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Human factors guidelines for the display of uncertain information

Henry A. Cutler
San Jose State University

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**HUMAN FACTORS GUIDELINES FOR THE DISPLAY
OF UNCERTAIN INFORMATION**

A Thesis

Presented to

The Faculty of the Program of Human Factors/Ergonomics

San Jose State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

Henry A. Cutler

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APPROVED FOR THE GRADUATE STUDIES OFFICE

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

Louis E. Freund, Ph.D., Industrial & Systems Engineering, Member

Steve J. Selcon, Ph.D., UK Defense Evaluation and Research Agency, Member

APPROVED FOR THE UNIVERSITY

ABSTRACT

HUMAN FACTORS GUIDELINES FOR THE DISPLAY OF UNCERTAIN INFORMATION

by Henry A. Cutler

This paper discusses studies evaluating the utility of position and heading uncertainty symbology for aircraft navigation, tactical and situation awareness displays. Graphic and text symbologies were tested.

Experiment 1 examined positional uncertainty symbology in a navigation task. The pilot's objective was to avoid collisions while minimizing course deviation. It was hypothesized that representing uncertainty would allow pilots to decrease separation under accurate conditions, and that uncertainty symbology would cause pilots to increase separation when uncertainty was present. Only the explicit graphical symbology group avoided most collisions under uncertainty. Subjects using text and color symbology showed increases in collisions under uncertainty

The second experiment investigated the utility of symbology for heading uncertainty. Subjects performed a tactical task in which targets were displayed with one type of symbology or none. When data was uncertain, subjects without uncertainty symbology showed a greater accuracy decrement than those who used the symbology.

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INTRODUCTION AND REVIEW

Advanced Navigation and Situation Awareness Displays

Perhaps the most common trend in modern military and commercial avionics is the implementation of advanced navigational and situation awareness displays, made possible by recent advancements in sensor technologies and sensor fusion integration. In the context of aircraft, such displays may be used for airborne route guidance, weapons aiming, traffic awareness, or airport surface navigation. The surface navigation system, for example, might depict the positions of aircraft as well as other vehicles (e.g., luggage transports, fuel and service vehicles) and objects on an electronic moving map display of the airport surface (Andre, 1995). Depending on the available sensor information and processing capabilities, attributes such as position, velocity, heading and size can be displayed for the ownship as well as other aircraft and vehicles. Arguably, the presentation of this information is vital towards maintaining the pilots' "big picture" or situation awareness, especially under low-visibility conditions.

In the military domain the accelerated pace and increased complexity of air combat produce a corresponding increase in the information processing required of pilots and other crewmembers. Current military aircraft provide more complex information, in greater quantity than a single human can comprehend. As a result, it is a challenge for aircraft interface designers to provide pilots with mission critical information in a timely and effective manner. Further, such information must be provided in such a manner as to

facilitate intuitive and accurate comprehension of the aircraft systems involved (Brickman, Hettinger and Haas, 1997).

Similar types of navigational displays are finding their way into non-aviation applications as well. As the cost of GPS receivers drops, such systems are being used in automotive, recreational yachting and hand-held navigation displays for outdoor sports and other activities. Certain aspects of land transportation technologies such as ATIS (Advanced Traffic Information Systems), IVHS (Intelligent Vehicle Highway Systems) and ATMS (Advanced Traffic Management Systems) also share many features with the aircraft navigation display systems.

Data Uncertainty

Notwithstanding the potential gains afforded by advanced navigation and situation awareness displays, there are several complex issues to be resolved that relate to the presentation of probabilistic and uncertain data. Uncertainty is generally defined as a lack of sureness or definite knowledge about an outcome or result. In a navigational display, uncertainty is the possible variation of the displayed information from the real world information at that point in time. If the issue of data uncertainty is not properly considered in the design of these displays, then certain key information such as the location or heading of traffic might appear more reliable to the pilot than they truly are.

In the context of aircraft or other navigational displays, only a small body of work explores the issue of displaying uncertainty. Amar, Hansman, Vaneck, Chaudry and Hannon (1995) tested two types of symbology for representing uncertainty within

electronic taxi chart displays. Through a series of probe questions, they found that the representation of uncertainty improved pilot situation awareness in some situations.

In a 1995 poster presentation, Williamson and Williamson proposed to investigate the effect of information format of uncertain information in navigational displays. Their study aims to compare the effects, on situation awareness and navigational performance, of graphical and numerical representation of uncertain information. No study appears to have been performed at the time of this writing.

Selcon (1990) tested the utility of Expert Decision Support systems for driving/navigation decision-making under conditions of uncertainty. It was found that providing unambiguous probabilistic information to the decision-maker achieved performance gains without apparent detriment to memory for the relevant decision options. Subjects demonstrated both faster response times, and increased levels of confidence when the uncertainty information was provided.

Weitzman (1993) tested air traffic controllers to determine the relative importance of various aircraft conflict information attributes. An information attribute referred to as "certainty" was included in the list, defined as the probability that separation assurance would be violated, based on aircraft flight data (e.g. trajectories, speed, altitude), weather and other situational factors. Of the 18 chosen information attributes, Weitzman found that the air traffic controllers ranked "certainty" sixth in terms of relative importance for conflict identification and resolution.

Another study lending support for the investigation of including uncertainty data in navigational displays is Abdel-Aty, Kitamura and Jovanis (1995). In this paper

studying the impacts of Advanced Traveler Information Systems (ATIS) on driver's route choices the authors indicated that there is a need to investigate whether to display reliability information to drivers. However, this concept was not elaborated in greater detail.

The inclusion of uncertainty information has occasionally been discussed in the context of situation awareness displays. Hasegawa and Inagaki (1994) presented a decision support system that can process and display the uncertainty within plant or process control information. This paper discusses a mathematical approach for representing plant state information. Both the operator's opinion about the plant state and the plant state information provided by the decision support system are represented in terms of belief structures. Information about plant state recognition is derived by mathematically combining these two belief structures. Hasegawa and Inagaki do not make recommendations about how this information would be displayed to the plant operators, and their evaluation is limited to a mathematical proof, with no perceptual testing.

Endsley (1995) presented a theoretical model of situation awareness, based on its role in dynamic human decision-making. In this paper the author explores the relationship between situation awareness and various individual and environmental factors. The impacts of such factors as design features, system complexity and automation on operator situation awareness are addressed. The discussion of uncertainty representation is brief, but the inclusion of a context feature representing the degree of uncertainty in situation models is suggested.

With modern sensor fusion displays, tactical decision-makers rely on highly processed information to make decisions and solve problems. Problems of interpretation of the tactical scene arise because of the difficulties associated with understanding not only the complex information space, but also the inherent uncertainties in the information. Coury, Donald, Dykton, and Piatko (1997) describe a visualization tool developed to represent the information associated with the tactical scene for Navy command decision-makers. This system allows the decision-maker to examine and evaluate the source, type of processing and the contribution of each information source to the overall reasoning process. The authors conclude that "How best to visualize uncertainty and explain the basis for it remains a major, and increasingly important, research issue in decision environments that rely on highly processed information".

Issues related to the inclusion of uncertainty or quality of spatial data in displays have been studied extensively in other fields such as cartography, particularly for computerized GIS (geographic information systems) applications. Numerous papers (Beard and MacKanness, 1993; Buttenfield, 1993; Buttenfield and Beard, 1991; Chrisman, 1991; Guptill, 1989; Hunter and Goodchild, 1995; Robinson and Frank, 1985) explore the nature of spatial data quality and recommend the inclusion of accuracy information in GIS applications. Similarly, Wittenbrink, Saxon, Furman, Pang and Lodha (1995) and Pang, Furman and Nuss (1994) explore the visualization of uncertainty in meteorological and other environmental vector displays.

Collectively, these studies lend considerable support for the inclusion of uncertainty information in aircraft navigational displays. Some of the techniques utilized

to represent uncertainty for the many applications that have been discussed will be examined in greater detail later in this paper.

Types of Uncertainty

In a navigational display data uncertainty can be classified along dimensions of accuracy (precision) or time (temporal). The following sections elaborate on the different types of uncertainty, and possible strategies to deal with them.

Precision Uncertainty. The most intuitive and important attribute of any navigational display is the precise and accurate depiction of these elements and their attributes as they occur in the real world and specifically, in relation to the ownship. While precision and accuracy have different meanings, they are both relevant in this context. Precision refers to the increments of measurement. A high precision measurement or display utilizes smaller increments. Accuracy refers to the match between the measurement and the objects being measured. Thus it is possible to have low precision but high accuracy. An example would be the display of aircraft locations to the nearest kilometer. The information might be accurate, but the precision could be too low for the display to be of any use. Conversely, low accuracy may be coupled to high precision. Displaying aircraft to ten meter accuracy when, in fact, they were only measured to the nearest 100 meters is an example. In this case the precise display implies greater accuracy than the measurement actually warrants. The latter situation is the primary concern of the present paper.

The accuracy within and between navigational and informational sensor systems varies widely. Accordingly, when multiple sources are integrated into one display, different objects, and different object attributes, will vary in the accuracy of their data. Because the accuracy of the various information sources are often known, there exists the opportunities to either correct any inaccuracies in the data (data adjustment or smoothing) or display the uncertainty to the pilot. As an example of the latter, one might imagine displaying the uncertainty of the position of an enemy aircraft as a circle with a radius of the accuracy level surrounding the object (Amar et al., 1995). Likewise, the verbal display of positional accuracy information is commonly used in cartography, and mechanical drawing, in the form of tolerances accompanying the dimensioning text. For example, a part of 10mm nominal length might be dimensioned " $10 \pm .01\text{mm}$ " to specify that parts manufactured between 9.99mm and 10.01mm are acceptable.

Temporal Uncertainty. While reality is continuous, the observation and measurement of reality is often necessarily discrete. Thus uncertainty may also be of a temporal nature, as information elements are often represented to pilots in discrete chunks and updated periodically, instead of being displayed continuously. Complicating the problem is the fact that the dynamics of aviation are such that object information that is only a few seconds old may no longer be useful or reliable. The update rate of the displayed data depends on both the source (sensors) and computing hardware used. Often, there is both a delay between the movement of an aircraft and the transfer of information about that movement from the sensors to the ownship, and a limitation in the

update rate of the display of that movement data. Additionally, the various data sources utilized for the display may have different update rates, meaning that objects on the navigational display may have different degrees of temporal uncertainty at any given point in time. For example, while the ownship may be updated nearly continuously, there may be a three second lag between the actual movement of an enemy aircraft and the appearance of that motion on the display. As with precision uncertainty, there exists the opportunity to either correct any inaccuracies in the data through data adjustment or smoothing, or to display the uncertainty to the pilot.

Consequences of Uncertainty

Reliance on unreliable information in a navigational display can have disastrous consequences. Consider the following fictional example of a pilot using an electronic taxi display under low-visibility conditions: The pilot looks at a symbol on the map representing another, smaller aircraft on Taxiway A having just passed the intersection of Taxiway A and J. Given the appearance of that aircraft having about 100m clearance from the intersection, the pilot continues to maneuver his aircraft toward the same intersection via Taxiway J. However, this information is nearing the end of its 6-second update cycle. During the past 5 seconds the aircraft have moved 60 meters closer to each other. Additionally, both aircraft are depicted on the map display at locations 25 meters off their actual coordinates when the information was "fresh." Should the pilot maintain this course the two aircraft will collide, despite having the appearance of adequate clearance. Such worst-case-scenario possibilities must be made apparent to the viewer of

such a display. We argue that by appropriately representing this uncertainty in the navigational display, such scenarios would rarely or never occur.

Designing for Uncertainty

The design of systems to support critical decision-making in the presence of spatial uncertainty is a challenging task. The system must present first-order information about the domain itself, as well as second-order information about the reliability of the first-order information (Williamson and Williamson, 1995). Ideally, the representation of the second order uncertainty information should not interfere with the utility of the first order information represented on the display.

There are a number of possible methods by which data uncertainty can be treated, some of which can be implemented simultaneously. These include: do nothing, explicitly display the raw data, smooth the raw data, and display the uncertainty with the data. Furthermore, there are several ways in which one might display uncertainty, using either the verbal or spatial modality. The verbal display of data uncertainty might take the form of a text descriptor accompanying an object or area on the map. On the other hand, the visual or graphic display of uncertainty might take the form of static symbols or dynamic analog display elements.

Do Nothing. Of course, one option is to omit all explicit references to data uncertainty. Such a display would simply represent the data provided in “as is” condition, with no attempt to “improve” the data or supply information about the reliability of the

data. In this case the pilots are left to their own devices to make decisions based on their knowledge or assumptions of the data validity. Such a system requires greater mental processing on the part of the pilot, and assumes the pilot is knowledgeable about the accuracy of the various data sources. Heavy demands may also be placed on the short-term memory of the pilot keeping track of various display elements. See Aretz (1991) for discussion of the mental workload demands of pilots. Such an approach places pilots and others who must rely on such information at risk. However, this is precisely the manner in which information is generally presented on modern navigation and situation awareness displays.

Leave the Data Raw. An alternative to “doing nothing” is to specifically express the nature of the “raw” data. Such a system is probably most obviously appropriate for displaying temporal uncertainty, which may be represented by explicitly displaying the data update rate. A notable example of this display type is the sweep of a radar screen as the antenna rotates. Objects are highlighted as the sweep hand travels around the display, and may decay as the information “ages.” In such a system the update rate and decay of the information is immediately apparent to the viewer, as the rotational location of the sweep hand is always visible.

Smooth the Data. Another tactic is the use of computerized algorithms to smooth out the data, based on assumptions about the properties of each object displayed and the data source. For example, instead of relocating a symbol of a vehicle on the display once

every 6 seconds (its true update rate), its probable location can be updated numerous times each second through interpolation. Such smoothing would be based on extrapolation of a history of the data, as well as knowledge of certain attributes of the object in question. The result of data smoothing is that the vehicle will appear to be continuously moving along a path, instead of jumping from point to point with each update. For vehicles with relatively consistent motion paths, such as a taxiing jetliner, data smoothing would generally yield accurate reflections of the actual aircraft movements. On the other hand, combat aircraft maneuvering in flight and other highly maneuverable vehicles such as airport ground support vehicles or automobiles will often stray from the displayed extrapolated path. Thus, while smoothing may sometimes improve display reliability, it can also increase inaccuracy.

The decision to smooth data, and the rate at which to smooth, should be based on a careful analysis of the bandwidth of aircraft movement, the data bandwidth available to the display system and the context in which the data is used (i.e., the pilot's task). While smoothing data is a common and useful technique for estimating aircraft position, heading or velocity, the unassuming pilot might make improper judgments based on the display of sometimes false information. Even when the data is smoothed it is important to represent uncertainty in the navigational display.

Displaying Uncertainty

While a considerable body of work recommends the inclusion of uncertainty representation in spatial displays, only a few sources actually describe methods for the

representation of uncertainty. Some examples from the cartographic GIS literature include: Fisher (1993); Fisher (1994a); Forier and Canters (1996); Goodchild, Battenfield and Wood (1994); Goodchild, Chih-Chang and Leung (1994); Hunter and Goodchild (1994); Maffini, Arno and Bitterlich (1989) and MacEachren (1992). Of the techniques described in the GIS literature, only a small portion would be suitable for aircraft navigational displays. Following is a discussion of some of the more relevant techniques for representing uncertainty found in the literature.

Bertin, cartographer and graphic theorist, outlined a basic system of graphic variables for building a map image. Bertin's variables include: location, size, value, texture, color, orientation and shape (Bertin, 1985). MacEachren (1992) and McGranahan (1993) discussed how Bertin's system of graphic variables (perhaps with modifications or additions) could be logically matched with different types of data uncertainty. Of Bertin's variables, MacEachren cites size and value as the most appropriate for depicting uncertainty in numerical information, while color (hue), shape and maybe orientation can be used to display uncertainty in nominal information. Adding to Bertin's original set of variables, MacEachren suggests color saturation as a logical variable to be used for the representation of uncertainty in GIS map displays. Another variable suggested by MacEachren is "focus," the presentation of uncertain data as one would see it through an out-of-focus camera, or simply at a lower spatial resolution.

McGranahan adds "presence," "realism" and "time" to the list of graphic variables to be considered for the representation of uncertainty. The simple presence of a symbol signifies a nominal scale distinction between existence and non-existence. Realism refers

to the degree of photo-realism of the image appearance. McGranahan suggests that uncertainty could be inversely mapped to realism, such that lower uncertainty data would appear more realistic. Such a system is already used in the design trades, where low realism models and sketches are used in the earlier stages of product development. At this point there is a high degree of uncertainty about the appearance of the final product, and low realism deliberately prevents observers from ascribing too much permanence to the forms. Since printed maps are static, McGranahan's inclusion of "time" as a new variable for cartography highlights the map's entry into the computerized age. Of course, the navigational displays of importance to this paper already include time as a key variable. However, in a primarily static map (such as most GIS applications) time is the basis for animation, which offer a number of new symbolic options. Along these lines, this paper suggests blinking, fading and moving symbols to symbolize data quality.

McGranahan points out that regardless of the chosen strategy, the relationship between the graphical symbols and their meanings (e.g. positional uncertainty of 20m radius) must be perceptible to the user, and these codes should follow convention whenever possible. As McGranahan indicates, the meanings of the symbols are in the users and not in the map.

Coury et al. (1997) describe a visualization tool called the Reasoning Systems and Information Space Navigator, used to represent the information associated with a tactical scene for Navy command decision-makers. The underlying assumption in their development of the RSIS Navigator is that the representations of tactical entities on sensor fusion integrated displays are *hypotheses* about the tactical situation based on

conclusions from reasoning and processing systems. Thus, a tactical graphic on a display is the product of considerable processing of evidence from a variety of information sources, and only represents the most likely conclusion about the identity and attributes of an object. The authors postulate that understanding the basis for the tactical scene is critical to effective decision-making. The decision-maker must understand the source of the information, how the information was processed and the contribution of each information source to the overall reasoning process. Their goal was to develop a visualization tool to allow a decision-maker to explore these three aspects of the tactical information space. The resulting visualization system is comprised of a series of linked cubes. The series of cubes depict the levels of reasoning and sensor data processing involved in the overall conclusion. Each cube represents a specific system that has contributed to a particular stage of processing. Each facet of a cube displays specific information about that stage of processing. The interface design intent of this system was to provide a single, graphical representation of complex processing that maintains both a global and local view of the situation. Such a graphically complex system might be inappropriate for time-critical aircraft navigational displays, but nonetheless represents a novel approach to representing this type of second-order information (information about information).

As mentioned earlier, the addition of uncertainty information should not interfere with the first-order function of the navigational display. As an electronic map display increases in complexity it should take longer for a pilot to process the information (Aretz, 1988). Thus, symbology for the representation of uncertainty information should add as

little clutter to the display as possible. To maximize the use of display space Tufte (1990) recommends maximizing the “data-ink ratio” of each display element, instead of merely minimizing complexity. In the following sections, a generalized model of strategies for displaying uncertainty is discussed. Included are implicit and explicit graphical representations, text descriptors, and animation displays. Graphical and other strategies for expressing temporal uncertainty are also discussed.

Explicit Display of Uncertainty. Instead of showing an object at a discrete location, positional uncertainty can be represented by displaying the region of possible locations.

Figure 1. Position uncertainty represented by a yellow circle with radius mapped to the degree of unreliability. Larger circles represent a greater degree of uncertainty.

This region could be displayed as a simple geometric shape such as an ellipse, cone or circle, as shown in Figure 1. This type of system was proposed by Amar et al. (1995).

The location of the aircraft's cockpit was represented by the apex of a green triangle

pointing in the direction of the aircraft's heading. The triangle was surrounded by a yellow circle representing position uncertainty, centered at the apex of the triangle.

Alternatively, the region could be represented by a more complex shape calculated from the object's size, velocity and heading, and inertial properties of the vehicle, in addition to the error components. Figure 2 demonstrates one example of such a probabilistically calculated region of uncertainty.

Figure 2. Probabilistically calculated regions of uncertainty. Larger uncertainty regions demonstrate greater uncertainty.

Similarly, heading uncertainty could be mapped to a symbol that explicitly displays the range of possible headings. An additional pair of lines at the front of an object, angled in the appropriate directions could represent heading uncertainty.

Implicit Display of Uncertainty. Instead of giving the user a clear indication of the specific data value, region or attribute, the display could graphically imply that the data quality is such that the user should regard it with caution (McGranahan, 1993). Color-coding is one such example. As shown in Figure 3 the symbol for a normally green

object could progressively be changed to yellow, then red to represent increased data uncertainty. The change in hue could either be progressive, which might be suitable to show a gradual “aging” of the data, or categorical.

Figure 3. Color change from green to red to implicitly represent uncertainty.

Alternatively, “growing” symbols that describe the region of uncertainty as they increase in size could represent position uncertainty. Similarly, line thickness can be mapped to levels of uncertainty. A drawback to this approach is that thicker or bolder lines visually stand out and would tend to draw visual attention to the uncertainly located objects. A possible solution is to counter the effect of the thicker lines or surfaces by reducing the brightness of these objects (May and Wickens, 1996; Wittenbrink et al., 1995). MacEachren (1992) proposed color saturation (purity) as another graphic variable to represent uncertainty. Symbols would be varied from pure hues for very certain information to unsaturated hues (gray) for uncertain information. Three dimensions define colors: hue, saturation and value. Theoretically, each of these dimensions could be coded to represent variables within the display. However, it is questionable how viewers would perform using such a display (Tufte, 1990).

Ambiguous symbols can implicitly convey uncertainty. Location uncertainty could be coded using positional ambiguity such as with distorted object symbols (Figure 4). Along these lines, focus may be a promising variable for the representation of uncertainty, as suggested by MacEachren (1992).

Figure 4. Reducing the focus of symbols to represent uncertainty. In this case the uncertainty is implied by the ambiguity of the fuzzy symbol.

Likewise, reducing the directionality of the object symbols could imply heading uncertainty. The resultant heading ambiguity deliberately leads to a reduction in confidence in the judgement of the object's heading. As shown in Figure 5, a triangular or chevron shaped aircraft could be displayed with rounded corners, or as a circle under conditions of diminished heading reliability.

Figure 5. Reduced directionality of symbol shape to represent heading uncertainty.

Alternatively, the symbol for an object may be rotationally distorted or blurred, as shown in Figure 6. Such distortion may either be directly mapped to the degree of heading uncertainty, or simply a categorical change. Whenever the object symbols are altered considerably, care must be taken to be sure the modified symbols are not easily mistaken for other objects.

Figure 6. Rotationally blurred aircraft symbols to represent heading uncertainty. These symbols are mapped to 0, 15 and 30 degrees of heading uncertainty.

This concept of spatial ambiguity has been applied to what Hunter and Goodchild (1994) refer to as an error model. In their work with geographical information systems (GIS) they defined an error model as a process capable of generating a population of distorted versions of the same reality, with each version being a sample from the same population. In the context of GIS the decision-maker is often concerned with studying the range of possibilities presented. For aircraft navigation the avoidance of collisions between the displayed objects is of primary importance. Thus, the concern is primarily with the region containing the possible positions of an object.

Utilizing such an error model, uncertainty can be coded through the positional ambiguity resulting from displaying an object in multiple positions. This effect could be achieved either with a static display or through the use of animation. However, it would be difficult to avoid having an overly cluttered display if objects were statically displayed in multiple locations simultaneously.

Another technique to implicitly code uncertainty is the use of "glyphs," symbols that can represent first and second order information through visual properties such as color, shape, size and orientation. Glyphs can vary infinitely in their design, by mapping various information attributes to different dimensions of the symbol. Wittenbrink et al. (1995) developed glyphs for the visualization of uncertainty in environmental vector fields such as ocean currents. They focused on the ability to clearly display uncertainty in magnitude and direction, as well as representing the magnitude and direction of the currents. These glyphs were arrows that varied along a number of dimensions, with each dimension mapped to one dimension of the data or uncertainty. In an application such as a display of ocean currents, effective use of glyphs in dense displays was an important design consideration. Unfortunately, only subjective testing was performed to evaluate the effectiveness of these new glyphs. The author is not aware of examples of the use of glyphs to represent positional uncertainty of discrete objects (as opposed to vector fields). However, it seems feasible that the form of displayed objects, such as aircraft, could be varied along a number of dimensions to implicitly code the positional uncertainty.

Attach Descriptors to the Display. Alternatively, positional, heading and temporal uncertainty could be presented as some form of verbal descriptor to the objects in question. Below are aircraft symbols with text descriptors for heading uncertainty (see Figure 7).

Figure 7. Text descriptors to represent heading uncertainty. The number refers to the heading uncertainty in degrees.

Descriptors such as epsilon bands, reliability diagrams and root mean square estimates are often utilized in GIS and cartography. Similarly, measurement tolerances are commonly found in mechanical drawing applications. Like the implicit graphical representations of uncertainty, descriptors offer warnings about the data validity, but do not effectively show the potential spatial variation (Goodchild, Chih-Chang and Leung, 1994). The issue of scale is an additional difficulty with the use of text descriptors in an aircraft navigational display. The inclusion of a positional descriptor such as "50m," referring to a 50 meter radius of uncertainty may not be easy to spatially translate into real world terms by the viewer of a 12 inch wide display of 1/4 inch symbols representing aircraft.

Animation Displays. Another method for display of uncertainty that has been investigated by the GIS community is the use of animation (Ehlschlaeger and Goodchild, 1994; Fisher, 1993, 1994a; MacEachren, 1992; McGranahan, 1993). In the context of electronic soil maps Fisher (1993, 1994a) described an animation method of integrating the quality of the information with the display. The method, called error animation, is used to present data quality information about the data in the display. The location of features are revised by random selection as the map is displayed, and the length of time the viewer sees an effect in the animation is intended to represent the probability that this condition will exist in the real world. As a result, it is believed that the positional uncertainty is communicated to the user. At the same time the information in the original map should be retained. In essence, this is simply a dynamic method of displaying the region of uncertainty.

Perceptual testing to determine whether the intended information is conveyed, and to examine what level of training, skill, knowledge is necessary have not yet been performed. For example, the optimal rate of change needs to be established by empirical testing. Whether different rates of change convey different information also needs to be investigated (Fisher, 1993). Ehlschlaeger and Goodchild (1994) also discussed the animation of uncertainty information. They argued that the fades between realizations are not statistically sound, causing error effects to be displayed for the incorrect duration. It is also mentioned that, even for use in GIS, this visualization technique can exceed the attention span of the viewer, especially under very low probability conditions, where several minutes could be required to see the relevant realizations. In the context of

aircraft navigation, such a display format would be highly impractical if long periods of viewing time were required to extract the necessary information. Information in an aircraft navigational display should be available “at a glance.”

Simple animations may be of value to represent data uncertainty within navigational displays. An example is the use of oscillating symbology to represent heading uncertainty. In Figure 8, the aircraft symbol rotates back and forth around its central axis. The amount of rotation may be mapped to the degree of heading uncertainty.

Figure 8. Oscillating aircraft symbol to represent heading uncertainty. Range of oscillation is mapped to amount of heading uncertainty.

An alternate method of representing heading uncertainty through a simple animation is for only the uncertainty symbology to oscillate, while the aircraft symbol remains stationary. Figure 9 shows such a “windshield wiper” strategy, where the yellow angle line moves back and forth.

Figure 9. The windshield wiper motion of the yellow heading uncertainty line is mapped to the range of possible headings.

Displaying Temporal Uncertainty. The representation of temporal uncertainty in two-dimensional space presents special challenges. While the representation of time as an attribute does not necessarily require time, modern, computerized displays allow the dynamic representation of temporal dimensions. MacEachren (1994a) outlined four dynamic variables for the representation of time: duration, rate of change, order and phase.

Earlier it was suggested that displaying the data update rate such as with the sweep of a radar screen could represent temporal uncertainty. Objects are highlighted as the sweep hand rotates through the display area. In some radar displays the highlighted objects gradually fade as the reliability of the information decays (greater temporal uncertainty). As the rotational location of the sweep hand is always visible, the update rate and decay of the information is immediately apparent to the viewer. Metaphorically, a similar tactic could be used with electronically displayed information from GPS and other radar/sensor sources. After each update the display symbol for an object could appear to decay, perhaps by altering color intensity or hue, or other graphical changes. However, the graphical method employed to represent the decay of the information

reliability should not interfere with the effectiveness of displaying the first-order navigational information. It would be counterproductive, for example, to "decay" the objects so that their salience was reduced; more salient information in a display tends to be mentally processed over less salient information. Similarly, humans tend to be biased against the use of the absence of information (Wickens, 1992). Thus, objects that disappear from the display in order to show some aspect of uncertainty might simply be omitted from the decision-making process during their absence. Just because the data describing the location or other attributes of an aircraft are unreliable doesn't mean the presence of the aircraft can be ignored.

The dynamic manipulation of the displayed objects provides many opportunities to express temporal uncertainty or smoothed data. Figure 10 shows some examples of trails and leaders for moving objects. The lighter trails and leaders distinguish the interpolated data points from the "true" data points. This type of strategy is especially suitable for the representation of the uncertainty associated with data smoothing. Other strategies for representing temporal uncertainty include implicit symbols that change along some dimension, such as color, focus or size as temporal uncertainty grows, and explicit uncertainty regions calculated from the object's trajectory and attributes, and error components.

Figure 10. Trails and leaders to express temporal uncertainty and data smoothing.

Empirical Findings

An overwhelming portion of the work in visualization of data with uncertainty has been performed in the GIS field. Unfortunately, little or no perceptual testing of uncertainty display principles has been performed in this area. As one exception, from the aviation psychology literature, Amar et al. (1995) tested two types of positional uncertainty symbology in their study of electronic taxi charts for airport surface situation awareness. The first symbology type was a variable radius circle displaying an estimate of the current GPS accuracy. The second was a constant radius circle displaying a worst-case system accuracy of 100m. It was found that when pilots used the 100m worst-case position uncertainty display situation awareness was not improved over the no-GPS case. However, situation awareness did improve when more accurate GPS data were displayed

with the variable radius circle. Additionally, response latencies were shorter for all levels of position error for the variable radius circle than for the constant radius circle condition.

Many previous studies of decision-making under conditions of uncertainty have focused on the use of known probability values. Such probability studies have found that decision-making performance was better when the uncertainty was represented graphically, than when presented verbally. It is suggested that the graphical representation may enhance performance for spatial problems. Kirschenbaum and Arruda (1994) investigated the effect that a newly developed, graphic representation would have on the performance of submarine decision-makers. Their study compared the new graphic representation to a conventional verbal representation of uncertainty. The graphic representation was the output of a maximum likelihood algorithm developed to provide a decision-maker with an indication of solution accuracy. It was displayed as a 95% certainty ellipse, describing the area of uncertainty around the estimated position of a target. For submarines, range is the most important parameter for both weapon firing and collision avoidance. Thus, range accuracy was used as the performance measure of interest in this study. In current submarine displays the values of location parameters are displayed both numerically and graphically, but the uncertainty associated with the range estimates is only displayed in numerical format. Under moderately difficult conditions subjects using the graphic confidence ellipse gave range estimates that were significantly more accurate than the range estimates of those who used only verbally expressed uncertainty information. This extends previous findings that graphic displays yield better performance for spatial problems (Boles and Wickens, 1987; Schwartz and Howell,

1985). Graphic representations such as the uncertainty ellipse seem to require less processing than verbal information for spatial decision-making.

SUMMARY

While the literature demonstrates that a graphical representation is the most promising method of displaying positional uncertainty, little work has been performed to evaluate and compare the various display possibilities. Indeed, the only empirical study directly relevant, while finding that a display incorporating positional uncertainty could improve pilot situation awareness, used the same symbology (a circle with a radius representing the GPS accuracy) in all conditions (Amar et al., 1995). Additionally, the issues of displaying heading and temporal uncertainty appear to be unexplored.

We therefore proposed to perform several studies aimed at evaluating and comparing the utility of various types of uncertainty symbology for aircraft navigation, tactical and situation awareness displays. The studies were performed on a PC in the context of aircraft navigation and tactical tasks. In some studies participants were asked to navigate a route under varying levels of data reliability while maintaining proper levels of separation from other objects. In addition, the participants were asked for subjective information such as confidence scores and their preferences for the symbology types. Other studies investigated the utility of various types of uncertainty symbology for tactical battle situations. Subjects were required to perform various simulated battle tasks under various levels of data reliability.

THE PRESENT EXPERIMENTS

The primary purpose of the following series of experiments was to compare the effect on situational awareness of displaying vs. not displaying positional and heading uncertainty. Three types of uncertainty symbology were tested including text descriptors, explicit graphic displays and global (implicit) graphic displays. The text descriptors simply attached numbers representing the positional or heading uncertainty to the relevant object. The explicit display graphically mapped the degree of uncertainty to the representation as in the variable radius circle of Amar et al. The implicit display only represented whether uncertainty was present or not in qualitative terms. Color change from green for reliable data, to yellow for moderately reliable, and finally to red for unreliable data was chosen as the implicit representation of uncertainty for these experiments.

The first experiment, referred to as “collision-position” tested the effects of displaying positional uncertainty on pilot situation awareness and risk bias. Subjects piloted the ownship through a game of “chicken” while a projectile (referred to as a meteor) maintained a head-on course. The pilot’s objective was to minimize course deviation while avoiding a collision at all costs.

The second experiment was called “invader-heading.” This experiment investigated the explicit utility of the uncertainty symbology types for expressing tactical heading uncertainty. Subjects performed an anti-aircraft battle task in which the target

aircraft were displayed with either one type of uncertainty symbology or no representation of the uncertainty.

Although they are not discussed in the present paper, a series of subsequent experiments expands on the findings of the first two experiments. The third experiment was similar in format to invader-heading, except that this one investigated the utility of the uncertainty symbology types for expressing tactical position uncertainty.

Accordingly, it was referred to as “invader-position.” The fourth and fifth experiments expanded on the findings of the two “invader” experiments by incorporating asymmetrical uncertainty symbology. In the asymmetrical invader experiments the displayed (unreliable) position and heading were not restricted to symmetry with respect to the actual data. These experiments allowed the authors to examine the effects of the uncertainty symbology on subject behavior in a context more representative of real-world use. The two asymmetrical experiments were called “invader-heading-asymmetrical” and “invader-position-asymmetrical,” and utilized very similar formats to their symmetrical counterparts. Only the first two experiments, “collision-position” and “invader-heading” will be discussed in this paper.

Levels of Uncertainty

Three levels of data uncertainty were used in the experiments: accurate, moderate uncertainty and high uncertainty (see Table 1). The three levels of uncertainty were intended to correspond to the following levels of difficulty: Under accurate data conditions the subject should be able to perform without error. Under moderate

uncertainty conditions some errors would probably occur without the representation of uncertainty. Without display of uncertainty or extremely cautious navigation in the collision experiment, errors would definitely occur under the high uncertainty conditions.

Data Uncertainty	Positional Accuracy	Heading Accuracy
Accurate	Accurate	Accurate
Moderately Uncertain	Position up to 15 pixels (0.2") off	Heading up to 10 off
Highly Uncertain	Position up to 50 pixels (0.7") off	Heading up to 30 off

Table 1. Position and heading uncertainty.

Symbology

Three basic types of symbology to represent positional and heading uncertainty were tested: text descriptors, explicit graphic displays, and global or implicit graphic displays. Each symbology type represented a different approach to displaying uncertainty. Uncertainty symbology was displayed in yellow for high contrast against the black screen and because the color yellow is stereotyped as being representative of "caution." The default symbol for an aircraft (under accurate conditions) was a green triangle with a short line extending from the nose of the craft (Figure 11). The triangular symbol was chosen to minimize the complexity and "ink use" of the symbol while still explicitly representing directionality. Other objects, such as the meteor used in the first

experiment were also represented by the most basic of graphical symbols. The default symbol for the meteor was a solid green circle.

Figure 11. Default symbols for the meteor (left) and aircraft (right).

Text Descriptors. The text descriptors displayed the magnitude of the uncertainty through the addition of numerical descriptors to the relevant object (Figure 12). The text was displayed in 10 point type, the smallest size that provided adequate legibility. Heading and positional uncertainty were differentiated by location. Heading uncertainty descriptors were presented just ahead of the aircraft symbol. Positional uncertainty descriptor was presented in the middle of the object symbol, inside the aircraft triangle or meteor circle. Positional uncertainty descriptors referred to the radius (in pixels) of the region of uncertainty. Heading descriptors referred to angular uncertainty (in degrees). Reliable data was shown without any descriptor or uncertainty symbology.

Figure 12. Meteor and aircraft symbols with text descriptors for positional and heading uncertainty respectively.

Graphical-Explicit. The explicit display graphically mapped the degree of uncertainty to the representation symbology as in the variable radius circle of Amar et al. (1995). These experiments utilized variations on the theme of a yellow circle around the object. The positional uncertainty symbology mapped the radius of the yellow uncertainty circle to the level of data uncertainty. At approximately 0.75", the moderate uncertainty circles were only slightly larger than the meteor and aircraft symbols, which were roughly 0.6" along their longest dimension. Under conditions of high uncertainty the positional uncertainty circles grew to approximately 2.0". Accurately displayed objects were shown without uncertainty circles.

Two types of explicit heading uncertainty were tested (see Figure 13). In the first, a segment of the circle, mapped to the angle of uncertainty, was eliminated. The endpoints of the remaining circle segment were accentuated with two short, yellow lines angled such that they would meet at the nose of the aircraft symbol. The second symbology type was similar except that the circle was eliminated in favor of displaying just the short segment within the angle of heading uncertainty. This system also used the

short heading lines at the end of the segment. Again, accurate data was shown without uncertainty symbology.

Figure 13. Meteor with graphical-explicit position symbology (left). Aircraft with two types of explicit heading symbology (center and right).

Graphical-Implicit. The implicit-graphical display discriminates between accurate data and the two levels of uncertainty, but does not explicitly show the degree of uncertainty. This symbology type was tested only for positional uncertainty. Positional uncertainty was represented by a change in symbol color from green for accurate, to yellow for moderately uncertain data, and finally to red for high uncertainty data (Figure 14).

Figure 14. Meteor and aircraft with implicit-graphical uncertainty symbology. Green refers to accurate data, yellow to moderately uncertain, and red to highly uncertain data.

EXPERIMENT 1 METHOD: COLLISION-POSITION

The first experiment tested the effects of displaying positional uncertainty on pilot situation awareness and risk bias. Subjects piloted the ownship through a flight navigation task simulating the game commonly known as “chicken.” In this game the pilot’s objective is to minimize course deviation while avoiding a collision with another object on a collision course. Situational awareness was measured in terms of collision frequency and RMSE of the course deviation. Effects of positional uncertainty representation on pilot behavior were also of concern. Separation distance and collision frequency were also considered as measures of pilot risk bias. It was hypothesized that the inclusion of positional uncertainty representation would have the effect of allowing pilots to decrease separation distances with fewer collisions under accurate data conditions. At the same time it was hypothesized that the representation of uncertain data conditions would effect more conservative behavior in the pilots, causing them to increase separation distances, especially for the graphical-explicit representation conditions.

Apparatus and Display

The electronic navigational display with animated objects was presented on an IBM-compatible PC with an Intel Pentium 100 CPU and a 17 inch color monitor. Subjects interacted with the system through a joystick. Please refer to Figure 15 for details of the screen layout. The ownship was represented by a white triangle. On a black

background the ownship was presented at the bottom of the display and the goal area, represented by a horizontally oriented pair of small gray circles was shown at the top of the screen. A magenta line represented the direct path to the goal (a straight line). The object to be avoided was a meteor represented by a green circle approximately twice the size of the ownship. The oncoming object was described as a "meteor" because its behavior mimicked that of an unpiloted projectile. That is, its course and velocity were fixed. The meteor would appear from the top of the screen and travel downward, along a straight path directly opposite to the for the ownship's direct course to the goal. Both objects traveled at a predetermined, constant speed, slowly enough to allow the subject precise control of the ownship. The meteor moved at half the speed of the ownship. Feedback of collisions between the ownship and the meteor was provided in the form of a brief display of an explosion followed by a screen displaying the word "Collision." No score was recorded when a collision occurred. Successful completion of the task was noted with the words "Mission Completed" on the screen. If the subject failed to maneuver the ownship through the goal area the following screen would display the message "Goal Missed." This occurrence was not actually recorded in the data, but the feedback was included to reinforce the importance of following the direct path as closely as possible.

Figure 15. Screen layout for the collision-position experiment.

Levels of Uncertainty. In this experiment the display uncertainty of the meteor was manipulated, while the display of the ownship remained accurate in all trials. Under uncertainty conditions the actual location of the meteor (as opposed to the displayed location) was randomly varied along the x and y axes, within the radius specified by the level of uncertainty (Table 2). Figure 16 shows the regions of position uncertainty for moderate uncertainty and high uncertainty data conditions. The meteor was always displayed with its center on the magenta line, regardless of uncertainty level.

Data Uncertainty	Positional Accuracy
Accurate	Accurate
Moderately Uncertain	Position up to 15 pixels (0.2") off
Highly Uncertain	Position up to 50 pixels (0.7") off

Table 2. Position uncertainty at each level of uncertainty.

Figure 16. Region of position uncertainty for moderately uncertain conditions (left) and highly uncertain conditions (right). Accurate conditions (not shown) were depicted accurately.

Symbology. Only positional uncertainty was present in this experiment, so heading uncertainty symbology was not included. In the no-representation conditions the meteor was displayed as the green circle, without any uncertainty symbology (Figure 17).

Note that the meteor was represented in the same manner for all levels of display certainty.

Figure 17. Symbology for the no-representation conditions. The same green meteor is displayed in all data conditions.

In the text conditions a yellow descriptor number inside the meteor represented the positional uncertainty (Figure 18). The number referred to the radius of positional uncertainty (in pixels). No descriptor was present under accurate data conditions.

Figure 18. Symbology for the text descriptor conditions.

Color change was utilized for the graphical-implicit conditions (Figure 19). A green meteor refers to accurate data, yellow to moderately uncertain conditions, and red to highly uncertain conditions.

Figure 19. Symbology for the graphical-implicit conditions. Green is displayed under accurate conditions, yellow under moderately uncertain, and red for highly uncertain.

The explicit graphical symbology utilized the variable radius circle, without the missing segment for heading uncertainty (Figure 20). The yellow circle explicitly shows the region of uncertainty. No circle was shown in accurate data conditions.

Figure 20. Symbology for the graphical-explicit representation conditions. Accurate data has no ring (left). Moderate data has a small ring (center), and highly uncertain data has a large ring (right).

Procedure

After initial screening, each subject completed a practice block in order to become familiar with the electronic display and the joystick control. For the experimental trials the pilots were instructed to avoid collisions with the meteor at all cost, while “hugging” the meteor as closely as possible in order to fly the most direct route to the goal. It was emphasized that the avoidance of collisions was the primary goal. These instructions were repeated before each block of trials.

Each trial was performed in the following manner: By pressing a button on the joystick the pilot started the trial. The ownship would appear at the bottom of the display, moving along the magenta line, toward the goal at the top of the display. As the pilot

navigated toward the goal the meteor would appear from the top of the screen, on a path directly opposite to the ownship. As instructed, the pilot attempted to minimize course deviation while still avoiding a collision with the meteor. As discussed above, in the case of a collision between the ownship and the meteor, feedback was provided to the pilot in the form of a brief explosion and the end of the trial. Successful completion of the task was signaled with the words "Mission Completed" on the screen. Each trial was about 15 seconds long, depending on whether a collision occurred. Each pilot performed 30 trials of each of the three conditions. The order of conditions was distributed randomly amongst the 90 trials, with each subject testing one representation type. Subjects were allowed rest breaks between blocks. After the experiment, each subject completed a brief subjective survey that asked about their strategy to maximize their performance in the experiment. This experiment required about 40 minutes for each subject, including the practice block and the survey.

Design

A three data uncertainty conditions (accurate, moderately uncertain and highly uncertain) by four uncertainty symbology types (none, text descriptor, graphic-implicit, and graphic-explicit) factorial design was used in this experiment. Data uncertainty was a within subjects factors, while symbology type was manipulated between subjects. Each subject tested one symbology type at each level of uncertainty.

	Represent Uncertainty			Don't Represent Uncertainty
Symbology Type:	Text Descriptor	Graphic Explicit (rings)	Graphic Implicit (colors)	No Uncertainty Symbology
Accurate	1	2	3	4
Moderately Uncertain	5	6	6	8
Highly Uncertain	9	10	11	12

Table 3. Factorial design for the collision-position experiment.

Dependent Measures

Dependent measures included course deviation and collision frequency. Course deviation was measured as the root mean square error (RMSE) of the lateral deviation of the ownship from the central, magenta line to the goal. Collision frequency was scored as the number of times the ownship collided with the meteor.

RESULTS: COLLISION-POSITION

		Text Descriptor	Graphic Explicit (rings)	Graphic Implicit (colors)	No Uncertainty Symbology	Total
Accurate	RMSE	19.46	21.06	21.34	28.46	22.58
	Collide %	13.3	15.3	9.7	5.0	10.8
Moderately Uncertain	RMSE	24.66	28.09	30.52	29.46	28.18
	Collide %	7.7	5.7	4.3	11.0	7.2
Highly Uncertain	RMSE	33.20	51.31	36.77	28.42	37.42
	Collide %	26.7	4.3	19.3	33.0	20.8
Total	RMSE	25.77	33.49	29.54	28.78	29.40
	Collide %	15.9	8.4	11.1	16.3	12.9

Table 4. Mean scores for Collision-position experiment.

Symbology Type

Analysis of Variance was conducted using SPSS ANOVA to determine the main effects of symbology on the number of collisions and on the root mean square error (RMSE), which is a measure of the subject's course deviation. It was found that symbology had no main effect on number of collisions ($F(3,36) = 2.06, n.s.$). Symbology type also did not have a main effect on course deviation ($F(3,36) = 2.19, n.s.$).

Data Uncertainty

Analysis of Variance was conducted to determine the effects of data uncertainty on the number of collisions and RMSE. Uncertainty had a significant effect on the number of collisions ($F(2,72) = 36.63, p < .001$). As expected, the subject pilots had more collisions under highly uncertain data conditions. It was also found that uncertainty had a significant effect on course deviation, with subjects steering farther from the meteor under less accurate display conditions. A significant negative correlation ($-.66, p < .001$) was found between course deviation and percentage of trials with collisions, suggesting a risk-bias trade-off between these two variables.

Interaction Effects

A significant interaction effect on the number of collisions was found between symbology type and uncertainty ($F(6,72) = 12.46, p < .001$). There was also a significant interaction effect on course deviation ($F(6,72) = 41.24, p < .001$). The chart in Figure 21 graphically demonstrates these relationships. Note how linearly the collision frequency increases with uncertainty for the “none” conditions. Also of note is the decrease in collision frequency and the corresponding increase in course deviation for the graphical-explicit symbology (rings) under conditions of high uncertainty. The interaction effects demonstrate that depending on the symbology type, the uncertainty level had different effects on subject performance and behavior. The following sections describe these interactions by symbology type.

Figure 21. Interaction effects between Symboly and Uncertainty, on collision frequency and course deviation.

No Representation. As expected, increasing uncertainty was accompanied by an increase in the number of collisions in the no-representation of uncertainty conditions. When data was accurate subjects collided in 5% of trials. Under moderately uncertain and highly uncertain conditions collisions jumped to 11% and 33% of trials, respectively. The average course deviation for no representation of uncertainty trials is the same for

each level of uncertainty. This is no surprise considering that subjects had no indication of the data quality.

Text Descriptors. When data uncertainty was represented with text descriptors there were fewer collisions under moderately uncertain conditions (7.7%) than accurate conditions (13.3%). Under highly uncertain conditions the number of collisions jumped to 26.7%.

As expected, course deviation increased as the data uncertainty increased. However, this effect was less pronounced than for the two graphical symbology types. Under accurate conditions the average RMSE was 19.46. Average RMSE increased to 24.66 for moderately uncertain data and then to 33.20 for highly uncertain data.

Graphical-Implicit. The graphical-implicit (color change) subjects showed a similar performance pattern to those who used the text descriptors. There were fewer collisions under conditions of moderate uncertainty (4.3%) than accurate conditions (9.7%). Under highly uncertain conditions the number of collisions jumped to 19.3%.

As with the text descriptor conditions, course deviation increased as uncertainty increased. For trials with accurate conditions the average RMSE was 21.34. Average RMSE increased to 30.52 for moderately uncertain conditions, and then to 36.77 for trials with highly uncertain data.

Graphical-Explicit. When data uncertainty was represented with the graphical-explicit symbology system of a variable radius circle the number of collisions actually dropped as the data uncertainty increased. Under accurate conditions subjects using the rings symbology collided in 15.3% of trials. Under moderately uncertain conditions there were collisions in 5.7% of trials. Surprisingly, there were collisions in only 4.3% of the highly uncertain trials. Course deviation varied most markedly when the graphical-explicit symbology was present, demonstrating that subjects adopt a more conservative risk bias in response to the variable radius rings. Under accurate and moderately uncertain conditions average RMSE was similar to the other symbology types. However, under highly uncertain conditions the average RMSE was much higher than the other symbology types at 51.31.

DISCUSSION: COLLISION-POSITION

Symbology Type

Subjects using graphical-explicit symbology averaged only about half as many collisions as those subjects using no uncertainty symbology. Surprisingly, no main effect was found for symbology on the number of collisions with the meteor. It is possible that this between-subjects factor lacked the power necessary to demonstrate a significant effect. However, an important interaction between symbology and uncertainty will be discussed later.

Symbology type also did not have a main effect on the subjects' course deviation around the meteor. While the inclusion of uncertainty symbology allows the subject to fly a closer path around the meteor under accurate and moderately uncertain conditions, it also promotes a highly conservative (large course deviation) risk bias under highly uncertain conditions. Overall, these effects seemed to have cancelled each other out, leading to very similar average RMSE for each symbology type.

Uncertainty Level

As expected, uncertainty level had a significant main effect on the number of collisions. Not surprisingly, subjects had more collisions under highly uncertain data conditions than the accurate or the moderately uncertain conditions. Recall that the subjects were informed and frequently reminded of the uncertainty inherent in the display.

Despite an awareness of the uncertainty, subjects were still unable to avoid an increased frequency of collisions under conditions of uncertainty. This result confirms one of the basic premises of this study: that uncertainty leads to pilot errors such as collisions. Such a finding simply reinforces the need for an effective representation of uncertainty in navigational displays.

It was also found that uncertainty had a significant effect on course deviation, with subjects steering farther from the meteor under conditions of higher uncertainty. Because average course deviation did not vary within the no-symbology conditions, this effect must be a result of subjects reacting to the uncertainty symbology by steering farther from the meteor when the display was uncertain. Thus, these uncertainty symbologies effectively induce subjects to adopt greater course deviations. Alternatively, we could say that the uncertainty symbology is capable of eliciting a more conservative risk bias. The strong negative correlation between course deviation and collisions suggests a risk bias trade-off. More conservative behavior is rewarded with fewer collisions, but a higher RMSE score. Subjects who hugged the meteor more closely produced lower RMSE scores, but had more collisions. Display strategies that tend to elicit highly conservative course deviation behavior seem appropriate in most navigational situations.

Interaction Effects

A significant interaction effect on the number of collisions was found between symbology type and uncertainty level. There was also a significant interaction effect on course deviation. Depending on the symbology type, manipulation of the uncertainty

level had different effects on subject performance and behavior. The interaction effects are discussed in terms of each representation type below.

No Uncertainty Symbology. When data uncertainty was not represented to the pilot (no symbology) performance worsened with the data uncertainty. Each incremental increase in uncertainty was accompanied by an increase in the number of collisions. This pattern occurred because the average course deviation for no-symbology trials was the same for each level of uncertainty. It is intuitive that course deviation should remain constant when subjects have no indication of the uncertainty level. The pilot has no means of adjusting their course deviation to the uncertainty of each trial.

It might be assumed that subjects would generally adopt a conservative course deviation in the absence of information about data uncertainty. However, this was often not the case. It was observed that in the first trials subjects would often experiment to see how close they could fly around the meteor. Each time a collision occurred they would adopt a wider course deviation. However, no subject ever chose paths so wide that they could avoid collisions altogether. Additionally, it seems that after completing few trials without a collision many subjects would begin reducing the course deviation until they collided again. It appears that without constant reminder of the spatial uncertainty subjects would either ignore or forget about the uncertainty, or take unnecessary risks. It seems probable that risk bias would be markedly different if tested under real-world piloting conditions. If this is the case, a computer-game simulation lacking powerful negative feedback (such as a plane crash) is an unfair test of risk bias behavior.

Nonetheless, this experiment demonstrates the tendency for individuals to ignore hidden decision criteria.

Other subjects in the no-symbolology group were not so systematic in their behavior. Despite repeated instructions to “avoid collisions with the meteor” there were a few subjects who repeatedly chose to “hot-dog,” by flying as close as possible to the displayed meteor. It didn’t seem to be the case that these subjects didn’t understand the instructions, or just didn’t care about the results. Regardless of the cause, it is notable that such behavior only occurred amongst those in the no-symbolology group. Again, the results support the premise that information must be present in order to be reliably incorporated into a decision-making process.

Text Descriptors and Graphical-Implicit. The subjects in the text descriptor and graphical-implicit conditions showed similar patterns in terms of collision frequency. For both symbolology types there were actually fewer collisions under moderately uncertain data conditions than accurate conditions. This result can be explained by two factors. Under accurate conditions subjects would often fly extremely close to the meteor in an effort to minimize the course deviation. Considering that the meteor was truly located as it was shown on the display, any miscalculation in the direction of the meteor would lead to a collision. Many subjects reported hitting the meteor under these seemingly “easy” circumstances. Subjects had fewer collisions under moderately uncertain conditions because even when the pilot flew within the actual radius of uncertainty (the danger zone) their chance of coinciding with the location of the meteor was relatively small. Thus,

despite the less certain display, the use of uncertainty symbology provided the pilots with a safety cushion.

Under highly uncertain conditions the average course deviations did not increase by nearly as much as the increase in uncertainty radius. Despite having been shown the regions of uncertainty in their instructions, subjects repeatedly underestimated the course deviation necessary to avoid collisions. As a result, subjects using the text and color symbology showed a marked increase in collisions when the data was highly uncertain. Those using the color symbology had slightly higher course deviations and lower collision rates than the text group at all levels of uncertainty, although these differences did not prove statistically significant.

Apparently, the display of the uncertainty radius as a number was no more helpful to pilots than a warning by color change. Subjects did not seem to be able to accurately translate the uncertainty number into spatial terms in order to choose a suitable course to avoid collisions with the meteor. As such, the text descriptors appear to have performed as implicit or categorical uncertainty information (accurate, moderate, and uncertain). The results of this experiment suggest that symbology that serves primarily as a categorical warning is inadequate for representing spatial uncertainty information when there is a high degree of data uncertainty.

Graphical-Explicit. The hypothesis that the graphical-explicit symbology of variable radius rings would provide the best performance was borne out by the results of this experiment. Only this symbology type elicited adequately conservative behavior for

subjects to avoid collisions under highly uncertain conditions. All the other symbology types led to significantly worse performance when the data was highly uncertain. When the actual radius of uncertainty was displayed in the form of a yellow circle, subjects would avoid entering the uncertainty region. Most subjects chose to follow the boundary of the uncertainty region (the yellow line). In fact, it might be the case that pilots will tend to incorporate such boundaries into their course whenever uncertainty is explicitly represented. In this experiment, the result was that the graphical-explicit symbology resulted in far fewer collisions than the other symbology types when data was highly uncertain.

It might seem counterintuitive that there were actually fewer collisions under highly uncertain conditions than under moderately uncertain or even accurate conditions. However, this phenomenon can be explained by the lower probability that the meteor was actually near the boundary area of the large uncertainty region. Thus, even if the pilot were to accidentally cut through part of the uncertainty circle, there was a relatively low probability that the meteor was also in that region of the circle.

Summary. Not only does it appear to be important to represent uncertainty for the purpose of eliciting conservative risk behavior, it is also clearly beneficial to represent the spatial uncertainty explicitly, with graphical symbology. When spatial uncertainty is graphically represented as a region around an object, subjects generally appear to be unwilling to enter this region of uncertainty.

EXPERIMENT 2 METHOD: INVADER-HEADING

The second experiment investigated the explicit utility of the different symbology types for expressing tactical heading uncertainty. Subjects performed an anti-aircraft battle task in which the target aircraft were displayed with either one type of uncertainty symbology or no uncertainty symbology. The subject's task was to kill only those aircraft whose heading would allow them to be a threat. Thus, the aircraft were classified as "friendlies" or "bogeys," based on their heading. Only heading uncertainty symbology types were tested in this experiment. It was hypothesized that the inclusion of uncertainty symbology would improve the gunner's ability to distinguish the bogeys from the friendlies. Of the symbology types tested it was hypothesized that the explicit graphic displays would provide better performance than the text descriptor, and that the no uncertainty symbology condition would have the worst performance.

Apparatus and Display

An animated anti-aircraft battle display was presented on the same Pentium PC system as the previous experiment. Figure 22 shows the layout for the screen for invader-heading. At the bottom of the screen the subject's gun barrel was displayed, protruding from a two inch wide semicircle (as if it were part of a gun turret). The gun was aimed by means of a joystick control. In the screen area above the gun, five aircraft were represented by the green triangular symbols described earlier. To prevent confusion as to which aircraft the gunner was aiming for, the craft were positioned on the screen

Figure 22. Screen layout for the Invader-Heading experiment. The subject fired at the aircraft from the gun turret (bottom center).

such that there was no overlap between the different craft from the gunner's perspective. In different terms, the craft were arranged so that each was within its own "lane" extending outward radially from the pivot point of the gun. To further ensure that the gunner knew which aircraft was "in their sights," a white circle would appear around whichever symbol was targeted. Within each trial all five enemy craft were always presented at the same level of uncertainty, and coded with the same symbology. Of the

five craft on the screen, between one and four of the five aircraft were “bogeys”; that is, they were aimed at the gunner. The remaining craft were considered harmless, and categorized as “friendly.” All of the aircraft were incapable of motion or rotation and could not fire back at the gunner.

The trials were self-paced, beginning and ending when the subject pressed the joystick thumb button. Each pull of the joystick trigger released one shot. The subject was limited to eight shots per trial, but in practice this limit was inconsequential because the shots were virtually assured of hitting the target. The aircraft were actually very easy to hit. With a generous “kill region” and the white circle highlighting the targeted aircraft a hit was assured with each shot, as long as the aircraft in the zone had not already been killed. Thus, the measure of interest was the target choice, not the aiming utility. Aircraft were killed instantly when hit, disappearing from the screen.

Levels of Uncertainty. When uncertainty conditions were present, the actual heading of the craft varied randomly from the displayed heading, within the range of angular rotation specified by the degree of uncertainty. Under accurate conditions the displayed headings were accurate. Under moderately uncertain conditions the actual heading could vary by as much as five degrees to either side of the displayed heading. The variance could be as much as 15 degrees to either side under highly uncertain conditions.

Data Uncertainty	Heading Accuracy
Accurate	Accurate
Moderately Uncertain	Heading up to 10° off
Highly Uncertain	Heading up to 30° off

Table 5. Levels of heading uncertainty.

Figure 23. Angular uncertainty for the moderately uncertain (left) and highly uncertain conditions (right).

Symbology. Because only heading uncertainty was manipulated in this experiment, the positional uncertainty symbology was not included. In the no-symbology conditions the same green aircraft symbol was used for all levels of uncertainty (Figure 24).

Figure 24. Symbology for no-symbology conditions. The same symbol was displayed at all levels of uncertainty

In the text descriptor conditions a yellow number to the front of each aircraft represented heading uncertainty (Figure 18). For example, a descriptor of "10" means the total heading uncertainty was 10 degrees, and that the actual heading could be up to five degrees to either side of the displayed heading. No descriptor was displayed under accurate conditions.

Figure 25. Symbology for the text descriptor conditions. The number referred to the angular uncertainty in degrees.

Two types of explicit graphical heading symbology were tested. The first was the circle with missing segment type as shown in Figure 26. The second was the segment

only type, without the ring, shown in Figure 27. The circular segments were of a diameter large enough to fit the aircraft symbol inside. The diameter remained constant because there was no positional uncertainty to be represented. The yellow heading lines referred to the angle of heading uncertainty. No uncertainty symbology was displayed under accurate data conditions.

Figure 26. Symbology for graphical-explicit (1) conditions. Accurate conditions are displayed without the uncertainty symbols (left). Moderately uncertain (center) and highly uncertain conditions used the angled lines mapped to the angular uncertainty.

Figure 27. Symbology for graphical-explicit (2) conditions. As in the graphical-explicit (1) symbology accurate conditions are displayed without the uncertainty symbols (left). Moderately uncertain (center) and highly uncertain conditions used the angled lines mapped to the angular uncertainty.

Procedure

After initial screening, each subject completed a practice block to become familiar with the electronic display and joystick control. The subject gunners were informed of the scoring system and of the ideal strategy as follows: hitting a bogey aircraft = +25 points, hitting a friendly aircraft or missing = -25 points. Additionally, deducting one point from the score for each second of the trial encouraged speed. Thus, to achieve the highest score, the subjects were instructed to kill only the bogeys, as quickly as possible.

There were no markings on the aircraft to help the pilot discriminate between bogey and friendly aircraft. This required the gunner to judge whether the aircraft's heading posed a threat or not. Increasing the difficulty of this heading judgement task was the data uncertainty. Depending on the degree of heading uncertainty, the enemy craft would not necessarily appear to be aimed in the direction indicated by the apex of the triangular symbol. As a result, the assessment of the threat posed by a craft was obscured. Because of this decision process certain aircraft, deemed the "maybe bogeys" played an important role. The maybe bogeys were those aircraft positioned such that they would be a friendly under reliable conditions, but a bogey under either moderate or unreliable conditions. These maybes were important because they appear to be friendlies to those without uncertainty symbology, but bogeys to those viewing them with the symbology. For an example of a maybe bogey, look at the third aircraft from the left in Figure 28. Note that the highlighted region, corresponding to the heading uncertainty, overlaps the gun turret. It was anticipated that the subjects using the graphic-explicit uncertainty symbologies would kill a greater percentage of these maybe bogeys.

The target area was very large and the targeted aircraft was highlighted with a white circle, so once the decision of which craft to kill was made, hitting them was easy. Sparing use of the ammunition was encouraged. For any shot that did not kill a bogey 25 points were deducted from the subject's score. Each shot was classified by the target choice: whether it hit a bogey, a friendly or nothing.

Figure 28. Heading uncertainty regions for unreliable conditions in the Invader-Heading experiment.

Each trial was self-paced, initiated by the subject's press of a joystick button. The display would appear with all five craft in their static locations and the subject's gun

ready to fire. Timing was performed automatically by the computer, beginning when the display appeared and ending with the subject's press of another joystick button. Each subject performed 24 trials of each of the three conditions. The order of conditions was distributed randomly amongst the 72 trials, which were broken into three blocks of 24 trials. Each block was composed of six of each of the four bogey/friendly number combinations. Subjects were allowed rest breaks between blocks.

Design

A three data uncertainty conditions (accurate, moderately uncertain and highly uncertain) by four uncertainty symbology types (none, text descriptor, graphic-explicit type 1, and graphic-explicit type 2) factorial design was used in this experiment. Data uncertainty was a within subjects factors, while symbology type was manipulated between subjects. Each subject tested one symbology type at each level of uncertainty.

	Represent Uncertainty			Don't Represent Uncertainty
Symbology Type:	Text Descriptor	Graphic Explicit (rings)	Graphic Explicit (arcs)	No Uncertainty Symbology
Accurate	1	2	3	4
Moderately Uncertain	5	6	7	8
Highly Uncertain	9	10	11	12

Table 6. Factorial Design.

Dependent Measures

Dependent measures included points score and percentage of bogeys and friendlies killed. Elapsed time to kill each aircraft, and total time for each trial were also recorded.

RESULTS: INVADER-HEADING

		Text Descriptor	Graphic Explicit 1 (rings)	Graphic Explicit 2 (arcs)	No Uncertainty Symbology	Total
Accurate	Bogey %	94.71	96.79	93.49	96.46	95.36
	Friendly %	10.15	9.13	7.11	14.52	10.23
	Time (sec)	6.68	7.18	6.85	7.32	7.01
Moderately Uncertain	Bogey %	93.72	96.89	93.62	95.21	94.86
	Friendly %	20.8	19.97	17.49	20.11	19.59
	Time (sec)	7.36	7.81	8.20	7.80	7.79
Highly Uncertain	Bogey %	84.82	87	86.97	75.89	83.67
	Friendly %	9.39	10.12	10.81	5.99	9.08
	Time (sec)	8.17	8.70	9.14	8.24	8.56
Total	Bogey %	91.08	93.56	91.36	89.19	91.3
	Friendly %	13.45	13.07	11.81	13.54	12.97
	Time (sec)	7.4	7.90	8.06	7.78	7.79

Table 7. Mean scores for Invader-Heading experiment.

Symbology Type

Analysis of variance was conducted using SPSS ANOVA to determine the effects of symbology type on percentage of bogeys killed, percentage of friendlies killed and

elapsed time per trial. It was found that symbology type had no main effect on bogeys killed ($F(3,32) = 1.57, n.s.$), friendlies killed ($F(3,32) = .39, n.s.$), or elapsed time per trial ($F(3,32) = .21, n.s.$).

Figure 29. Friendlies and bogeys killed by symbology and reliability.

Data Uncertainty

Analysis of Variance was conducted to determine the effects of data uncertainty on percentage of bogeys killed, percentage of friendlies killed and elapsed time per trial. Uncertainty level had a significant effect on the number of bogeys killed ($F(2,64) = 36.21, p < .001$), with higher levels of uncertainty leading to fewer bogeys killed. Under accurate and moderately uncertain conditions subjects killed 95-96% of bogeys. This figure decreased about 20% to 76% when the data was highly uncertain.

Uncertainty also showed a significant effect on the number of friendlies killed ($F(2,64) = 82.18, p < .001$). As expected, more friendlies were killed under conditions of higher uncertainty. Uncertainty level also demonstrated a significant effect on time ($F(2,64) = 54.74, p < .001$). Subjects completed the self-paced trials more slowly under less reliable conditions.

Interaction Effects

A significant interaction effect on the number of bogeys killed was found between symbology type and uncertainty ($F(6,64) = 2.39, p < .05$). There was also a significant interaction effect between symbology and uncertainty on friendlies killed ($F(6,64) = 4.49, p < .001$). No interaction was found for elapsed time ($F(6,64) = 1.95, n.s.$). As hypothesized, and as the collision experiment previously demonstrated, differences between the symbology types were magnified by increased data uncertainty. The following sections describe these interaction effects by symbology type.

No Symbology. Under accurate and moderately uncertain conditions performance in terms of the number of bogeys killed was very similar for each symbology type. Bogeys killed were tightly clustered between 93.5% to 96.9% for all symbology types in accurate and moderate uncertainty conditions. Variation amongst friendlies killed was somewhat greater. Under accurate conditions friendlies killed ranged from 7.1% for arcs to 14.5% for no-symbology. The text and rings groups were in the middle at 10.2% and 9.1%, respectively. Under conditions of moderate uncertainty friendlies killed increased to 17.5% to 20.8%, with arcs lowest at 17.49. When conditions were highly uncertain, performance of the no-symbology subjects showed a much greater decrement than for those using the three uncertainty symbology systems. Bogeys killed went down to 75.9% for the no-symbology group, while only dropping to 85-87% for each of the uncertainty symbology groups. Interestingly, under conditions of high uncertainty friendlies killed dropped considerably, to 6.0% for no-symbology, and approximately 10% for each of the other symbology types.

Uncertainty Symbologies. Subjects showed very similar performance trends with each of the three uncertainty symbology types. Percentage of bogeys killed remained constant between accurate and moderately uncertain data conditions, and then decreased by about 10% under highly uncertain conditions. This is about half the decrement seen in the no-symbology group.

The friendlies killed scores showed a different trend that was also shared by each of these representation symbology types. Approximately 10% of friendlies were killed

when the data was either accurate or highly uncertain. Interestingly, about 20% of the friendlies were killed when the data was moderately uncertain.

Detailed Analysis

After conducting the previously discussed analysis the author observed that the between-symbolology effects had been diluted by an evaluation of mean scores for all responses, instead of just those shots aimed at intruders whose "bogey status" changed as a function of reliability level. These difficult-to-classify intruders were referred to as "maybes" because they were oriented such that they were friendlies in reliable conditions, but bogeys in unreliable conditions. The important result of this dynamic is that these intruders appeared to be friendlies to those without uncertainty symbolology, but as bogeys when the uncertainty symbolology was added. Please recall that the subjects were instructed to regard an intruder as a bogey if it *could* be aimed at the turret, given the level of uncertainty. The heading uncertainty symbolology should have allowed the subjects to more accurately judge whether these "maybe" intruders were bogeys or friendlies. Those subjects in the no-symbolology group had no indication of the reliability level to aid their decision process.

In order to investigate whether subjects' judgement accuracy for these crucial stimuli was aided or hindered by the uncertainty symbolology, a post hoc analysis was conducted. This analysis exclusively examined the aircraft that changed their bogey/friendly status as a function of data reliability. Specifically, the main effect of

symbology type on the three measures of time, bogeys killed, and friendlies killed were examined.

Because the experimental program did not record the specific intruder killed with each shot in the datafiles, another means of choosing extracting this data had to be utilized. The resulting selection method was very simple: Only those trials with unreliable conditions, where all of the bogeys were also maybes were included in the analysis.

	No Uncertainty Symbology	Text Descriptor	Graphic Explicit 1 (rings)	Graphic Explicit 2 (arcs)
Time	7.47	7.37	8.35	8.49
Bogey	62.96	81.48	78.70	87.96
Friendly	7.72	19.91	11.27	18.06

Table 8. Mean scores for "maybe" trials in Invader-Heading experiment.

Figure 30. Percentage of “maybe” intruders killed by bogey status and symbology type.

Symbology

Multivariate analysis of variance (MANOVA) was conducted to determine the effect of symbology type on bogeys killed, friendlies killed and elapsed time per trial. It was found that symbology type had a significant main effect on friendlies killed ($F(3,32) = 3.20$, $p < .05$), but not on bogeys killed ($F(3,32) = 2.04$, $n.s.$), or elapsed time ($F(3,32) = .704$, $n.s.$). Most notably, the no-symbology subjects killed fewer friendlies than those using uncertainty symbology (see Table 8). It also appears that the no-symbology subjects killed fewer bogeys. However, the latter trend did not demonstrate statistical significance.

DISCUSSION: INVADER-HEADING

Data Uncertainty

As expected, higher levels of uncertainty led to subjects killing fewer bogeys. When aircraft headings were highly uncertain, more bogeys were incorrectly classified as friendlies and vice versa. As aircraft headings became less certain, subjects tended to incorrectly classify friendlies as bogeys, killing them. These effects demonstrate the increased difficulty of the task under conditions of higher uncertainty.

Uncertainty level also demonstrated a significant effect on the average time to complete each trial. Subjects completed the self-paced trials more slowly under less reliable conditions, indicating that heading uncertainty adds to pilot processing time for the performance of a heading judgement task. Thus, another goal for the representation of uncertainty may be to reduce pilot processing time under uncertain conditions. However, no interaction effect on time was found between uncertainty and symbology type in this experiment. The reader might be inclined to deduce that the uncertainty symbology types tested in this experiment did not succeed in reducing pilot processing time under unreliable conditions. However, this is probably not the case, because the number of aircraft the subject killed confounds the elapsed time per trial. If a subject were to mistake some of the bogeys for friendlies, the trial would be ended prematurely, reducing the elapsed time. Conversely, if the elapsed time was the same but fewer aircraft were killed, we could conclude that the processing time per aircraft was longer.

In fact, this was exactly the case for the high uncertainty conditions. As compared to the symbology groups, the no-symbology group showed a considerable reduction in both bogeys and friendlies killed, while all groups required approximately the same time to complete the trials. Thus, it appears that the uncertainty symbology enabled subjects to reduce their response times.

Symbology Type

Having established that uncertainty results in slower and more error-prone target detection performance, we next evaluate whether these performance decrements can be mediated by various representations of unreliability. The initial analysis, in which the effects on the “maybe” intruders were diluted by an evaluation of mean scores for responses to all bogey intruders, found no significant main effect for symbology on the number of bogeys killed, friendlies killed, or the elapsed time per trial. However, the second, detailed analysis separated the pivotal “maybe” intruders from the other responses and demonstrated that the symbology effects were actually stronger than they appeared in the first analysis. This post hoc analysis specifically examined the aircraft that changed their bogey/friendly status as a function of reliability. This facilitated the investigation of whether subjects’ judgement accuracy for these crucial maybe intruders was helped or hindered by the various uncertainty symbology conditions.

The results of the detailed analysis found that symbology type had a significant effect on friendlies killed, and a strong trend on bogeys killed that did not prove statistically significant. These data suggest that the representations of uncertainty have a

positive overall effect on the accuracy of target detection in conditions of data uncertainty.

One explanation for this behavior is that the no-symbolology subjects adopted a conservative risk bias to avoid killing friendlies. Because they had no indication of reliability level, the decision to kill a “maybe” intruder was purely guesswork. Perhaps some of the no-symbolology subjects chose to kill only the perfectly aimed bogeys.

However, there is another explanation that fits the emerging model of behavior in the presence of spatial uncertainty. The results of the collision experiment indicated that the presence of uncertainty tends to be ignored in the absence of some uncertainty representation. A similar conclusion could be drawn from the observation that the no-symbolology group killed fewer intruders (both bogey and friendly) than the symbolology groups. It is likely that the no-symbolology subjects only killed those aircraft that were perfectly aimed at the turret because they were not considering the (invisible) heading uncertainty. Once again, we have evidence that data uncertainty will be ignored or forgotten in the absence of some type of representation.

Interaction Effects

Significant interaction effects were found on the number of bogeys killed and on the number of friendlies killed, demonstrating that performance differences over the range of uncertainty conditions varied with symbolology type.

Under accurate and moderately uncertain conditions bogeys killed and friendlies killed scores were very similar for all symbolology conditions, including no-symbolology.

When the data was highly uncertain, accuracy of the no-symbolology subjects showed a much greater decrement than for the three uncertainty symbology systems groups. It seems that any type of uncertainty representation is better than none, lending support to the position that it is necessary to represent data uncertainty under uncertain data conditions. However, as discussed in the Introduction, it is important to be able to represent the second-order data certainty information without interfering with the first-order information of the display. For example, the representation of uncertainty information should not lead to performance decrements under accurate conditions, as compared to a no-symbolology system. When compared to the no-symbolology condition, none of the uncertainty symbology systems tested in this experiment demonstrated a significant performance decrement under any conditions.

Subjects showed very similar performance trends when using each of the three uncertainty representation symbology types. Interestingly, about twice as many friendlies were killed under moderately uncertain conditions than either the accurate or highly uncertain conditions. The large number of friendlies killed under moderate conditions may be a result of subjects overestimating the angle of the heading symbology, leading them to incorrectly classify some friendlies as bogies. Some evidence against this explanation, though, is that this trend was seen for all symbology types, including no-symbolology that displayed no uncertainty angle to overestimate.

The number of bogeys killed remained constant between accurate and moderately uncertain data conditions. However, under highly uncertain conditions each of the uncertainty symbology groups showed only about half the performance decrement of the

no-symbolology group. Not only does this result support the hypothesis that the representation of uncertainty will improve performance when heading data is unreliable, it also suggests that the use of uncertainty symbolology doesn't negatively affect performance under reliable conditions.

GENERAL DISCUSSION

The primary purpose of these two studies was to compare the effect on situational awareness of displaying positional and heading uncertainty. In Experiment 1, it was hypothesized that the representation of positional uncertainty would allow pilots to safely decrease separation distances under accurate data conditions, while leading pilots to increase separation when data was uncertain. Indeed, it was found that without representation of uncertainty each incremental decrease in data certainty was accompanied by an increase in the number of collisions. Without some representation of uncertainty, no subject ever chose paths wide enough to avoid collisions altogether. Additionally, without constant reminder of the unreliability subjects would often ignore or forget about the spatial uncertainty. This experiment powerfully demonstrates the tendency to ignore hidden decision criteria.

Of the tested symbology types, only the graphical-explicit symbology elicited adequately conservative behavior for subjects to avoid collisions under highly uncertain conditions. Displaying the actual region of uncertainty led subjects to keep clear of this area. As a result, there were far fewer collisions with graphical-explicit symbology than any of the other symbology types when data was highly uncertain. In order to elicit conservative risk behavior it is important to represent spatial uncertainty explicitly, with graphical symbology.

The results of the second experiment again suggest that the presence of uncertainty tends to be ignored in the absence of uncertainty representation. In this case,

it was observed that the no-symbology group killed fewer intruders (bogey and friendly) than the symbology groups. As discussed earlier, it is likely that the no-symbology subjects didn't kill the maybe intruders because they were not considering the (invisible) heading uncertainty. Once again, the results support the concept that spatial uncertainty will be ignored or forgotten in the absence of some type of uncertainty representation.

It was hypothesized that that the inclusion of heading uncertainty symbology would improve heading judgement under uncertain conditions in the intruder experiment. Indeed, it was found that those subjects performing this heading judgement task without uncertainty symbology showed about twice the performance decrement of those using uncertainty symbology, under highly uncertain conditions. Although this experiment did not demonstrate significant differences between the tested symbology types, it seems that any type of uncertainty representation may be better than none. Future research should include refinement of uncertainty symbology and other graphical strategies used to represent uncertainty.

CONCLUSIONS

Reliance on unreliable information can have unacceptable consequences in many applications. The representation of this uncertainty information is critical to maintain the pilots' (or other type of operator) "big picture" or situation awareness under conditions of uncertain data. Even when the uncertainty symbology serves only as a warning signal, it may have the benefit of effecting risk-conservative behavior, preventing pilot errors.

Now that the utility of representing uncertainty in navigational displays has been demonstrated, a number of issues remain to be addressed: Later studies in this series will examine symbology types for representing uncertainty under more realistic circumstances, such as asymmetrical spatial uncertainty. The utility of other graphical strategies to represent different types of uncertainty also needs to be investigated. For example, the use of dynamic manipulation of objects provides many opportunities to express temporal uncertainty or smoothed data. The end result should be a unified system of graphical symbology to coherently represent the necessary types of uncertainty in the same display.

REFERENCES

- Abdel-Aty, M.A., Kitamura, R., & Jovanis, P.P. (1995) Impact of ATIS on route choice. Proceedings of Transportation Congress, New York, NY. Vol. 1, 304-314.
- Amar, M.J., Hansman, J., Vaneck, T.W., Chaudhry, A.I., & Hannon D.J. (1995). A preliminary evaluation of electronic taxi charts with GPS derived position for airport surface situational awareness. Proceedings of the 8th International Symposium on Aviation Psychology, Columbus, OH. 499-504.
- Andre, A.D. (1995). Information requirements for low-visibility taxi operations: What pilots say. Proceedings of the 8th International Symposium on Aviation Psychology, Columbus, OH. 484-488.
- Aretz, A.J. (1988). A model of electronic map interpretation. Proceedings of the Human Factors Society 32nd Annual Meeting, 130-135.
- Aretz, A.J. (1991). The design of electronic map displays. Human Factors, 33(1). 85-101.
- Beard, M.K., & MacKanness, W. (1993). Visual access to data quality in geographic information systems. Cartographica, 30(2/3), 37-45.
- Bertin, J. (1985). Semiology of Graphics. Madison, WI: University of Wisconsin Press.
- Boles, D.B., & Wickens, C.D. (1987). Display formatting in information integration and nonintegration tasks. Human Factors, 29, 395-406.
- Brickman, B.J., Hettinger, & Haas, M.W. (1997). Tactical aviation and human factors: designing the SIRE supercockpit. Proceedings of the Human Factors Society 41st Annual Meeting, 299-303.
- Buttenfield, B.P., & Beard, M.K. (1991). Visualizing the quality of spatial information. Proceedings of Auto-Carto 10, Baltimore, MD. Vol. 6, 423-427.
- Buttenfield, B.P. (1993). Representing data quality. Cartographica, 30(2/3), 1-7.
- Chrisman, N.R. (1991). The error component in spatial data. In Maguire, D.J., Goodchild, M.F., & Rhind, D.W. (eds), Geographical Information Systems, (vol. 1, pp.165-174) London: Longman .

Coury, B.G., Donald, C.R., Dykton, M.D., & Piatko, C.D. (1997). Visualizing and exploring highly processed information spaces in tactical decision-making. Proceedings of the Human Factors Society 41st Annual Meeting, 330-334.

Ehlschlaeger, C.R., & Goodchild, M.F. (1994). Uncertainty in spatial data: defining, visualizing, and managing data errors. Proceedings of GIS/LIS 1994, 246-53.

Endsley, M.R. (1995). Toward a theory of situational awareness in dynamic systems. Human Factors, 37(1), 32-64.

Fisher, P.F. (1993). Visualizing uncertainty in soil maps by animation. Cartographica, 30, 20-27.

Fisher, P.F. (1994a). Animation and sound for the visualization of uncertain spatial information. In Hearnshaw, H.H., & Unwin, D.J. (eds), Visualization in Geographical Information Systems (pp. 181-185). Chichester: John Wiley & Sons.

Forier, F., & Canters, F. (1996). A user-friendly tool for error modeling and error propagation in a GIS environment. [On-line], Available: <http://orca.vub.ac.be/~frforier/artikel1.html>.

Goodchild, M.F., Battenfield, B., & Wood, J. (1994). Introduction to visualizing data validity. In Hearnshaw, H.H. & Unwin, D.J. (eds), Visualization in Geographical Information Systems (pp. 141-149). Chichester: John Wiley & Sons.

Goodchild, M.F., Chih-Chang, L., & Leung, Y. (1994). Visualizing fuzzy maps. In Hearnshaw, H.H., & Unwin, D.J. (eds), Visualization in Geographical Information Systems (pp. 158-167). Chichester: John Wiley & Sons.

Guptill, S.C. (1989). Inclusion of accuracy data in a feature based, object-oriented data model. In Accuracy of Spatial Databases (pp. 91-97). London: Taylor & Francis.

Hasegawa, S., & Inagaki, T. (1994). Dempster-Shafer theoretic design of a decision support system for a large-complex system. Proceedings of the 3rd IEEE International Workshop on Robot and Human Communications, 94TH0679-1, 345-350.

Hunter, G.J., & Goodchild, M. (1994). Design and application of a methodology for reporting uncertainty in spatial databases. In URISA [On-line], 771-786. Available: <http://www.sgi.ursus.maine.edu/gisweb/spatdb/urisa/ur94069.html>.

Hunter, G.J., & Goodchild, M. (1995). Dealing with uncertainty in spatial databases: a simple case study. Photogrammetric Engineering and Remote Sensing, 61(5), 529-537.

Kirschenbaum, S.S., & Arruda, J.E. (1994). Effects of graphic and verbal probability information on command decision-making. Human Factors, 36, 406-418.

Maffini, G., Arno, M., & Bitterlich, W. (1989). Observations and comments on the generation and treatment of error in digital GIS data. In Accuracy of Spatial Databases (pp. 55-67). London: Taylor & Francis.

May, P.A., & Wickens, C.D. (1995). Role of visual attention in head-up displays: design implications for varying symbol intensity. Proceedings of Human Factors and Ergonomics Society 39th Annual Meeting. Vol. 1, 50-54.

MacEachren, A.M. (1992). Visualizing uncertain information. Cartographic Perspectives, 13, 10-19.

MacEachren, A.M. (1994a). Time as a cartographic variable. In Hearnshaw, H.H. & Unwin, D.J. (eds) Visualization in geographical information systems (pp. 181-185). Chichester: John Wiley & Sons.

McGranahan, M. (1993). A cartographic view of spatial data quality. Cartographica, 30(2/3), 28-36.

Pang, A., Furman, J., & Nuss, W. (1994). Data quality issues in visualization. SPIE Proceedings on Visual Data Exploration and Analysis I, 2178, 12-23.

Robinson, V.B., & Frank, A.U. (1985). About different kinds of uncertainty in collections of spatial data. Proceedings, AUTO-CARTO 7, Washington, DC, 11-14.

Schwartz, D.R., & Howell, W.C. (1985). Optional stopping performance under graphic and numeric CRT formatting. Human Factors, 27(4), 433-444.

Selcon, S.J. (1990). Decision support in the cockpit: Probably a good thing? Proceedings of the Human Factors and Ergonomics Society 34th Annual Meeting, 46-50.

Tufte, E.R. (1990). Envisioning Information. Cheshire, CT: Graphics Press.

Weitzman, D. (1993). Identifying Information Requirements for Air Traffic Control Problem Solving. Proceedings of the Human Factors and Ergonomics Society 37th Annual Meeting, 103- 107.