features they desired to see on a taxi map display. Fig. 31 shows the results of this query. The most

common suggestions were: 1) to show other aircraft on the map, 2) to include holding bar markings on the map, 3) to have a less obtrusive Route Guidance, and 4) to give status as to what part of the route has been completed (highlight the text directions) and what part of the route is upcoming (flashing text).

Fig. 31. "What features would you prefer on a taxi map display?"

DISCUSSION

Visibility

Visibility was not found to have a significant effect on route completion time or navigation errors. Thus, pilots performed the same whether or not their visibility was restricted by the simulated fog. However, this surprising finding can be viewed as evidence of the tremendous benefits of using an electronic moving map display during taxi operations. In other words, the presence of the map display was able to make up for the relative lack of information provided by the degraded low-visibility environment.

The high-visibility condition significantly increased incursion detection accuracy and decreased incursion response times over the low-visibility condition. This is not surprising since the map display in this experiment did not supply any information that could aid the pilot in detecting other aircraft (i.e. it did not show other traffic). Therefore, the sole source of this information was the view out the cockpit window. Accordingly, under low-visibility conditions, performance was relatively poor on the unexpected incursion task. Indeed, the pilot survey indicated that the number one desired feature was to include other aircraft on the map display—an important fact to remember for future taxi map designs.

Frame of Reference

Most studies on map orientation have forced subjects to perform with one map orientation or another (e.g. Aretz, 1991; Andre et al., 1991; Wickens et al.,

1993) and then compared performance between these conditions. This study, however, gave the pilots the option of navigating with either map at anytime—a condition similar to the electronic map displays offered in cars today (Antin, 1992). The evidence from this study, however, suggests that there is no need to include the north-up map orientation option. The north-up map was selected only 4% of the time. Moreover, only 2 pilots reported that they used it for anything other than satisfying their curiosity. These 2 pilots still used the track-up orientation an overwhelming amount of time (91%). Further, their rationale as to why they used the north-up orientation—"To give the big picture" and "To give a better view"—is a bit curious. While studies in the past have provided north-up maps that showed a significantly larger (more global) portion of the environment than their track-up counterparts, in the present study the north-up orientation revealed the same portion of the environment as the track-up orientation. Thus, a "bigger" or "more global picture" certainly was not revealed through the selection of the north-up orientation. Also, it is hard to imagine what one pilot in the survey meant by "a better view" when he referred to the benefits of the north-up orientation since he used the track-up orientation 96% of the time. Perhaps the 2 pilots' expectations had been biased due to exposure to previous map studies or articles addressing these issues.

In summary, past studies have indicated that pilots perform local navigation tasks such as taxiing better with track-up maps (Aretz, 1991; Levine, 1982; Andre and Koonce, 1991). This study indicates that the pilots also prefer to use the track-up orientation and, accordingly, describe it as more helpful. Collectively, to the display designer, the combination of these facts

suggests the exclusion of the north-up orientation.

Zoom Level

The pilots shared the time almost equally between the "closest", "close" and "far" zoom levels (27, 34, and 38%, respectively). Although the results were not quite significant, a trend showed that the further the pilot zoomed out, the less time was spent on-route. It seems that as the pilots became disoriented and went off-route, they chose to zoom out in order to see more of the airport environment and, presumably, reorient themselves. As was mentioned before, no single preferred zoom level emerged from this study. Further, the one zoom level not used very much (the furthest—used only 1% of the time), was reported in the survey as a problem because "not all the taxiway graphic labels could be seen." In other words, the *zoom level* may not have been the problem per se. The problem may lie in our inability to put map runway labels that were big enough to be legible at this zoom level. Note however, our map was relatively small and, therefore, in the furthest zoom level it was difficult to read the text labels. If a larger map were provided with legible labels, the furthest zoom level would become more appealing and the zoom level choice distribution would most likely change. In fact, in the previously mentioned airport taxiing study by Batson and Hunt (1994), the labels were much more readable and their results showed that the furthest zoom levels were chosen more often than were ours. We conclude that, indeed, multiple zoom levels are desirable; however, further studies and analysis are needed in order to obtain design recommendations concerning the optimal range and selection of zoom levels.

Wedge

Aretz (1991) showed the Wedge design to be useful when there were contradicting reference frames that had to be "mentally tied together." This study did not force map orientations (reference frames) on the pilots. A choice was given and the pilots overwhelmingly chose the track-up orientation, which corresponded with their view out the window. As a result of this consensus towards track-up, it would not be expected that the Wedge would have a significant effect on navigation performance since the reference frames of the track-up map and the cockpit view corresponded with each other. Indeed, the Wedge did not show a significant effect on the performance measures. Although when the Wedge was present, pilots used the north-up orientation more—since the benefits of the Wedge are better realized when the map is oriented in this manner (Aretz, 1991).

Note, however, that more than half of the pilots reported that the Wedge was indeed helpful. Specifically, they reported that it was "helpful in planning turns, and in knowing when to expect a taxiway or terminal to appear in the forward field of view." This may indeed have been true. Thus, the value of the Wedge when combined with a track-up map orientation and Route Guidance needs to be investigated further.

One beneficial "feature" of the Wedge that was not manipulated in our study is that it can assist the pilot in orienting the aircraft when using a relatively far zoom level. In our map display, the aircraft size was kept at actual size. This means that when the pilot zoomed out, the aircraft icon became smaller. At the furthest zoom level, the icon was so small that it was

difficult to quickly determine which way the aircraft was pointing. In this case, the Wedge outline can be very helpful. In effect, the Wedge outline acts as a large aircraft icon assisting the pilot in determining orientation. However, in the present study, due to the small map details, little time was spent in the furthest zoom level. As a result of this, there was not enough data to analyze this effect. This is another issue that needs to be further investigated.

Route Guidance

Route Guidance had a significant effect on nearly all the performance measures and was clearly the single most helpful aid in navigating. With Route Guidance, the pilots not only completed the routes in less time, but also with fewer errors.

The post-experimental survey revealed that some pilots were not satisfied with the actual Route Guidance outline. Because of the graphic limitations of the simulator, the outline was larger and more obtrusive than we would have liked. A thinner line is clearly recommended.

One item that needs to be addressed however is the concern about complacency. Some pilots reported that it made them "lazy when it came to watching their progress," that they "relaxed with this crutch [Route Guidance]," and as a result they "missed a turn once or twice." They claimed that they were not looking outside the window as much as they felt they should. On the other hand, the survey revealed that some pilots' claim that Route Guidance enables them to "look outside the cockpit *more*" and thus "spend more time looking for obstacles." This apparent contradiction clearly

needs to be studied further.

There is a large safety issue associated with the question of whether the existence of the Route Guidance causes the pilots to look out the cockpit window more or less. One indication as to where the pilots attention was located when the Route Guidance was present can be found in the incursion data. If the pilots were indeed looking outside more, then it would be expected that they would detect more of the unexpected traffic. Interestingly though, the pilots did no better at detecting the obstructing aircraft when Route Guidance was present. Also note that for the cases when the aircraft was detected, those with Route Guidance reacted significantly slower than those without it. Thus, based on our limited data, one would conclude that the benefits of Route Guidance are a mixed blessing.

CONCLUSION

As a result of the increase in airport traffic, this study was conducted in order to examine different map display design options that have now become feasible because of the availability of DGPS and Datalink systems, and the advancement in electronic display capabilities. These features were studied with the intent of learning more about the basic human factors associated with ground navigation displays in order to apply these human factors principles to the design of the display. As contrasted with the majority of navigational map studies, the pilots were allowed to choose many of the map's features. This is important in that not only is a more realistic model of the current environment created, but also data on performance and on preference can be separately obtained.

The results of this study not only encourage the application of human factors methods to taxi map display design, but also stress the need to investigate specific issues further. Route Guidance, for instance, was found to significantly aid the pilot in navigating, but concerns with pilot complacency clearly need to be studied more closely. Also, the zoom level preferences and the Wedge's assistance in pointing the aircraft need to be examined. Hopefully, the value of applying human factors in display design can be realized as a result of the issues that were examined in this study. At the same time, it is our hope that more research will be undertaken to resolve the remaining human factors issues relating to aircraft taxi navigation displays.

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APPENDIX A

PILOT INSTRUCTIONS

MAPVIEW EXPERIMENT #1

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 a computer monitor with various controls at your hand. Presented on the monitor will be an out-the-window view of San Francisco Airport (SFO) in addition to a moving map display. The display will consist of various features, some of which might change between experimental trials. Your task is to taxi the aircraft from the gate to the runway and vice versa. Don't worry about 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 is 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 far faster than you are used to. Finally, many of the routes require you to back-taxi on the runways (in fact, this study treats taxiways the same as runways--all are equal "roads"), and the routes are sometimes long and somewhat convoluted. This is done to simulate a more complex airport (e.g., O'Hare) than exists at SFO.

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
PILOT SURVEY

MAPVIEW EXPERIMENT #1
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? _____

MAPVIEW EXPERIMENT #1

PARTICIPANT POST-EXPERIMENT SURVEY

Participant # _____ Date _____ Experimenter: _____

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

Which map display did you use the most (track-up or north-up)? _____
Why?

Did you ever use the other map display? If so, when and why?

Was the wedge display helpful? If yes, how so?

Did you perform better or worse with the wedge? _____

Was the route guidance (red lines) helpful? If yes, how so?

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

Which zoom level did you use the most (closest, close, far, farthest away)? _____

Under what circumstances, if any, did you use each of the four zoom levels?

Closest -

Close -

Far -

Farthest -

Which speed level did you use the most (0,8,16,24,32,40,48)? _____

Under what circumstances, if any, did you use each of the speed levels?

0 -

8 -

16 -

24 -

32 -

40 -

48 -

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%)

When was the map display most helpful?

When was the outside view most helpful?

Please rate your preference on a scale from 1 (low) to 10 (high) for the following items:

Track-up map _____

North-up map _____

Wedge _____

Zoom Level:

closest

close

far

farthest

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

Route following _____
 Centerline accuracy _____
 Route completion time _____

What was the best feature of the map display?

What was the worst feature of the map display?

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

Only track-up map _____
 Only north-up map _____
 Both maps _____
 Wedge _____
 Only closest zoom level _____
 Only close zoom level _____
 Only far zoom level _____
 Only farthest zoom level _____
 All 4 zoom control levels _____
 Route guidance _____
 Other? _____

How many times did another aircraft appear in front of you? _____

Finally, what other features or information would you want to see on an aircraft taxi map display?

Thank you very much for your participation!!!!