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The use of moving map technology to prevent wire strikes in helicopter flight

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THE USE OF MOVING MAP TECHNOLOGY TO PREVENT WIRE STRIKES IN HELICOPTER FLIGHT

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by

Karen M. Jones

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ABSTRACT

THE USE OF MOVING MAP TECHNOLOGY TO PREVENT WIRE STRIKES IN HELICOPTER FLIGHT

by Karen M. Jones

Helicopter flight is unique in several aspects, and wire strikes, particularly, are common with low-level flight. While moving map technologies to support navigation and hazard awareness are relatively mature, few studies have focused on the efficacy of moving map displays for avoiding wire hazards. An experiment was conducted for the explicit purpose of determining an appropriate map format to help helicopter pilots avoid wires. Participants were given a 2D map with relative altitude information, a 3D map, or no map at all for use in avoiding wires. A digital indicator located on the left edge of the 2D map displayed the relative altitude information to the pilots. General findings were that the 3D map best supported wire avoidance.

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The Use of Moving Map Technology to Prevent Wire Strikes in Helicopter Flight

On May 1, 1998, a student pilot with 10 hours of flying time was practicing a normal landing approach in a Robinson R22 helicopter with the instructor following on the controls. The instructor had chosen the approach site and the flight was progressing normally when both the student and the instructor were startled to see electrical power transmission lines in front of them. The instructor took the controls and was able to clear one set of lines, but was unable to avoid a second set. The helicopter then fell sixty feet to the ground, landing on its side. There was one fatality and one serious injury in the accident. It was reported that the "instructor flew in this practice area almost daily and was well aware of the presence of the power lines" (NTSB LAX98FA149).

The Problem

The National Transportation Safety Board (NTSB) accident archives are filled with similar reports of helicopters colliding with wires. Many pilots have struck wires without ever seeing them, some reporting feeling an unexpected yaw or strong tug on the helicopter as their first alert to the problem (NTSB CHI99LA026). One pilot even stated that he thought he was experiencing engine failure, and initiated a hovering autorotation before realizing he still had engine power (NTSB CHI98LA021). Other pilots report not seeing the wire until the last minute, saying that the sun, overcast sky, or dusk conditions made the wires "virtually invisible" or "extremely difficult to see" (NTSB SEA99LA019, NTSB DEN99FA024). In one instance, a pilot, wanting to examine the wires after an accident, flew to the site under similar conditions of "daylight and visibility" only to report that the "wires could not be visually detected until the helicopter was 'extremely close to the wires'" (NTSB LAX99TA299). Other pilots, like the instructor in the NTSB narrative cited above, are in some cases quite familiar with the area they are flying. They may know that wires are present, and even know where the wires are, but have difficulty seeing them or keeping them in view when other tasks need their attention. In fact, according to "Agricultural Aviation" magazine's March – April 2000 issue online, "40 percent of all pilots who strike a wire admit that they were aware of the presence of the wire before they hit it" (Schleicher, 2000, p. 4). It is also interesting to note that a study of all helicopter accidents reported by the NTSB in a 9 year period (from 1990 to 1999) listed many of the pilots involved in accidents as experienced pilots with many hours flown in helicopters of the same make and model as the one in operation at the time of the accident (Hart, 2000).

The Helicopter Association International (HAI) has reported that wire strikes are the number one cause of helicopter accidents, and has noted factors including charting, airspace control, visual illusions, regulations, cable marking, visual limitations, and more, as causes (AvSafe Aviation Safety, n.d.). Certainly, wires are the most common objects struck by helicopters (Hart, 2000). Collisions vary in severity, and if main rotor control is lost, a safe landing may not be possible. Similarly, a tail rotor strike may result in a loss of directional control, which will also make a safe landing difficult, especially if the pilot does not have enough altitude to enter autorotation (Harris, Kasper, & Iseler, 2000). It has also been noted that most wire collisions occur during the daytime hours; however, those that occur at night tend to be more severe and more costly (Reynolds, Ivey, Johnson, & Rash, 1997). An analysis of U.S. civil rotorcraft accidents between 1963 and 1997 revealed that 720 accidents were caused by collisions with wires and poles (Harris et al., 2000). And indeed this number may be only a fraction of the number of wire strikes that actually occur, as "most incidents aren't reported unless they result in an injury or fatality" (Schleicher, 2000, p. 1). In fact, it has been shown by federal and private studies that only approximately "10 to 20 percent of all general aviation wire strikes are reported to the authorities" (Schleicher, 2000, p. 1).

Although wire strikes are not unique to helicopters, they are more prevalent in helicopters than other aircraft. One reason for this is because helicopters are typically involved in a greater number of low-level flight tasks. Low to the ground, there are a greater number of obstacles for the pilot to detect and avoid. An additional issue making low-level flight difficult is that close to the ground, time to react is minimal. It has been reported that between 70% and 85% of all wire strikes occur below 100 feet AGL (Feerst, 1995).

There are many types of wires in the environment serving various functions, and all can be difficult to detect and/or keep in view. Phase wires carry current, and are the least forgiving when hit due to their steel core. Static wires are particularly difficult to detect and act as shields to circuits from lightning. Guy wires act as support lines, which bear the load or ease tension on the structure to which they are attached (Feerst, 1995). They therefore often run at an angle from the structure to the ground. Guy wires are among the most frequently struck, and account for 17% of all wire strikes (Feerst, 1995). They have also been cited by one source as being the most fatal of all aircraft wire strikes due to the unyielding nature of their construction (Schleicher, 2000). Non-specular wires cause problems for pilots as well, because they are particularly difficult to detect. These wires have the shine "buffed or sandblasted" off of them so that they will not reflect light (Feerst, 1995, p. 28). Even phone wires can pose a threat to a low flying aircraft (Feerst, 1995).

The wire environment is constantly changing, which makes it even more difficult for helicopter pilots to visually acquire the wires. Utility companies frequently reroute power lines to facilitate construction, and new lines are constantly being added to service homes and businesses (Schleicher, 2000). Because of this, even the most recent maps often do not always contain the most recent wire information. However, an additional problem is that some wires are constructed by Independent Power Producers. These generating facilities may have wires built under different construction standards than most wires. If wires in the environment are all built to different standards, they will likely be without common identifying features. This will put the pilots at a disadvantage, because they will not be able to develop visual rules or guidelines for identifying wire hazards. Or worse, they may develop the rules and guidelines, but be surprised by wires that do not abide by them. Other wires are privately owned lines that are "frequently built out of code and with non-standard construction" (Feerst, 1995, p. 29). An additional problem is that utility companies, under pressure from environmentalists, have in recent years tried to make wires less noticeable (D. Borrows, personal communication, October 4, 2001). However, Feerst says that in many cases, wires disappear because they are beyond the limits of our eyes to resolve, not because they are camouflaged. He says that it is often the breaks in the continuity of the background that is seen, not the wire itself (Feerst, 1995). The NTSB accident archives are filled with narratives of wire strikes reporting that the wires were unmarked at the time of the accident (e.g., NTSB FTW01LA109, NTSB FTW02FA028, NTSB SEA99LA016, NTSB FTW98FA068, NTSB FTW98FA238). Clearly this contributes to their likelihood of being hit.

It is important to note that wires are very difficult to locate not only because their physical properties make them challenging to detect, but also because they are often encountered at times and in regions of high workload for the pilot. In helicopter flight particularly, low-level flight tasks are common. They are cognitively demanding and can facilitate problems with attention and mental workload. Pilots must divide their attention between clearing obstacles, the mission at hand, and all aspects of vehicle control, such as power (thrust), altitude, and attitude maintenance. These tasks compete for the pilot's limited processing resources. Any problems that arise can cause attentional narrowing, distracting the pilot from the "see and avoid" activities required for obstacle detection and avoidance. However, there need not be problems for shifts in the pilot's focus of attention to occur.

Relevant Sensor Technology in the Literature

One obvious approach to reduce the frequency and severity of these types of accidents is technology that can be implemented to help increase a pilot's awareness of wires. Sensor technologies have been discussed in the literature as a means of detecting obstacles. An Automated Nap of the Earth (NOE) Guidance and Control System (ANGCS) has been designed to help with obstacle avoidance and terrain-following tasks (Coppenbarger & Cheng, 1992). It will have sensors to detect, but not identify, the obstacles, although it will discriminate between obstacles and terrain. Symbology indicating the presence of obstacles and corresponding flight-director commands will be presented to the pilot via a helmet mounted display (HMD) (Coppenbarger & Cheng, 1992). While wire avoidance was never suggested as a focus for the system, a recent review has acknowledged the system's wire-sensing capabilities (Coppenbarger, 1994). Passive and active forward-looking sensors were discussed in greater detail (although the review revealed that the study assumed a "generalized, 'perfect'" sensor). Coppenbarger states that passive sensors, such as TV or Forward Looking Infrared (FLIR), are more appropriate for military applications because of the "high level of covertness they provide" (p. 352). However, he does note drawbacks to using these sensors. Among other things, the sensors' lack of resolution makes them incapable of detecting small obstacles, such as wires. Coppenbarger argued that a narrow field-of-view active sensor, such as a laser range finder or millimeter-wave radar, should be considered in addition to the more desirable broader field-of-view passive sensor.

The Navy has also conducted sensor research, and has a radar system that can detect wires and other small objects. It uses miniature ultra wideband (UWB) radar, and can detect these obstacles from several hundred feet. These sensor systems have been implemented in unmanned vehicles only, however, and are not considered systems to be used by pilots in helicopters (Fontana, Larrick, Cade, & Rivers, 1998).

Other systems have used terrain following radar systems, forward looking infrared imaging systems, night vision goggles, and integrated navigation systems to present terrain and obstacle information to pilots; again, the literature does not outline wire avoidance purposes specifically (Swenson et al., 1994; Hindson, Njaka, Aiken, & Barnhart, 1994).

Relevant Map Technology in the Literature

Electronic moving maps have been widely discussed in the literature as a method for displaying obstacles to the pilot. An electronic moving map is similar to a paper map in the information it displays. It is often located in the instrument panel of the cockpit, and can change and maintain an updated position in correspondence with the vehicle's current position. They are often praised because they can be easily updated with the most recent information available. Electronic moving maps can use both database and sensor technologies to display obstacle information to pilots. A map that utilizes database technology relies on the database to contain the most recent obstacle information, which is then processed for display to the pilot. This type of map may use sensors to determine where the ownship is located within the database, but not to detect obstacles. A map that utilizes sensor technologies to detect obstacles, on the other hand, does not have to rely on a predefined database to provide the pilot with the most recent information. However, once an object is detected, the sensor technology will have to rely on a real-time computer to then classify the object and present it to the pilot.

A large part of electronic moving map literature has focused not only on the detection of various obstacles, but on map format as well. This is an important focus, because, as will be discussed, pilot performance has been shown to vary with format type. Many studies have looked at whether maps should be track up or north up (e.g., Olmos, Liang, & Wickens, 1997; Boyer & Wickens, 1994; Wickens, Liang, Prevett, & Olmos, 1996; Schreiber, Wickens, Renner, & Alton, 1996; Rate & Wickens, 1993, Delzell & Battiste, 1993; Aretz, 1991, see pages 16-17 for a brief discussion) and whether they should be plan view or perspective view (e.g., Boyer & Wickens, 1994; Wickens et al., 1996;

Rate & Wickens, 1993; Merwin & Wickens, 1996; Wise et al., 1993; Ellis et al., 1987; McCormick & Wickens, 1995; Bemis et al., 1998; Banks & Wickens, 1997; St. John, Smallman, Oonk, & Cowen, 2000; Poole & Wickens, 1998; Wickens & May, 1994; Wickens, Campbell, Liang, & Merwin, 1995; Haskell & Wickens, 1993; Olmos, Liang, et al., 1997; Olmos, Wickens, & Chudy, 1997; Wickens et al., 1997; Wickens & Prevett, 1995; Schreiber et al., 1996; Theunissen, 1998; Burnett & Barfield, 1991; St. John, Smallman, Bank, et al., 2001; Andre, Wickens, Moorman, & Boschelli, 1991; Campbell, May, & Wickens, 1995, see pages 17-36 for a discussion).

Track up maps are rotated to "continually conform to the direction of the flight route" (Delzell & Battiste, 1993, p. 838). North up maps, on the other hand, do not rotate and continually display a north-up heading.

Further formatting issues, usually viewpoint related, also arise when perspective view (3D) maps are used in experiments. Factors such as geometric field of view (GFOV), elevation angle, and azimuth angle can be combined in various ways to provide the pilot with a unique view of the world. Geometric field of view is defined by McGreevy and Ellis (1985) as "the visual angle of the display screen as seen from the station point, which is sometimes called the center of projection or geometric eyepoint" (p. 532). The elevation angle is the angle at which the display 'camera' looks at a scene in a display. It can range from 0 to 90 degrees, where 0 degrees displays only horizontal information to the map viewer, and 90 degrees displays a top down view (Boyer

& Wickens, 1994). Finally, azimuth angle is the "angle away from the 'straight ahead' orientation" (Boyer & Wickens, 1994, p. 9). Various combinations of these factors result in differing views for the pilot. 3D maps can be egocentric or exocentric displays, for example. An egocentric display (also sometimes called an immersed view display) has information "displayed from the viewpoint of the operator as if viewing it with his/her own eyes" (Jordan, Hodgson, & Selcon, 1997, p. 46). So in an aviation application, it typically provides a view of the world that corresponds to the view that the pilot has from the cockpit. An exocentric display "is one where the information is displayed from the viewpoint of an external observer looking at the operator or aircraft" (Jordan, et al., p. 47). For example, "tethered displays" provide a view of the world from a fixed distance behind the aircraft. Rate and Wickens (1993) describe it as "the view seen from a chase plane or drone that is 'tethered' behind the aircraft at a constant distance" (p. 9).

It should be noted that throughout this paper, the terms "3D" and "perspective" map format are used interchangeably. Unless otherwise noted, a "3D" display will not be used to represent a true three-dimensional display with stereopsis or binocular depth cues, but rather a perspective view display formatted with monocular cues that create the perception of depth. Most of the studies with "3D" displays described in the literature review used monocular cues to create depth. Sekular and Blake (1994) define monocular as "seeing with one eye." When we process the 3D world with one eye, we must use information such as "linear perspective, occlusion, texture gradients, and motion perspective to resolve the spatial layout" (Yeh & Silverstein, 1992). These are the cues used in most of the studies to create the 3D perspective. Binocular, on the other hand, is defined by Sekular and Blake (1994) as "seeing with two eyes." This adds additional cues to the spatial layout for processing. Binocular disparity, which results from the fact that we see a slightly different image with each eye, can be used to "actualize relative depth and allow the decoding of camouflage when the observer is stationary" (Yeh & Silverstein, 1992). Stereopsis is a result of binocular disparity. It is a true depth cue that does not need to rely on the artistic imagery of monocular cues to create a perception of depth. Zenyuh et al. (1988) quote Spain as saying that it involves "simultaneously viewing some aspect of the external world from two slightly different advantage points and perceptually blending these two distinct perspectives into a unitary mental representation of the external world."

Advantages of 3D Displays

The literature reveals that there are both positive aspects and drawbacks to both plan view (2D) and perspective view (3D) formats. 3D displays have the advantage of being able to integrate a lot of information graphically into one display. Therefore, pilots can often glean much information from these displays with a single glance. This has the benefit of reducing mental effort, and decreasing the amount of time it might otherwise take to process and respond to information. Indeed, where wire avoidance is concerned, the pilot may need to receive wire location information in an integrated piece, because he/she may have limited time to react. 3D displays also have the advantage of being able to represent objects more naturally than can be done on a 2D display. This allows the objects on the display to more closely resemble the things they are meant to represent. In addition, by creating a view that resembles the world view that the pilot sees from the cockpit, it adheres to Roscoe's principle of pictorial realism (Roscoe, 1968). This congruency can lead to faster and more accurate judgment on tasks (Wickens, 1992).

Disadvantages of 3D Displays

There are also drawbacks to using 3D displays. These displays are subject to a variety of perceptual difficulties or biases. One is the overestimation of the elevation of an object in a display. This overestimation could cause problems with judging vertical separations, a problem that could have serious consequences for flight tasks (Boyer & Wickens, 1994).

Ambiguity, with respect to object position, along the line of sight is another perceptual bias found with the 3D display. This effect comes about when a 3D scene is depicted on a 2D static screen, yielding "an ambiguity as to the true position of any point in space" (Boyer & Wickens, 1994, p. 7). This results, Boyer and Wickens say, from "the fact that for a given 2D point within the display, there are an infinite number of potential 3D positions" (p. 7). Because this effect occurs most strongly when there are few depth cues in use on the display, a common response in an attempt to alleviate the bias is to increase the number of depth cues. This, however, creates further perceptual problems of foreshortening and resolution loss. Banks and Wickens (1997) define foreshortening as the bias that occurs when the "amount of information conveyed by cues regarding displacement in depth relative to the screen surface, is perceived as being smaller than the amount of lateral or vertical displacement" (p. 7). They say that "this leads to a distorted perception of objects within the display plane as being closer to the display surface, and in effect 'rotated' to a plane more parallel with the viewing surface than in actuality" (p. 7). The concern is that this phenomenon can lead to "overestimation in judging altitude relative to distance" (p. 7). Slopes of the terrain will look much steeper to the pilot than they actually are. Resolution loss is an effect "that is imposed on the human's basic sensory limitations" (Boyer & Wickens, 1994, p. 7) where 3D "distances orthogonal to the viewing line of sight will be represented with greater pixel resolution than those more parallel to the line of sight" (Wickens, Liang, Prevett, & Olmos, 1994, p. 5). The danger with this bias comes about when judgments regarding accurate position are required.

Another perceptual bias seen with 3D displays is the distortion that results from perspective projection. St. John, Smallman, Bank, and Cowen (2001) say perspective projection causes "distances in the x and z dimensions to scale linearly," but "distances in the y dimension to scale nonlinearly" (p. 3). Perspective projection, they say, is a cue to depth, but it "distorts distances and angles" (p. 3). It makes depth "more salient an image, but makes precise measurements more difficult" (p. 3). The perceptual limitations with this format may prove particularly detrimental where wire avoidance is concerned, because it is imperative that the precise location of the hazard be determined for successful avoidance.

In addition, although the 3D display has shown great benefits for integrated tasks, not all tasks are integrated, and some, in fact, require a focused attention on a particular axis or display point. The 3D display will not fare well for these tasks, as its integrated nature will make the specific points difficult to focus on singularly.

In addition, egocentric or immersed 3D displays also have the potential drawback of what has been termed "the keyhole effect." The effect is thus named because the display does not provide the pilot with any information regarding what is to the side or behind the aircraft. There is therefore a high cost of scanning when using this display, due to the amount of panning that the operator must do to view information around the aircraft. This, of course, assumes that the pilot is given panning capabilities with this display. Without panning capabilities, the pilot will simply miss out on information in these displays' "blind spots." This specific format, too, seems to have critical drawbacks where wire avoidance is concerned. In this situation, the pilot may not benefit from a display that allows such a limited view of the environment.

An exocentric 3D display, with the viewpoint located outside of the aircraft (usually behind and above), can be used to avoid the keyhole effect. While this display type allows information around the aircraft to be seen; it still suffers from some of the previously mentioned ambiguity problems. Exocentric displays in particular seem to have problems with the location of objects along the line of sight, and lateral maneuvers are often difficult with these types of displays.

Advantages of 2D Displays

Certain consequences associated with 3D displays can be avoided altogether by using a 2D display. 2D displays provide the viewer with information in an unintegrated fashion, allowing tasks that require a focus of attention on a single attribute to be completed successfully. In addition, 2D maps provide the pilot with a greater degree of spatial awareness. Pilots can see more of the entire database with a 2D map, and can form a better understanding of what the "big picture" looks like. This enhanced global awareness could prove extremely beneficial to pilots with the task of avoiding wires. With a better understanding of where things are in the environment, pilots should be able to plan out avoidance maneuvers in advance, allowing them a safety margin around the hazard. They should also be able to make abrupt avoidance maneuvers more safely, should they be necessary, since they would be more aware of clear areas available for them to quickly move in to.

Disadvantages of 2D Displays

Unfortunately, 2D maps come with certain costs as well. When the pilot must complete an integrated task (as is common in flight), 2D displays often require much mental integration of information. For example, helicopters are capable of abrupt maneuvers that allow them to quickly change their position in all three dimensions. This is often done during low-level helicopter flight to avoid obstacles. With a 2D map display, where the vertical dimension is typically absent from view, the pilot will have to get information about this dimension from other sources (e.g., instruments, charts) and integrate it with the 2D map information to form a single mental picture of the world he or she is flying through. In addition, these displays often have large working memory requirements. This can slow the pilot's decision-making process, and facilitate errors (Wickens, 1992).

With these benefits and drawbacks noted, many researchers have conducted studies attempting to find the best display for their task. However, results regarding which map type yields the best overall performance have varied.

Frame of Reference Studies in the Literature

In studies investigating frame of reference issues, the track up map, due to its congruence with the pilot's forward view, generally leads to better pilot performance (e.g., Olmos, Liang, & Wickens, 1997; Boyer & Wickens, 1994; Wickens, Liang, Prevett, and Olmos, 1996; Schreiber, Wickens, Renner, &

Alton, 1996; Rate & Wickens, 1993). However, there have been notable exceptions to this finding (e.g., Delzell & Battiste, 1993; Aretz, 1991). Aretz (1991), for example, suggested that although track up maps might lead to better performance on navigational tasks, north up maps, due to their better stability and consistency, are better for learning the location of one's surroundings, and for sharing or exchanging information when each person is looking at his or her own separate map. His study raised the issue that the selection of map type could depend on the type of task being performed.

Map Dimensionality Studies in the Literature

There has been even less consensus on which map yields the best performance in studies comparing 2D and 3D map formats.

Studies with 2D-Favorable Outcomes. Boyer and Wickens (1994) explored the effectiveness of 2D and 3D displays for the task of weather avoidance in a fixed wing aircraft. The experiment incorporated 2D, 3D, north up, and track up map components. Participants were to "construct a 3-D path around the weather, by creating a series of connected linear vectors, beginning at the origin on the south side of the weather; and ending at a 3-D fix, designated by a point in space on the north side" (pp. 13-14). The results were that in general, the 3D perspective display fared poorly relative to the 2D display. Routes planned with 3D maps were longer and less efficient, and they took more time to generate. Otherwise, both displays provided equally accurate paths, and there was no difference in vertical control. Boyer and

Wickens concluded that there were “no benefits to 3D representation” (p. 25) in this study, although they were also quick to note that costs were not particularly substantial either.

In exploring reasons for these findings, they note that the “3D time penalty is presumably related to either perceptual/cognitive factors in planning the route and adjusting the vector to avoid weather formations, or to perceptual motor factors required to precisely reach the final destination” (p. 24). They also hypothesized that participants with the 3D maps created longer paths to assure that “the ambiguous representation in the lateral axis” (p. 24) did not lead them into the weather. If weather avoidance tasks can be compared to wire avoidance tasks, these findings could have important implications. A large number of helicopter pilots who find themselves flying low in the wire environment are engaged in search and rescue type missions. Pilots with these missions will not be helped by a map that leads them to create longer, less efficient routes.

Wickens et al. (1996) conducted a series of two experiments exploring effects of frame of reference and dimensionality. Participants were given 2D and 3D maps with either a north up or a track up component. In experiment one, they had three tasks to accomplish while flying approach paths along a predefined course: a position report task, a frozen screen task, and a map reconstruction task. Results revealed no difference between 2D and 3D maps in terms of lateral tracking. However, vertical tracking was much worse with the

3D display. Pilots were less accurate in their reports of vertical position with the 3D display. However, with the 3D display, pilots were also quicker to answer questions of absolute bearing (though no more accurately than with the 2D display). In experiment two, improvements were made to the 2D and 3D maps. The tasks remained the same with the exception of the frozen screen task, which was deleted. Results from experiment two showed that, again, vertical tracking error was greater with the 3D display than with the 2D display. Likewise, lateral error, again, did not differ between the two displays. Additionally, pilots performed better on the map draw task when they were given the 2D display. Overall it would seem that results favored the 2D display in this study.

Wickens et al. point to resolution limitations and the line of sight/ambiguity of position problems with the 3D display as explanations for this map's poor performance in vertical tracking and vertical position reporting tasks. It is likely that the poor performance on the map reconstruction task with the 3D map is due to reduced global awareness. 3D maps, even the exocentric format examined here, have a more restricted field of view than what 2D maps can generally provide. This can lead to a better sense of global awareness for the pilots with the 2D map, and that may have been crucial for successfully completing the map reconstruction task in this experiment. Here, the position report task, in particular, seemed relevant to wire avoidance. If pilots are to successfully avoid wires, it is critical that they be able to judge their precise location at all times. In addition, the lack of global awareness that caused participants problems on the tasks in this study may cause pilots problems when avoiding wires. The results of this study imply that the 3D map may not be the best tool to implement for wire avoidance tasks.

Rate and Wickens (1993) also explored map dimensionality and frame of reference. In their study, participants saw 2D, 3D, north up, and track up combinations. They were given two primary tasks to complete. They were to fly the aircraft in a manner that minimized flight path deviations, and answer situational awareness themed questions regarding hazards, threats, and potential conflicts. Results of this study showed clear advantages for the 2D display. It was the superior display for measures of control of lateral deviations, vertical flight performance, and response accuracy to situational awareness questions concerning the judgments of relative bearing, height, and absolute bearing.

Rate and Wickens gave two possible reasons for the lateral and vertical control findings. They suggested that resolution issues and ambiguity along the viewing axis might have been behind the difficulties participants had with the 3D display. The other possible explanation they provided was that the simplified flight dynamics seen in their study, along with the absence of predictor symbols, may have "lessened the need for integration" (p. 20), thereby lessening the benefits of using the 3D display. Therefore, the task "may well have been one in which sequential control of lateral and vertical axes was employed on both two- and three-dimensional displays" (p. 20). As previous studies have shown, sequentially controlled axes are "better supported by separate displays" (p. 20). This was also cited as the reason accuracy of answers to situational awareness questions was poorer than expected with the 3D display. Rate and Wickens stated that judgment tasks in this experiment were not integrative in nature, and in fact required "sequential judgments along the two orthogonal axes, rather than simultaneous integration of both" (p. 23). They commented that "this would account for better performance using the two-dimensional display which presented these two axes explicitly and linearly for focused attention tasks" (p. 23). 3D displays are known to better support judgment tasks along a single axis. Because a great deal of situational awareness is involved with wire avoidance, the findings with regard to questions concerning hazards, threats, and potential conflicts were of particular interest. If indeed the judgment tasks involved with wire avoidance are not integrated in nature (in other words, if they require focus on a single piece of information that is presented in an otherwise combined manner on a 3D display), then a 2D display will certainly be preferred for these tasks.

Merwin and Wickens (1996) also looked at map formats for avoiding hazards. Specifically, they examined air traffic hazards on a Cockpit Display of Traffic Information (CDTI) display. Participants' tasks were to fly routes containing air traffic hazards. They were to determine if it would be necessary to deviate from their path in order to avoid the traffic, based on the position, speed, and bearing of the traffic hazard. Results indicated superior performance was seen with the 2D coplanar display than was seen with either of the perspective displays for all measures.

Merwin and Wickens hypothesized that the costs associated with conflict detection for the 3D display were due to integration of the x (horizontal), y (vertical), and z (depth) axes. They suggested that this integration lead to ambiguities with the perspective display which caused confusion of object positioning. In addition, they proposed that the problems of symbology occlusion and compression of the vertical axis seen with the 3D display were the likely cause of the maneuvering decision difficulties the participants had in this experiment. If traffic avoidance tasks can be compared to wire avoidance tasks, these findings could have important implications. If object positioning ambiguities seen with the 3D display in this task transfer to the task of wire avoidance, a 3D display should not be implemented.

The results of these studies favor a 2D rather than 3D map format. Though none of the studies looked at wire avoidance specifically, all of the tasks had components that were similar and relevant to the task of wire avoidance. The outcomes of these studies might therefore suggest that a 2D map would be the better format to implement for the task of wire avoidance. However, it is unclear how much results found with tasks that are *similar* to wire avoidance but *not* wire avoidance will transfer to specific wire avoidance situations.

Studies with 3D-Favorable Outcomes. Several studies have reported advantages for 3D maps. Wise et al. (1993) examined how a "3-D display of navigation data affects pilot decision making" (p. 54) in a flight-maneuvering task. Three types of maps were used in the study: an electronic "pseudo 3-D perspective map display" (p. 55), a 2D electronic plan view map display, and a paper plan view map display. All were static display formats. Participants were instructed to fly the simulator, maintaining a 10 degree heading and altitude of 100 feet. They were to use their maps to interpret their location and select maneuvers to avoid a Terminal Control Area (TCA), if necessary. The results showed that the pilots initiated fewer unnecessary avoidance maneuvers with the 3D display than they did with either of the 2D displays. Additionally, pilots initiated more vertical maneuvers with the 3D display than with either of the 2D displays, and more horizontal avoidance maneuvers with the 2D displays. Wise et al. believe this latter finding was behind the increase in the "number of possible negative avoidance maneuver outcomes" (p. 56) seen in trials with the 2D displays. Their overall conclusion, given the superior performance of the 3D display in this study, was that the 3D display's usefulness should be considered for tasks involving the avoidance of potential traffic conflicts.

They did not elaborate on potential reasons these results were found, but a likely cause was integration of the horizontal, vertical, and depth axes. If pilots could have more easily seen all of their maneuvering and avoidance options with a single glance, their workload may have decreased, and the speed with which they made decisions may have increased. This would have been important, because their task was one that required quick interpretation of precise location. With the 2D representation, they might have been required to mentally integrate information to determine their location relative to a TCA. This could have been time consuming enough that they may have chosen a conservative strategy to steer clear of anything that looked like it could pose even a potential threat. Pilots' tasks in this study seemed similar enough to wire avoidance tasks to warrant a close examination of results. The conservative strategy mentioned as a possibility for this task would not always be a possibility for many helicopter missions. For low to the ground missions in a wire environment, for example, pilots will be forced to fly among hazards, and will benefit from a display that facilitates the best wire avoidance performance. The greater efficiency seen with the 3D display in this study could mean safer avoidance maneuvers for wire avoidance tasks. Pilots would have more time to plan out a safe maneuver with such an efficient display.

Ellis et al. (1987) ran a study comparing perspective and plan view displays. The participants' task was to assume they were flying ownship, watch for conflicting traffic, and recommend avoidance maneuvers. After making avoidance decisions, they answered several questions. Results showed that pilot decision time was significantly faster with the perspective display than it was with the plan view display for all traffic except head-on. For head-on traffic, this finding was reversed. This was thought to be the result of symbology becoming difficult to interpret as the traffic flew along the viewing vector. Additionally, pilots made more vertical maneuvers with the perspective display, and more horizontal maneuvers with the plan view display. Ellis et al. pointed out that this was important for two reasons that concern us here. First, the Traffic alert and Collision Avoidance System (TCAS) commands will only offer vertical maneuver commands initially. Second, when pilots have little time to respond, vertical maneuvers, particularly descents, are quicker to execute than turns. This finding clearly favors the 3D display. The perspective view also showed improved avoidance maneuvering, with "fewer blunders and fewer unsuccessful attempts to achieve a specified separation" (p. 381).

Overall, it was concluded that natural display formats, such as 3D displays, are useful for "integrated presentation of three-dimensional separation information" (p. 381). The 2D displays presented the pilot with multiple pieces of information to integrate and interpret, putting them at a disadvantage that might have been responsible for the performance results. These findings have important implications for the task of seeing and avoiding wire hazards. Having extra time to react and plan an optimal avoidance strategy with the perspective display could lead to safer avoidance maneuvers overall. The increased vertical maneuvering seen with the perspective display could also have important implications for wire avoidance tasks, because these kinds of maneuvers seem much more useful for quickly avoiding wires than horizontal maneuvers. Indeed, that there were "fewer unsuccessful attempts to achieve a specified separation" (p. 381) with the perspective display makes it an important choice to consider for wire strike avoidance.

McCormick and Wickens (1995) examined three 'features of virtual reality': display dimensionality, frame of reference, and stereo viewing in the task of navigating 3D space. Participants were given a 2D split screen display, a monoscopic 3D display with immersed (egocentric) or non-immersed (exocentric) reference frames, and a stereoscopic 3D display with immersed or non-immersed reference frames for use at completing their mission. Their goal was to navigate 3D space "as quickly and with as little joystick input as possible" (p. 17). They had the task of moving an icon along a path to find, and subsequently intercept, flashing target cubes. Additionally, participants were asked periodically throughout the trial to make a "precise relative judgment" (p. 17) of the location of an object. Then, after each trial, they were asked a "global pattern" question. McCormick and Wickens found that in terms of dimensionality, participants performed better at all tasks with the 3D displays than they did with the 2D displays. In terms of frame of reference, they found trade-offs. The immersed view fared worse on searching tasks, but better than the non-immersed view on "performance during the travel phase" (p. 26). In terms of stereo effects, benefits were found with its use in ambiguous situations, such as travel in the 3D exocentric viewing condition and local judgments in both 3D conditions. However, no benefits were found with stereo on search performance or immersed travel performance.

For dimensionality, McCormick and Wickens believe results favored the 3D display because, as the proximity compatibility principle states, a task that requires integration of information sources (in this case, axes) is best served by a display with an integrated format regarding those dimensions (or in this case, axes) (Wickens, 1992). McCormick and Wickens additionally felt that the 2D display had costs of visual scanning, that "mental gymnastics" were required to integrate movement and position, and that these factors contributed to the 3D benefits. For frame of reference, they believed the immersed view's costs were a result of the "keyhole phenomenon," and the benefits were the result of the view's ecological compatibility with the world. They also believe that the "flow field" seen with this view resulted in a strong sense of ego motion, which was also a benefit to performance because of the motion and altitude cues it helped provide. Further, they felt that the exocentric 3D view might have had some line of sight ambiguities that lead to poorer position judgments. For stereo, it was felt the achieved results came about because "when ample depth cues are available from motion parallax (as they were here in the ego, but not the exocentric displays), the addition of stereo cues offer few, if any, benefits" (p. 28).

These results should be considered for hazard avoidance. Hazard avoidance, like the task in this experiment, will require "precise relative judgment" (p. 17) of the location of an object. It is therefore important to note that the exocentric view did not appear to support position judgments as well as other formats, due to line of sight ambiguities. However, if pilots' problems with search tasks transfer to wire detection tasks, the immersed view map, with its "keyhole" issues should not be implemented either. These are interesting conclusions because these 3D maps fared much better than the 2D map on the task at hand. The visual scanning and mental gymnastics costs, as well as the lack of an integrated view associated with the 2D display, could cause severe hindrances to pilots with the task of avoiding wires. Clearly a 2D map does not appear to be a good format to implement, either. It remains unclear from this research what the ideal implementation for wire avoidance should be, although a sense of which formats will show advantages in specific areas can be had from McCormick and Wickens' results.

Bemis et al. (1998) compared a "conventional display" to a perspective display in their study. Participants' tasks were to detect a threat and select the closest interceptor for each threat. Results showed a clear benefit for the perspective display in reducing errors of detection and interceptor selection, and in decreasing reaction time to select interceptors. Bemis et al. hypothesized that the integration of axes seen with the 3D display removed the additional steps that were required to obtain altitude information, and in that way reduce workload. These findings may be important to our interests. If the task of threat detection is as similar to wire detection as it sounds, the results of this study indicate that a 2D display will not be useful to pilots. 3D displays were found to have fewer detection errors, which is critical in the wire environment.

The results of these studies favor a 3D rather than a 2D map format. Though, again, none of the studies looked at wire avoidance specifically, all of the tasks were similar and relevant in some way to the task of wire avoidance. The outcomes of these studies might therefore suggest that a 3D map would be the better format choice for wire avoidance. However, an issue of concern is whether the tasks performed in the experiments are similar enough to wire avoidance to allow the findings to transfer to actual wire avoidance situations.

Studies with Mixed Performance Outcomes. Still other studies cited mixed findings in their exploration of 2D and 3D map performance. Banks and Wickens (1997) found mixed results in their dimensionality study. Participants were given a 2D contour map display, a 3D static, exocentric display, and a 3D interactive display to use in a battlefield task. They were to view battlefield scenarios on each of these map displays and then answer questions regarding the relative distance of units, make mobility assessments, and make line-of-sight judgments. The distance judgments, in particular, were thought to be relevant to wire avoidance tasks. Their findings were that "accuracy when making distance judgments was highest with the 2D display, while accurate performance on line-of-sight judgments was best supported by the 3D interactive display" (p. 31).

St. John, Smallman, Oonk, and Cowen (2000) found varying results in their dimensionality study, as well. Participants were given 2D and 3D formats to use in making distance judgments between two points on the maps. These distance judgments, again, were thought to be highly relevant to the task of avoiding wires. Their findings were that 3D maps were better for understanding the shapes of objects, as well as terrain layout. The 2D maps, on the other hand, were better for making relative position judgments about objects.

Wickens and May (1994) compared 2D and 3D maps in an air traffic control task and also reported mixed findings. Participants had to determine whether or not an aircraft would collide with terrain if it continued on its current course. If they decided that it would collide with terrain, they had to pinpoint where the collision would occur. Following that, participants had the task of determining whether a lost plane was "safe," "marginally safe," or "unsafe." If the plane was determined to be unsafe, the participant was to do the least amount of vectoring in order to make the plane safe. Finally, participants were given the task of issuing the fewest vectors that would get a plane to its desired location. The first task, in particular, was though to be relevant to wire avoidance. Their findings were that controllers more accurately judged whether or not a plane was on a collision course with terrain with the 2D display (though equivalent performance was seen with the two displays for pilots). Controllers also had larger errors when indicating the lateral position where the plane would have contacted the terrain, with the 3D display. For the vectoring tasks, the 2D displays resulted in more accurate vectoring, but the 3D displays lead to more efficient vectoring (i.e., fewer altitude clearances were issued).

Wickens, Campbell, Liang, and Merwin (1995) conducted a very similar study, and also reported mixed results. Participants performed weather avoidance tasks with 2D and 3D displays. Like the last study, they had to determine whether or not an aircraft would penetrate a weather formation if it continued on its current course. If participants decided that it would, they had to pinpoint where this penetration would occur and issue a single vector that would put them clear of the weather conflict. Following that, they had to vector an aircraft to its requested destination using the fewest number of vectors possible, while being sure to steer the plane clear of any weather hazards. Again, the first task was thought to be particularly relevant to wire hazard avoidance. Wickens et al. found that participants made more rapid discriminations with the 2D display on the weather penetration judgment task. However, they also found that participants issued wider clearances around weather and issued fewer vectors with the 3D display for the vectoring tasks.

Haskell and Wickens (1993) also experimented with 2D and 3D displays. Participants in their study were given the task of flying approaches while making judgments about intruder aircraft. They were to judge the altitude of the intruder, the distance forward of the intruder relative to the pilot, and where and when the intruder would pass closest to the pilot. The first two judgments were thought to be particularly relevant to the task of avoiding wires. Haskell and Wickens found that "neither the latency nor the accuracy of judgments of altitude, distance, or closest passage differed between the two displays" (p. 103). However, they noted that judgments about when the intruder would pass closest to the pilot interfered with flight path accuracy least when the pilot was using a 3D display. The converse also occurred when judgments were more separated, focused attention tasks (i.e., altitude judgments and distance forward judgments).

Olmos, Liang, et al. (1997) also explored dimensionality in a task where participants were asked to fly approaches while periodically being asked questions to assess their degree of situational awareness. A 3D display format, a 2D coplanar display format, and a 2D display format with an added "wedge" were used in the experiment. Participants completed a position report task that included questions of relative bearing, absolute bearing, and the altitude of objects relative to their aircraft. They also completed a Forward Field of View (FFOV)-map comparison task that required them to determine whether an object on the map was in the same location as the object seen in the FFOV. Next, they participated in a direction-indicating task, where the pilot was to judge the direction to a particular feature on the map after all features disappeared. Finally, they were to complete a map reconstruction task when the simulation was complete. All tasks were thought to be relevant to wire avoidance to some degree. Olmos, Liang, et al. found that the best approaches (in terms of flight path tracking) were made with the 3D display. However, they found the 3D display resulted in slowest performance for the position report task (vertical judgments particularly). Use of the 2D display with the wedge resulted in fewer errors on the FFOV-map comparison task. Both the 2D wedge display and the 3D display yielded superior performance relative to the 2D display for the direction-indicating task, and no difference in performance was found with any of the displays for the map reconstruction task.

Olmos, Wickens, and Chudy (1997) also conducted a study that examined the usefulness of 2D and 3D displays. The mission for their participants was to fly to various waypoints in 3D space. Along the way they sometimes encountered "no fly" zones or needed to characterize objects on the terrain or radar coverage zones. In addition, traffic sometimes appeared, and participants needed to estimate the bearing, range, and elevation angle of the traffic relative to ownship. This type of judgment task while navigating to waypoints was thought to be relevant to the wire hazard avoidance tasks pilots might typically encounter in a helicopter. Olmos, Wickens, et al. found that pilots with the 3D immersed display carried out their mission more quickly, and spent less time in the area of a hazard than they did with either of the other two displays. However, pilots with the 3D exocentric display responded much more quickly to a threat than they did with either of the other two displays. In addition, they found that it was the 2D coplanar display that resulted in best performance on the task of estimating intruder altitude. A second experiment was run, and each display had adjustments made to it to improve performance results, based on the findings of the first experiment. Results showed an improvement in each display's deficiencies such that, for all tasks, performance was "equalized" across the three displays.

Wickens et al. (1997) conducted a very similar study to that conducted by Olmos, Wickens, et al. Their task varied a little so that although the mission of flying to waypoints was the same, hazards in their path were red aircraft icons or what were called "pop up" hazards. If anything, this task seemed more relevant to wire avoidance than Olmos, Wickens, et al.'s task, and the results of the two studies were nearly identical.

Poole and Wickens (1998) conducted an experiment using 3D egocentric, 3D exocentric, and 2D map viewpoints for a hazard avoidance task in a helicopter simulator. Participants were to assume the role of a pilot transporting a team of scientists to conduct a geological survey. They were to fly low and slow, and stop to hover at predetermined points. They also needed to avoid power lines, towers, terrain, and weather hazards that crossed their path. All of these hazards except towers were displayed on the maps (see Figure 1 for a depiction of the maps used in the study). They were told to fly low and "skim" the terrain and man-made hazards as closely as possible. Participants were also asked situational awareness questions at various times

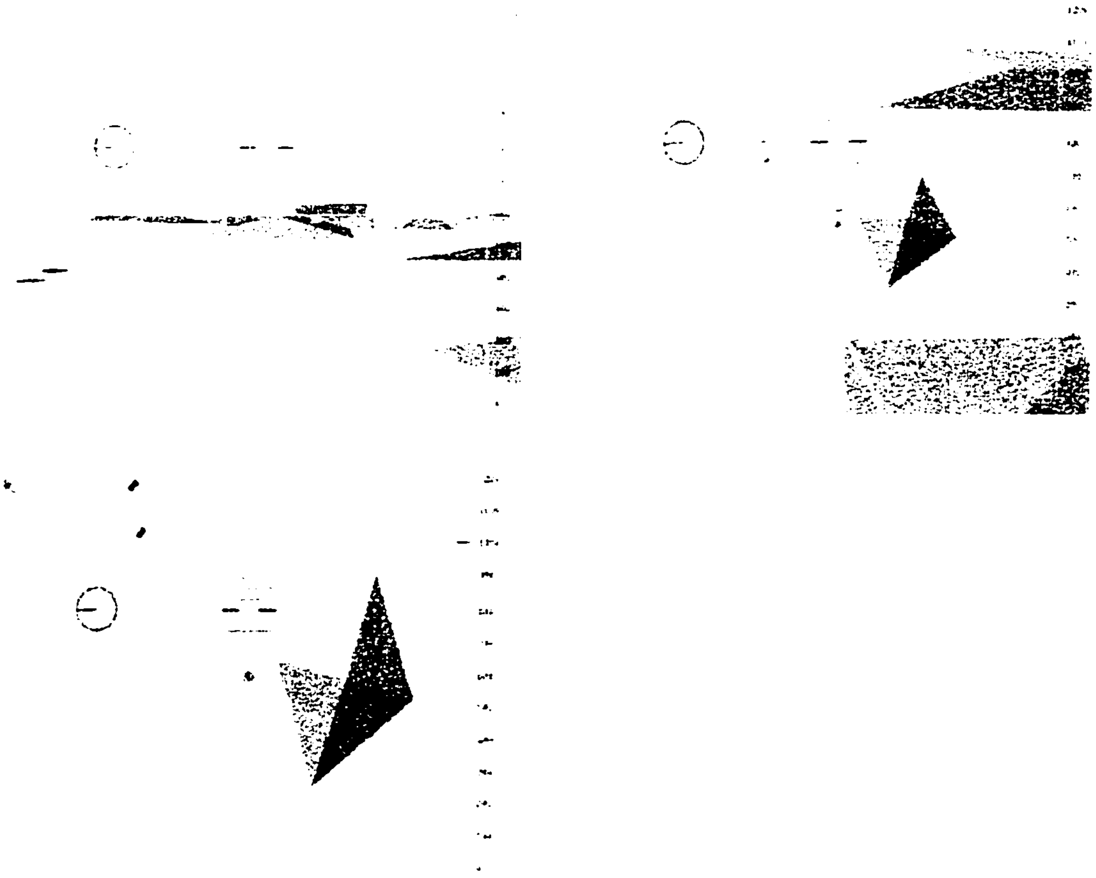

Figure 1. An example of the egocentric (3D), exocentric (3D), and planar (2D) displays pilots used in Poole and Wickens' study (1998).

throughout the experiment. This task was thought to be highly relevant to our concerns with wire hazards.

Results showed that equivalent performance was found between displays in terms of navigational ability. Pilots collided with terrain more frequently when they were flying with the 3D egocentric display, and the 2D display lead to more accurate performance in terms of stopping distance from hover points. However, regarding powerline strikes, the part of the study most relevant to our concerns, there were no significant differences found for display type. Poole and Wickens concluded that "the egocentric viewpoint should not be implemented into a rotorcraft cockpit because it does not provide any better local guidance ability during VFR flying than the exocentric or 2D viewpoints, but it has higher costs in regards to its shortcomings for providing sufficient hazard and global situation awareness. The exocentric viewpoint and the 2D viewpoint both appear to offer equivalent local guidance ability during VFR flying, however there is still uncertainty as to which of the two displays would provide better GSA performance" (p. 48). It would appear that even the study with the task most relevant to our interests in wire strikes found inconclusive results.

Reasons for Inconclusive Results

Knowing the positive aspects and drawbacks of each display type, conclusions can be drawn about why mixed results were found in so many studies. (For a complete list of these drawbacks and benefits, see pages 11-16.) But it does not provide a definite answer regarding which map display will be most helpful to pilots for the task of avoiding wires. In fact, even when studies had a clear result favoring one particular display, the fact that other studies could employ a similar task and find results favoring another display makes a clear answer regarding display choice for wire hazard tasks even more elusive.

Given that many of these tasks sound similar, it is interesting that so many results were mixed in this way. A closer look at why this might have been the case revealed that there were, in fact, quite a few differences between studies. Map types, for example, often varied somewhat from study to study. In some cases, this may have made the studies difficult to compare. 3D maps often had varying elevation angles, azimuth angles, GFOVs, and eyepoints (in fact, this sometimes even varied within a study, as a focus of comparison). Some studies used an egocentric, or immersed 3D display (e.g., Haskell & Wickens, 1993), others used a tethered, or some sort of exocentric 3D display (e.g., Olmos, Liang, et al. 1997), while still others incorporated both formats into their experiment as an additional factor of study (e.g., McCormick et al. (1998), Poole & Wickens (1998), Olmos, Wickens, et al. (1997), Banks & Wickens (1997)).

2D displays also varied from study to study. In some studies, the 2D maps were just straightforward planar maps. In others, however, the 2D displays were coplanar maps. These usually incorporated a vertical profile view into the display, which provided the pilots with altitude information that they otherwise would not have with the regular planar display (e.g., Wickens, Olmos, Chudy, & Davenport (1997), Haskell & Wickens (1993), Olmos, Liang, et al. (1997), Boyer & Wickens (1994), Wickens et al. (1996), Rate & Wickens (1993)).

In addition to the varying format types, maps often had many additional features built in that varied from study to study. These features were meant to aid the pilots with their tasks. For example, when there was no vertical profile component added to the 2D display, there were sometimes other ways of presenting altitude information. Some maps used data tags (e.g., Wickens et al. (1995), Boyer & Wickens (1994), Ellis et al. (1987)). Others used color-coding to convey types of altitude information (e.g., Banks & Wickens (1997), St. John, Smallman, Oonk, et al. (2000), Wickens & May (1994), Olmos, Liang, et al. (1997), Wickens et al. (1996)). (It should be noted, however, that color-coding was not solely used for altitude depiction (e.g., Wickens et al. (1995), Boyer & Wickens (1994). Wickens et al. (1995), for example, used color coding to depict different types of weather.) Altitude information was also sometimes conveyed to the pilot through use of contours (e.g., Banks & Wickens (1997), St. John, Smallman, Oonk, et al, Olmos, Liang, et al.). Still others presented displays that incorporated combinations of these features. For example, a color coding/contour combination was utilized by Banks and Wickens (1997), and St. John, Smallman, Oonk, et al. Other studies put different features to use, such as droplines on the 3D displays to help the pilot accurately determine the position of aircraft or other objects in the database (e.g., Wickens et al. (1997), Wickens & May (1994), Wickens et al. (1995), Olmos, Liang, et al., Boyer & Wickens (1994), Wickens et al. (1996)). Some studies also used predictors (e.g., Wickens et al. (1997), Haskell & Wickens (1993), Wickens et al. (1996), Ellis et al.) and pathway-in-the-sky symbology features (e.g., Haskell & Wickens (1993)) to assist pilots in traversing experimental routes. Other features, such as attitude directional indicators, airspeed indicators, a compass rose, a "perceptual wedge," concentric rings to "help pilots orient to the next waypoint," and zoom capabilities have all been used in various studies to aid pilots with their task. In addition to providing different levels of benefits to the pilots, all of these features may also have provided different levels of hindrances as well. Some displays may have become more or less difficult to mentally integrate with all the information provided, and cluttering may have created a problem to some degree for others, making results difficult to compare from study to study.

Other sources that varied across all of these experiments (or even within an experiment) were the participants themselves. They often came to the studies with very different professional backgrounds and experiences. (It should be noted that in some cases, this was recognized and controlled.) Studies employed a variety of people, such as air traffic controllers, pilots, student pilots, students, and military personnel, to participate in their experiments. The professional backgrounds of the participants in these various studies may have made them more or less suited to the specific tasks they were asked to perform. For example, a study by Wickens and May (1994) employed a mix of pilots and air traffic controllers in their experiment, and found different results depending on profession. In one study, pilots performed equally as well with both the plan view and perspective view display for a specific task, while controllers, who have a great deal of training with plan view displays, performed much better on the same task with the plan view display. Campbell, May, and Wickens (1995) reported similar outcomes. These may be pure transfer of training effects, but still function as evidence that participant background is important to take into account in order to be able to compare the outcomes of these studies. If the display, participant background, and other various differences were the likely cause of the mixed results, it cannot be known for certain if a helicopter wire avoidance study will yield results similar to any of the other studies, even if the exact same display and study design is used, because the task of avoiding wires differs slightly from most other tasks discussed.

It seems, then, that in order to achieve more predictable results from studies, a method should be developed for matching the correct combination of map format, participant, task, and other factors, in a manner that produces the best performance results. Work has been started toward achieving this goal.

Creating a Taxonomy and Model from Findings

Wickens has made some conclusions based on these general findings in the literature. He has created a taxonomy of 3D displays, outlining costs and benefits to the various viewpoints when various tasks are undertaken (Wickens, 2000). Many of these costs and benefits have been described earlier, and will not be mentioned again here. Wickens (1999) has also taken some of these findings one step further and has started developing a computational model for determining the costs of various map formats. He takes into account factors such as the amount of scanning the person will have to do, the visual angle of the display, the database integration requirements, the resolution of the display, the clutter of the display (which considers things such as density and the confusability of objects in the display), and the access the pilot has to the information (i.e., how much interactivity is allowed? For example, can the pilot declutter the display?). Perhaps such a computational model would help predict what type of map display would best benefit pilots in avoiding wires.

Similarly, some generalized findings emerged from the literature reviewed in this study. On tasks similar to wire avoidance, problems were seen with 3D displays that were reportedly caused by reduced global awareness, perceptual biases (in particular, ambiguities along the viewing axis), and the integrated nature of the display. The 2D displays' heightened global awareness and focus of attention on a single attribute allowed for superior performance on some of these tasks. On a great number of other tasks, however, integration of attributes was helpful to the task, and great benefits in performance were seen with the 3D displays while performance with the 2D displays suffered due to "mental gymnastics" that needed to be performed in order to integrate information. However, benefits were also commonly seen with the 2D when making position judgments, which was also highly relevant to hazard avoidance.

Implications for Wire Strike Formats

It has been established from these data that the type of information most beneficial to pilot performance would seem to depend highly on the task and other factor combinations. The question relevant to our concerns is, which map will best support activities associated with wire strike avoidance? As noted, this is a specific concern that few people have studied. Some of the weather and combat missions examined have similarities to wire avoidance. Clearly, for these things, evasive action must be taken that can be critical to the pilot's survival. However, the weather avoidance and combat missions are also different from wire avoidance tasks. Wires are arguably more difficult to visually detect and maneuver around, but have the advantage of being relatively static objects. Wickens et al. (1997) stated that "hazard awareness can be broken down in terms of the degree of precision with which location and trend must be determined" (p. 2). Among combat missions, weather, and wires, there are definitely differing degrees of precision. These task factors, as well as the benefits and drawbacks of each display format, must be taken into account when deciding which format to apply.

Wickens et al. (1997) warn that egocentric or immersed displays will not be good for avoiding hazards because the "keyhole" view they provide of the world will not support the gathering of information needed for hazard awareness. An exocentric viewpoint will help eliminate the problem. However, they argue that this display format will not be good for hazard avoidance either, due to the distortion that results from expanding this viewpoint. With the greater distortion, it will be difficult to judge the precise position of hazards. However, Wickens (2000) has stated that an exocentric 3D display will be beneficial for these sorts of tasks, as it provides a good "overall understanding of what a scene 'looks like'" (p. 405) and cites Endsley saying that this is crucial for hazard awareness and avoidance.

Additional research exploring 3D immersed and 3D exocentric display differences has been reviewed and supports this idea that the exocentric display is better than the egocentric display for our purposes. Theunissen (1998) found that the exocentric display utilized in his study yielded better collision avoidance than did the egocentric display that he utilized. Although some unfavorable results were also seen with their exocentric display, Wickens et al. (1997) found that, compared to their egocentric display, "response time to detect (and begin identifying) the pop-up threat" (p. 18) was shorter with the exocentric display. Poole and Wickens (1998) found that their egocentric display yielded a greater number of hazard contacts than did their exocentric display. Finally, Thomas, Wickens, and Merlo (1999) found that their tethered view lead to better global awareness than their immersed view. In their case, this meant better performance on a count of visible enemy units. They also found that significantly more changes to objects were detected with the tethered view than with the immersed view. Additionally, pilots with the immersed view had more trouble answering questions that required a pan of the environment than pilots with the tethered view. Evidence for cognitive tunneling was also found with more egocentric views in their study. From this research, it seems that a 3D exocentric display would support wire avoidance tasks better than a 3D egocentric display might.

However given some of the uncertainties mentioned earlier, pilots with a 2D display may still outperform them both. Global awareness should be enhanced with a 2D display, which would then allow for a better awareness of hazards in the environment. However, the 2D format has known deficiencies in dealing with integrated tasks. Since hazard avoidance can be thought of as an integrated task (change of position in all three dimensions in a single maneuver to avoid an obstacle), avoidance performance with a 2D display may not be superior to a 3D display.

At this point, then, it remains unclear from the literature which map will best support the specific task of avoiding wires. In addition, it is important to keep in mind that not only is wire avoidance a unique problem that has been given little attention, so is the task of low level helicopter flight itself. Most studies have focused on fixed wing aircraft, and it can be argued that fixed wing flight is different enough from helicopter flight that findings from fixed wing flight studies might not generalize to low-level helicopter flight studies.

Recent Wire Strike Display Research

To address the issue of wire avoidance during low-level helicopter flight more directly, McCann and Jones (2001) examined wire avoidance during a simulated low-level helicopter flight in a wire-rich environment. Participants were helicopter pilots whose task was to assume a role similar to an Emergency Medical Service (EMS) pilot and fly along surface roads, looking for the scene of an accident. A variety of forms of wires, including telephone lines, guy wires, and electrical power lines, bisected the roads at irregular intervals. Pilots were informed of the possibility of encountering wire hazards along each of three routes.

Participants ran through three conditions in the experiment: a baseline condition, a plan view map condition, and a perspective view map condition. In each condition participants were given a monitor displaying an out-the-window view of the simulated world (see Figure 2) and a monitor displaying instruments. In the plan (2D) and perspective (3D) view map conditions, a third monitor displayed the moving map, while in the baseline condition, this screen remained black. The monitors were arranged in a pyramid-like configuration (see Figure 3). In the plan view map condition, the moving map depicted a 2D

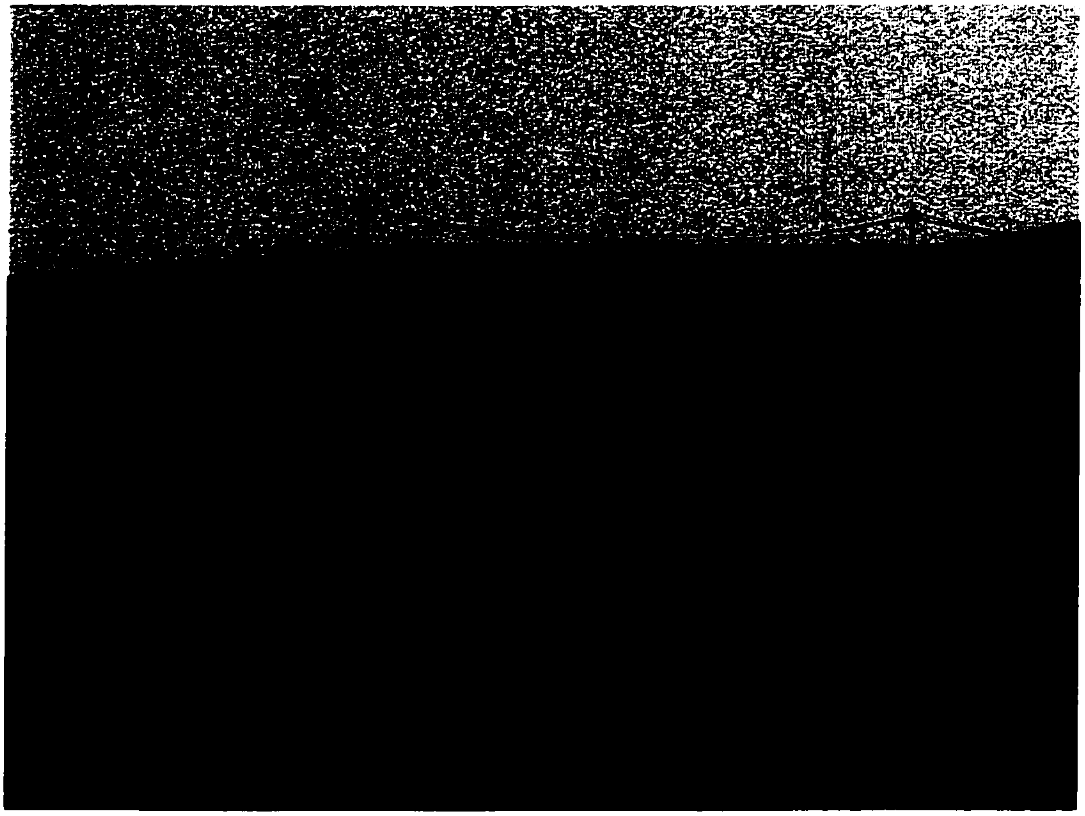

Figure 2. View out the “window” in the simulator. This is an example of how the forward view, which was present in all conditions, looked to the pilot in McCann and Jones 2001, and in the present study.

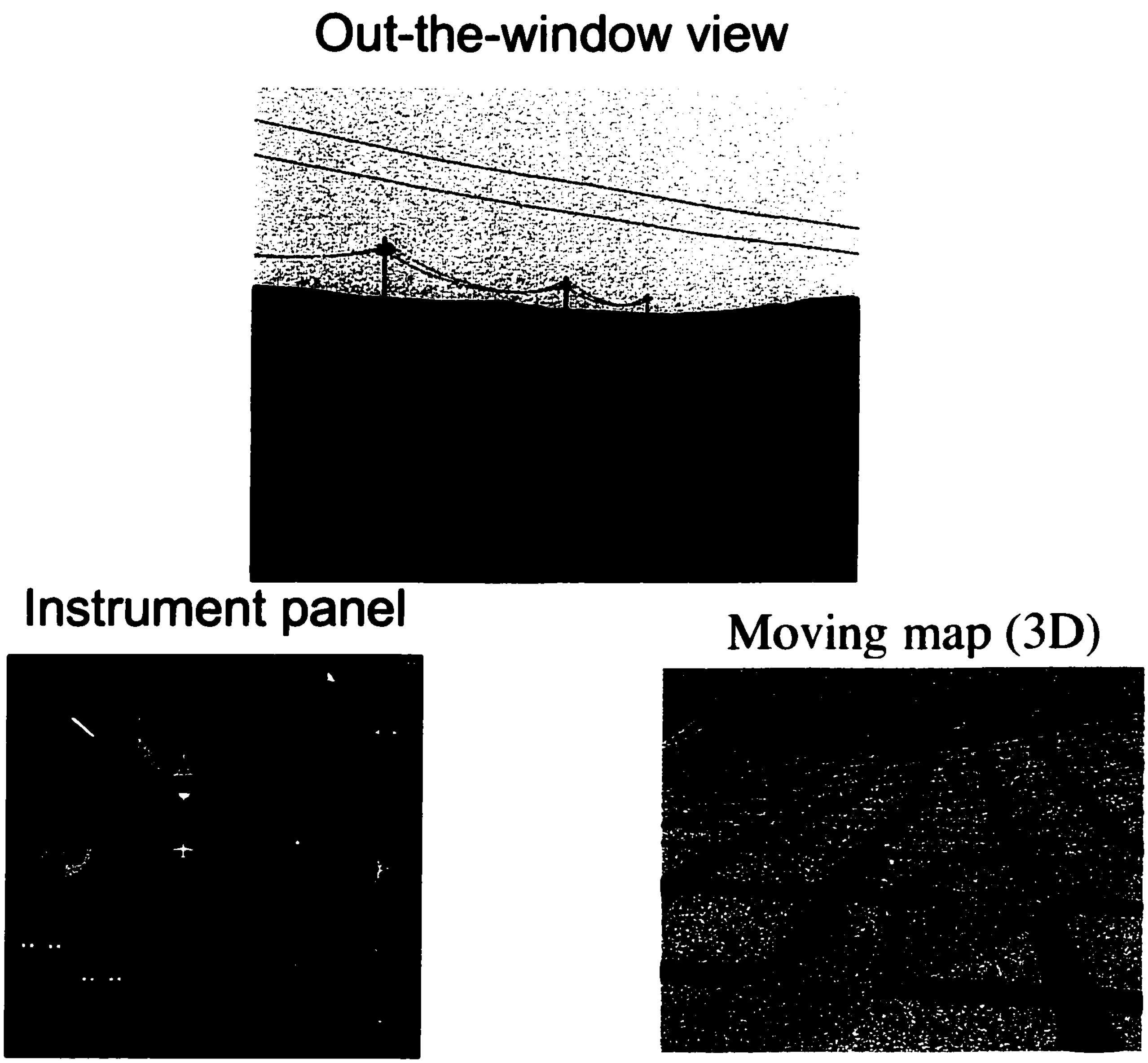

Figure 3. Pyramid-like configuration of the out-the-window view, instruments, and moving map display (when display was available) that the pilots saw in the helicopter simulator.

view of the immediate environment (see Figure 4). In the perspective view map condition, the moving map depicted a 3D view of the immediate environment (see Figure 5). A "tethered" view was chosen for the perspective view map based on the known benefits of this type of display relative to a fully immersed display for various flight tasks (e.g., Theunissen (1998), Wickens et al. (1997), Poole & Wickens (1998), Thomas, Wickens, & Merlo (1999)). In order to minimize distortions so prevalent in these exocentric views, a view at a moderate distance from the ownship was chosen. Both of the map displays provided the pilot with depictions of the wire hazards. Wires on both map formats were highlighted and color-coded in terms of how much danger they presented to the pilot (see page 61 for more details about color coding).

Participants struck a total of 12 wires in the baseline (no map) condition, 11 wires in the plan view condition, and 4 wires in the perspective view condition. In order to determine if there were differences between map conditions, an ANOVA was run on the number of wires participants struck in each condition. Results showed that there was no significant effect for map condition. However, data points representing the minimum distance pilots flew over the wires were examined, and the means and variance in this minimum altitude data revealed interesting trends. Pilots tended to fly over the hazards with less "margin for error" in the baseline and plan view conditions than in the perspective view condition. That is, the average vertical separation between the ownship and the wire hazards at time-of-passage did not appear to differ

Figure 4. View the pilot had looking at the Plan View Map in McCann and Jones, 2001.

Figure 5. View the pilot had looking at the Perspective View Map in McCann and Jones 2001, and in the present study.

between the plan view map condition and the baseline condition, but increased noticeably in the perspective view map condition. This trend toward a larger vertical separation with the perspective view map was accompanied by a decreasing trend in the variance. That is, whereas vertical separation was generally larger in the perspective view map condition than in the other two conditions, pilots were also more consistent about maintaining this vertical separation, compared to the other two map conditions. It appears that pilots produced their highest and most consistent flight over hazards when given the perspective map.

Although ANOVAs run on these data did not return significant results, the trends were still important. These opposing mean and variance trends can be combined into a single estimate of how probable it would be for pilots to deviate from the mean vertical separation by an amount sufficient to result in a wire strike, separately for each map condition. How likely participants were to strike wires in each condition could then be compared. The wire strike probability was determined in the following manner: First, each participant's mean minimum relative altitude over the wires and associated standard deviation was calculated for each condition. Using straightforward statistical inference, a theoretical normal cumulative distribution was then consulted to determine, for each condition, the probabilities of a deviation from the mean relative altitude large enough to result in a wire strike. It should be noted that the measure was conservative in that the error programmed into the determination of a wire strike in the simulation was not taken into consideration for the statistical analysis here (for more information on the error that was programmed into the determination of a wire strike, see page 61). Results showed that there was a significantly higher probability of a wire strike in the baseline and plan view map conditions than there was in the perspective view map condition.

Subjective data from the participant questionnaires were also collected (see page 71 for a list of questionnaire topics). Participants generally felt that they had more control over the aircraft in both the 2D and 3D map conditions than they did in the baseline condition. They felt that they had more spatial and overall situational awareness in these two map conditions than they felt they had in the baseline condition, and they generally felt that the 2D and 3D displays imposed less of a mental demand on them than the baseline condition did. In addition, participants rated their performance in the 2D and 3D conditions as superior to their performance in the baseline condition (but did not rate either one of the map displays as statistically superior to the other). In general, it appears that participants tended to rate both of the map conditions as superior to the baseline condition. Only ratings on usefulness of the displays for avoiding wires showed statistically significant differences among all map conditions. The results from these subjective rating measures are interesting given that the objective performance measures show the plan view map condition did not differ statistically from performance in the baseline condition. That is, there was a dissociation between the subjective value placed on the plan view map, and the objective performance data (See Andre & Wickens (1995) for a discussion of this phenomenon.).

Although the trend toward superior performance with the perspective view map relative to the baseline was not surprising, the lack of a difference in performance between the baseline condition and the plan view map condition was unanticipated. Pilots in the plan view condition flew just as low over the wires as pilots in the baseline condition (putting them more at risk for striking a wire than if they had flown at a higher altitude over the hazards-- such as that flown in the perspective view condition), yet they report utilizing the map in this condition, and often rated it equal to the perspective view map and superior to the baseline condition. This suggests the lack of an objective performance benefit from the 2D map was not the result of a failure to notice the hazards on the 2D map, but perhaps due to the lack of appropriate real-time information regarding the relative altitude between ownship and the wire hazards necessary to clear the wires. In other words, the pilots' knowledge of their altitude relative to the hazard may have been essential for successfully completing an avoidance maneuver. This relative altitude information is inherent in a perspective view of the world. However, with a top down view of the world, the vertical dimension is entirely eliminated from view, which thereby removes dynamic relative altitude information between the ownship and the upcoming wire hazard. Relative altitude information is arguably the most salient perceptual cue present in the 3D display that was absent from the 2D display.

The Present Study

The purpose of the present study was to explore the putative role of relative altitude information in producing superior performance of the perspective view (3D) map over the plan view (2D) map in McCann and Jones (2001). The study replicated McCann and Jones (2001), except that a relative altitude indicator was added to the plan view map display.

A digital display was chosen for the relative altitude indicator. While analog displays are better for displaying things like value comparisons or complex relationships such as rate of change, digital displays are better for displaying precise relational information (Wickens, 1992). Analog displays present information in a natural format, which may allow a relatively quick and easy interpretation of certain information. However, it can also be difficult to determine whether the correct information was interpreted from an analog display. Digital displays leave less room for this sort of error in interpretation, so there is not the same concern that the wrong information will be taken from the display. It was because of the greater precision and unambiguous presentation of information that the digital display was ultimately decided upon for this study.

This indicator displayed the dynamic vertical distance (in feet) between the ownship's current position and the position of the next (upcoming) wire hazard along the current route. (See pages 57-60 for a full description of the plan view and reference to a corresponding figure depicting this view.) If information about relative altitude was responsible for the 3D benefit in McCann and Jones (2001), then adding the digital read-out to the 2D display should equate performance between the 2D and the 3D conditions, and both conditions should be superior to the baseline condition.

An alternative hypothesis was that the way in which the information was presented to the pilot could make an important difference in terms of flight performance as well. Adding a relative altitude indicator to the 2D display might not result in equivalent performance if the format in which the relative altitude information is displayed was also critical. For example, a 3D format of relative altitude information could have advantages over a digital output of the same information based on its form. For instance, the graphic or spatial way in which the information is presented, as previously discussed, could be considered a more natural display of information that may make it quicker or easier to interpret. However, perceptual biases may also exist with this particular format of information, which may make aircraft/hazard separation deceptive or difficult to interpret. A digital readout of precise information which leaves no room for interpretation or guess-work may be a much more beneficial format to the pilot. It was important to conduct this second study, then, to determine whether providing relative altitude information on the 2D map would lead to more equivalent performance between the two map displays, or if something more was needed.

Method

Participants

Eighteen helicopter pilots were recruited to participate in the study. They were a mix of male and female pilots whose ages ranged from 24 to 55 (mean age=35). Most of the pilots' professional experience was with the Coast Guard, however, a few were military and EMS pilots, as well.

Apparatus

The experiment was conducted in a part-task helicopter simulator located at NASA Ames Research Center. The simulation consisted of three monitors, a pilot seat, and controls. A 21-inch diagonal SGI monitor centered in the cab presented the out-the-window view to the pilot. An instrument panel was displayed on a 17-inch diagonal monitor located below and left of the monitor displaying the out-the-window view. The third monitor (also 17-inch diagonal), located below and to the right of the out-the-window view, presented the moving map to the pilot (when the map was available for the pilot to use) (See Figure 2 for a view of the configuration.). The cab was also equipped with cyclic and collective controls, but rudder pedals were absent. To obtain a yawing motion, the pilot was required to twist the cyclic control.

Procedure

The study design was a single-factor, within-subjects experiment. The single-factor, map display, had three conditions: Baseline (no map), Plan View Map, and Perspective View Map. The Baseline condition consisted of the out-the-window view only; no map view was presented to the participant (see Figure 3). The monitor that would normally display the map in the other two conditions remained black in the baseline condition.

The Plan View Map gave the participant not only the out-the-window view presented in Figure 3, but also a 2D, or plan view map of the environment surrounding the ownship (see Figure 6). It displayed the road being followed in a grey color, void of any pavement markings that could be seen out the window. A grid like pattern covered the ground, overlaying any terrain features that could be seen out the window. An icon depicting the ownship was also displayed on the map, as well as the color-coded wire hazards. The 2D map was configured such that the ownship icon was placed towards the bottom of the screen, rather than in the center-screen position often found in 2D map studies. With an elevation angle of 90 degrees, the view port or "camera" was 675 meters above, and 135 meters behind ownship. This configuration was tailored towards our specific experimental task. If participants were to follow along a route, searching for the scene of an accident (for more details of the task, see page 63), they were expected to be involved in forward flight most of the time. Additionally, the only hazards to the pilot in this study were the wire hazards in

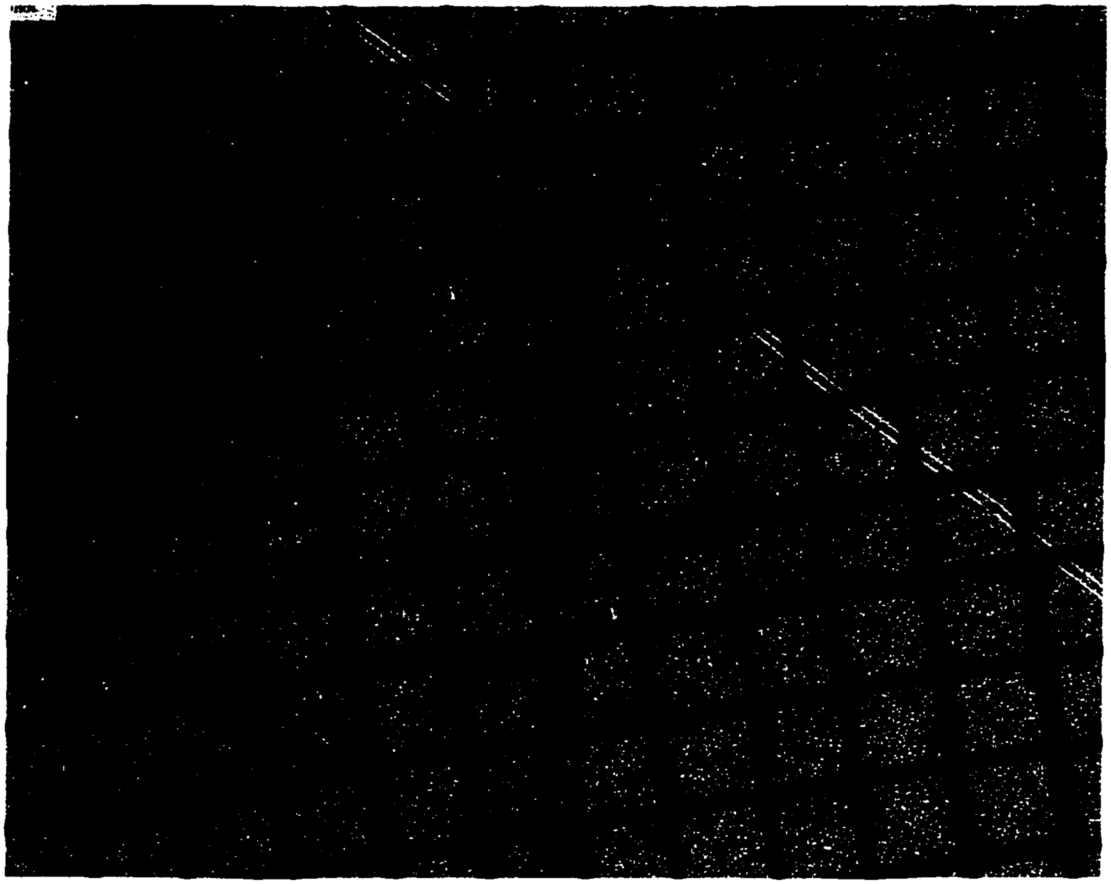

Figure 6. View the pilot had looking at the Plan View Map with Relative Altitude Indicator in the present study.

their flight path. These hazards were stationary, and unlike traffic or weather hazards, did not approach the pilot from behind. Therefore, it was decided that participants would benefit from a display with a larger viewing area in front of the aircraft than behind.

This map view, unlike the 2D view in the previous study (see Figure 4), included a relative altitude indicator located on the center left edge of the map display. For reasons previously discussed, a digital format was chosen for the display. It showed the number of feet the pilot was above or below the upcoming wire, as calculated from a point on the ownship to a target point at the center of the wire. A minus sign appeared to indicate the aircraft's altitude when it was below the wires. The display was black and square, and contained the words "Relative Wire Altitude" in white letters above the numbers (also white) which depicted that altitude. The numbers were enclosed in a thin red box. The center left edge was chosen for the placement of the indicator because here, it was thought to be close enough to the displayed hazard to allow for a quick check of the relative altitude, without requiring a large shift in the focus of attention. In addition, at this location it would not physically intrude on the map display in a way that would block relevant hazard information. The indicator was implemented with the intention of helping the pilots determine how high they were in relation to the wires shown on the map.

The relative altitude indicator remained on at all times, and always displayed the pilot's altitude relative to the wire that he or she was approaching.

When the pilot passed the wire hazard and it was safely behind him or her, the numbers on the indicator "blanked" for 4 seconds and then began displaying the relative altitude of the next wire hazard that the pilot was approaching. It should be noted that the wire hazard did not have to appear on the map before the indicator would start to display the pilot's altitude relative to that wire. The pilots were informed of this procedure. Limitations in computer hardware and programming prevented an indicator design that displayed relative altitude only when the wire of concern appeared on the map.

The Perspective View Condition gave the participant both the out-the-window view shown in Figure 3, and a map with a 3D view of the out-the-window scene (see Figure 5). It, too, displayed the road in a grey color, void of any pavement markings that could be seen out the window. A grid like pattern covered the ground, overlaying any terrain features that could be seen out the window. An icon depicting ownship was also displayed on the map, as well as the color-coded wire hazards. A tethered view was chosen, with the "camera" located 219 meters behind, 75 meters above, and 29 meters to the right of the aircraft. This viewpoint was chosen based on the known benefits of this type of display relative to a fully immersed display, as described by the relevant research in the field. The main concern with this viewpoint for the present study (as was the case for McCann & Jones, 2001) was avoiding the "keyhole" phenomenon, known to be detrimental to hazard avoidance.

On the 2D and 3D maps, as well as the out-the-window view of the world, a variety of wire types, including telephone lines, guy wires, and electrical power lines, bisected the roads at irregular intervals. On the 2D and 3D maps only, the wires were highlighted and color-coded to alert the pilot as to the current "danger level" they posed. Wires on the map remained green when the participant was 600 meters or more in Euclidean distance from the wire. Wires changed to yellow when the participant was less than 20 meters in relative altitude above the wire and entered a caution zone within 599-400 meters from the wire. When the pilot was 399 meters away from the wires or closer (and within 20 meters in relative altitude), the wires turned bright red in color and remained that way until the helicopter was out of the danger zone (see Figure 7 for a depiction of the color-coding).

The study incorporated 21 wire hazards (seven in each of the three routes the pilot was asked to fly). Minimum relative altitude data was recorded at three predetermined points (targets) along the wires. Additionally, a wire strike message appeared on the out-the-window screen for approximately one second when the wires were hit. The message read "WIRE STRIKE!" in bold red letters on a black background. This wire strike feature had an amount of error programmed into the determination of when a strike occurred. A wire strike occurred when the helicopter was within 34.0 meters left, right, front, or rear of any target, and within 3.4 meters above or below the closest target. This error was programmed into the determination of a wire strike because

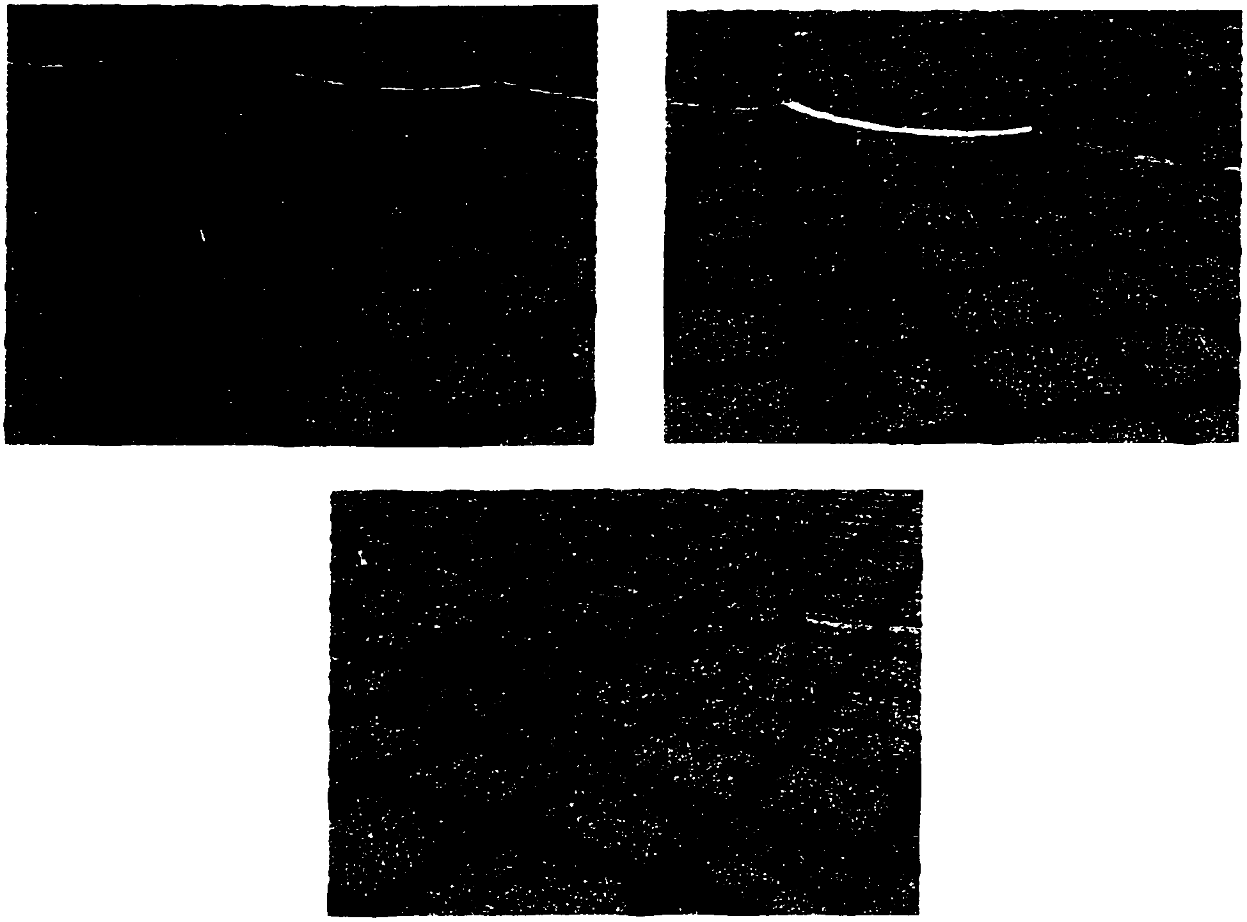

Figure 7. Wire highlighting and color-coding alerted pilots to the level of danger (in "real time") that the wires presented. Wires remained green when the pilot was 600 meters or more in Euclidean distance from the wire. Wires turned yellow when the participant was less than 20 meters in relative altitude above the wire and entered a caution zone within 599-400 meters from the wire. Wires turned red when the pilot was less than 20 meters in relative altitude above the wire and entered a danger zone 399 meters away from the wire or closer.

otherwise a wire strike would only occur when the mid-point of the helicopter was at exactly the same height as the wire at the time-of-passage. This would have been unrealistic, because actual helicopters can strike wires at points both above and below the vehicle mid-point with catastrophic results.

The simulation did not end when a collision occurred. After a collision registered and the wire strike message appeared, the helicopter would pass through the wire and continue on its course.

Task

The pilots were given an orientation to the experiment, and were then seated in the simulator. They were told that they were to assume a role similar to an EMS pilot, and scan the road ahead for the presence of an automobile accident. An accident was defined as being at least two cars, in physical contact, and at odd angles in the road. This was important information, since the participant encountered numerous “distracter cars” on the road before coming to the accident scene. The distracter cars were missing at least one of the elements that defined an accident site. All of the cars in the database were stationary. At the beginning of each mission, the aircraft was pointed in the direction of a particular road, and the participants were told that the accident would always be located at some point along the road that they were tracking. They were also told that they should be on alert for wire hazards. (See Appendix B for a copy of the instructions the pilots were given.)

At the beginning of the experiment, participants received a "free practice" in which they were allowed to fly around freely and become familiar with the handling qualities of the helicopter simulator. When the participant felt confident and ready to begin, he/she was then set up for the missions. Participants flew three experimental routes: one with the plan view map, one with the perspective view map, and one with no map. Each experimental route was preceded by a practice route, which allowed the participant to acquaint himself/herself with the technology available for that experimental route. Instead of freedom to fly anywhere, as in the free practice, the participant was told to follow the route to the accident scene, just as he/she would be expected to do in the experimental routes.

Each participant flew through each of the three routes, and the route/map display combination was completely counterbalanced to control for learning and fatigue effects. Participants were asked to complete the routes in as timely a manner as possible, while following the road and avoiding hazards. Each of the routes took approximately 20 minutes to complete. A flight of 200 feet above ground was suggested during the orientation, although participants were told that if they had to deviate from this height when a hazard was encountered, it was acceptable to do so. Participants' altitude above ground was not recorded, and a height of 200 feet was only suggested to persuade them to fly low enough to be able to identify cars and encounter hazards. They were told to call out the accident scene when they had it in sight. Upon completion of the experiment, participants were given a 10-point scale questionnaire (10 = fully acceptable) and were asked to rate the displays on variables such as: situational awareness, usefulness in avoiding wire hazards, aircraft control, mental demand, and general performance (see Appendix C).

Results

The dependent measures under investigation in this study included: 1. the absolute number of wire strikes, 2. the minimum distance flown above the wires (and mean and variance calculations of this data), and 3. the inferred probability of a wire strike.

Wire Strikes

Out of 126 wires that could potentially be hit in each condition, participants struck 7 wires in the baseline condition, 13 wires in the plan view condition, and no wires in the perspective condition. In this study, participants struck nearly twice as many wires in the plan view condition as they did in the baseline condition. This was unlike McCann and Jones (2001), where participants struck nearly equal numbers of wires in both the baseline and the plan view conditions. Because no wires were struck in the perspective view condition, an Analysis of Variance was not conducted on these data.

Minimum Distance Flown Above the Wires

Examination of the average minimum altitude flown over the wire hazards as a function of map condition (Figure 8) revealed that pilots flew over

ANOVA Table for subject means min rel alt

	DF	Sum of Squares	Mean Square	F-Value	P-Value	Lambda	Power
Subject	17	6063.092	356.652				
condition	2	1821.428	910.714	4.155	.0243	8.310	.694
condition * Subject	34	7451.848	219.172				

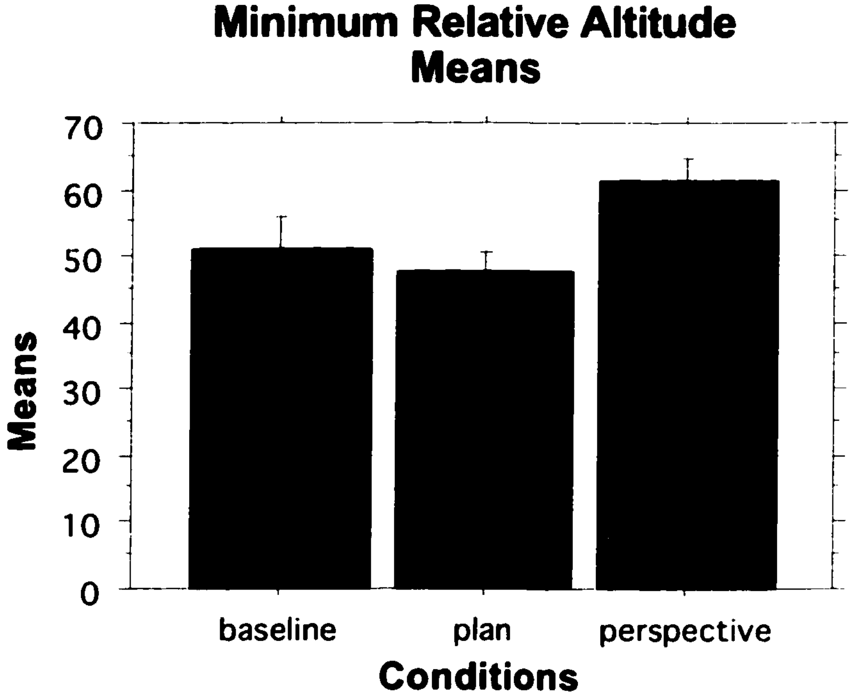

Figure 8. ANOVA table and bar plot of participants' mean minimum relative altitude over hazards. Error bars depict standard error. Results seen here were significant.

the wires with the greater margin of error in the perspective view condition (mean altitude = 61 feet) than in the plan view condition (mean altitude = 48 feet) or the baseline condition (mean altitude = 51 feet). An ANOVA revealed that the differences among the map conditions were significant ($F(2, 34)=4.155$, $p<.05$). Individual comparisons showed that the perspective view differed significantly from both the plan view condition ($t(17)=-2.709$, $p=.0149$) and the baseline condition ($t(17)=-2.358$, $p=.0306$). No other comparisons were significant.

Examination of the variance of the minimum altitude flown over the wire hazards revealed an interesting opposing pattern. As shown in Figure 9, pilots flew most consistently at their altitude over wires in the perspective view condition (mean standard deviation = 23) than in the plan view condition (mean standard deviation = 28) or the baseline condition (mean standard deviation = 32). An ANOVA revealed that the differences among the map conditions were significant, $F(2, 34)=8.988$, $p<.01$ (see Figure 9). Again, individual comparisons showed that the perspective view differed significantly from both the plan view condition, $t(17)=3.264$, $p<.01$, and the baseline condition, $t(17)=3.997$, $p<.01$. No other comparisons were significant. This configuration was important to the probabilistic measure discussed in detail in the following section. Probabilistically, these opposite mean and variance patterns would be expected to reduce the probability that subjects would deviate far enough from

ANOVA Table for subject std devs min rel alt

	DF	Sum of Squares	Mean Square	F-Value	P-Value	Lambda	Power
Subject	17	3925.435	230.908				
condition	2	801.324	400.662	8.988	.0007	17.976	.971
condition * Subject	34	1515.638	44.578				

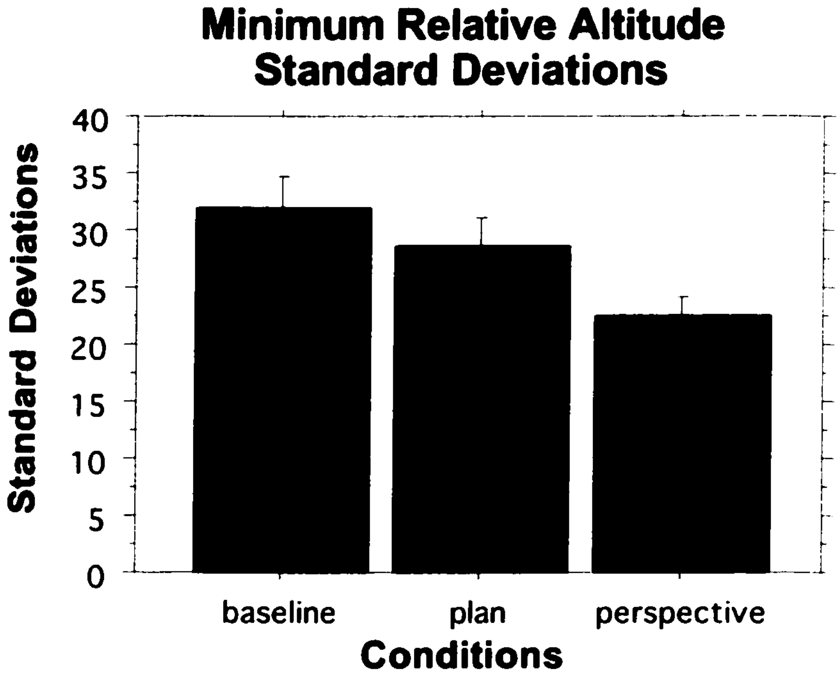

Figure 9. ANOVA table and bar plot of standard deviations of participants' minimum relative altitude over hazards. Error bars depict standard error. Results seen here were significant.

the mean to yield a wire strike in the perspective view condition compared to the other two conditions.

Wire Strike Probability

The probability for a wire strike was determined in the following manner: First, each participant's mean minimum relative altitude over the wires and standard deviation of this number for each condition was calculated. A theoretical normal cumulative distribution was then utilized to determine, for each condition, the probabilities of a deviation from the mean relative altitude large enough to result in a wire strike. It should be noted that the measure was conservative in that the error programmed into the determination of a wire strike in the simulation was not taken into consideration for the statistical analysis here. An ANOVA was then run on these numbers to determine whether there were differences in the likelihood of wire strikes among conditions. Results were significant, $F(2,34)=7.965$, $p<.01$ (see Figure 10). Individual comparisons revealed significant differences between the baseline and perspective view map conditions ($t(17)=3.876$, $p<.01$), and the plan and perspective view map conditions ($t(17)=3.791$, $p<.01$). The baseline and plan view map conditions did not differ. The addition of the relative altitude indicator, it would appear, failed to boost performance in the plan view condition to equal the level of performance seen with the perspective view condition.

ANOVA Table for probabilities THESIS

	DF	Sum of Squares	Mean Square	F-Value	P-Value	Lambda	Power
Subject	17	.038	.002				
condtions	2	.044	.022	7.965	.0015	15.929	.949
condtions * Subject	34	.094	.003				

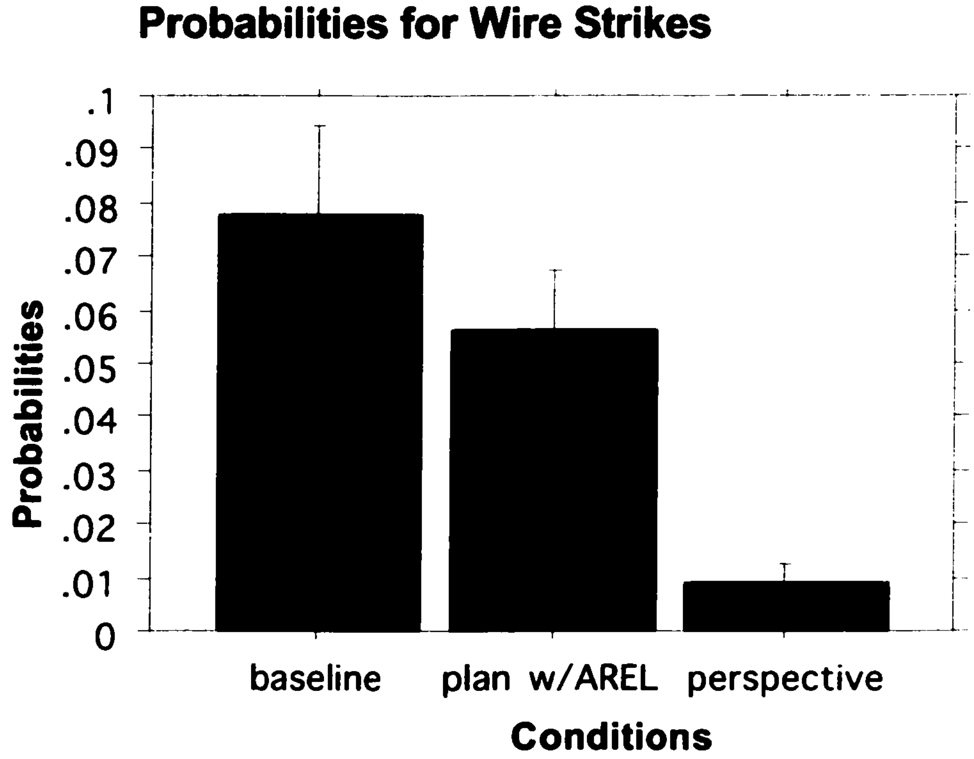

Figure 10. ANOVA table and bar plot of for the probability of striking wires in each condition. Error bars depict standard error. Differences seen here were significant.

Subjective Measures

Participant questionnaires included questions regarding how much control the participants felt they had over the aircraft, their perceived overall and spatial situational awareness, the usefulness of the map displays for avoiding wires, the usefulness of the map displays for reaching the target, the amount of mental demand imposed in each map condition, the adequacy of the map range, the time spent using the maps, how often information on the maps was used, an overall 2D map rating, an overall 3D map rating, and a personal rating of their overall performance in each condition. Some questionnaire items are not reviewed here. A copy of the questionnaire can be found in Appendix C. A complete list of the 10-point scale questions and their corresponding mean ratings (with significance among conditions noted where it existed) can be found in Table 1. A complete list of the open-ended questions along with a bulleted list of the participants' answers and comments can be found in Appendix D.

Results were significant for the amount of control the pilots felt they had over the aircraft, $F(2, 34)=3.541$, $p<.05$ (see Figure 11). The baseline received the lowest ratings. Ratings were higher for the plan view, and highest for the perspective view condition. However, only differences between the baseline and the perspective view conditions were significant. That is, the perspective view was rated significantly higher than the baseline condition, $t(17)=-2.754$,

Table 1

Questionnaire results

Question	Baseline	Plan View Map	Perspective View Map	Where significance lies
1. Spatial situation awareness	5.056	6.889	8.000	Between all conditions
2. Useful for avoiding hazards	4.111	6.941	8.222	Between all conditions
3. Color coding usefulness for avoiding hazards		8.222	8.667	No significant difference
4. Perceived control over aircraft	6.389	7.222	7.449	Between baseline and perspective
5. Mental demand	7.000	5.556	4.667	Between baseline and perspective and plan and

demand				and plan and perspective
6. Useful for reaching target site	4.611	6.778	7.833	Between all conditions
7. Overall situational awareness	4.333	7.833	8.500	Between baseline and perspective and between baseline and plan
8. Overall performance rating	5.889	6.167	7.944	Between baseline and perspective and plan and perspective
9. 2D map rating overall		6.722		Between plan and perspective (questions 9 and 10)
10. 3D map rating overall			7.944	Between plan and perspective

rating overall			perspective (questions 9 and 10)
11. Adequacy of map range	5.222	7.444	Between plan and perspective
12. Time spent using maps	3.389	4.444	Between plan and perspective
13. How often info on maps used	7.778	8.611	Between plan and perspective
14. Placement of displays	Instruments 6.611	Maps 6.471	No significant difference

Note. Shading indicates "best" score.
Numbers indicate mean ratings.

ANOVA Table for control of aircraft

	DF	Sum of Squares	Mean Square	F-Value	P-Value	Lambda	Power
Subject	17	142.315	8.371				
control of aircraft	2	11.148	5.574	3.541	.0401	7.082	.615
control of aircraft * Subject	34	53.519	1.574				

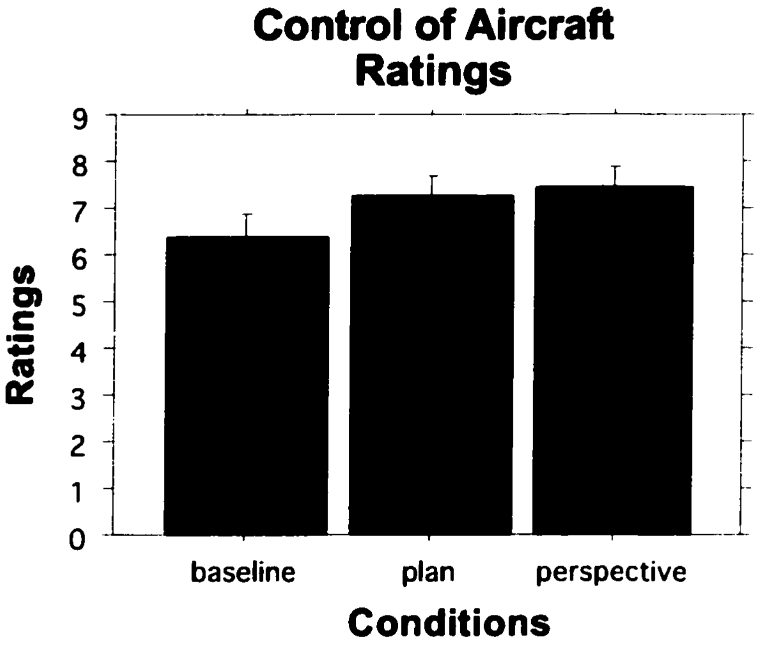

Figure 11. ANOVA table and bar plot of the amount of control pilots felt they had over the helicopter in each condition. Error bars depict standard error. Differences seen here were significant.

p=.0135, but the plan view condition was not rated significantly higher than the baseline, and the perspective view condition was not rated significantly higher than the plan view condition. Similar step-like patterns were seen with ratings of spatial and overall situational awareness. Results for spatial situational awareness were significant, *F*(2, 34)=23.707, *p*<.0001 (see Figure 12). In this case, the plan view map condition was rated significantly higher than the baseline condition, *t*(17)=-4.193, *p*=.0006, and the perspective view map condition was rated significantly higher than the plan view map condition, *t*(17)=-2.294, *p*=.0348. For overall situational awareness, significant differences were seen as well, *F*(2, 34)=40.876, *p*<.0001 (see Figure 13), however, these differences were with the baseline and plan view map conditions, *t*(17)=-6.436, *p*<.0001, and the baseline and perspective view map conditions, *t*(17)=-8.560, *p*<.0001.

A similar step-like pattern was seen for ratings of usefulness of the displays for avoiding wires. Differences among all conditions were significant, *F*(2, 32)=30.402, *p*<.0001 (see Figure 14). The plan view map condition was rated more useful than the baseline condition, *t*(17)=-4.791, *p*=.0002, and the perspective view map condition was rated higher than the plan view map condition in terms of usefulness, *t*(17)=-2.569, *p*=.0206. Ratings of usefulness of the display for reaching the target site also formed step-like patterns. Difference among all conditions were significant, *F*(2,34)=18.871, *p*<.0001 (see Figure 15). The plan view map was rated more useful than the baseline

ANOVA Table for spatial sa

	DF	Sum of Squares	Mean Square	F-Value	P-Value	Lambda	Power
Subject	17	53.648	3.156				
Spatial SA	2	79.593	39.796	23.707	<.0001	47.415	1.000
Spatial SA * Subject	34	57.074	1.679				

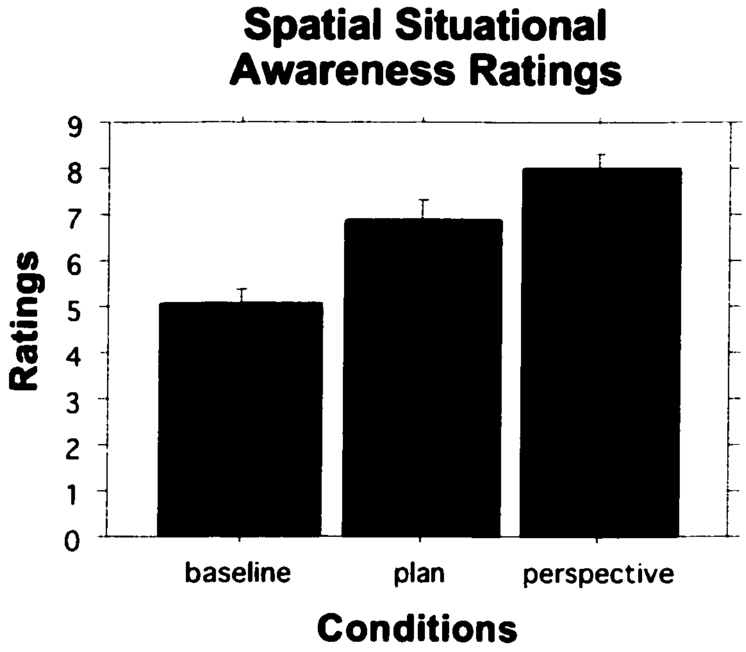

Figure 12. ANOVA table and bar plot of the amount of spatial situational awareness pilots felt they had in each condition. Error bars depict standard error. Differences seen here were significant.

ANOVA Table for Overall SA

	DF	Sum of Squares	Mean Square	F-Value	P-Value	Lambda	Power
Subject	17	98.000	5.765				
Overall SA	2	180.333	90.167	40.876	<.0001	81.751	1.000
Overall SA * Subject	34	75.000	2.206				

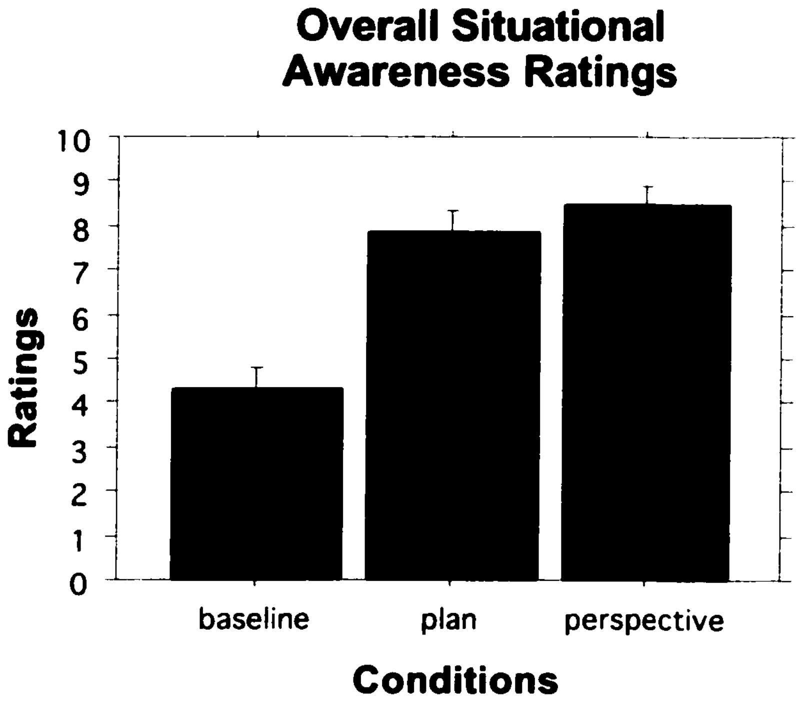

Figure 13. ANOVA table and bar plot of the amount of overall situational awareness pilots felt they had in each condition. Error bars depict standard error. Differences seen here were significant.

ANOVA Table for Useful avoidance

	DF	Sum of Squares	Mean Square	F-Value	P-Value	Lambda	Power
Subject	16	47.373	2.961				
Useful avoidance	2	158.118	79.059	30.402	<.0001	60.803	1.000
Useful avoidance * Subject	32	83.216	2.600				

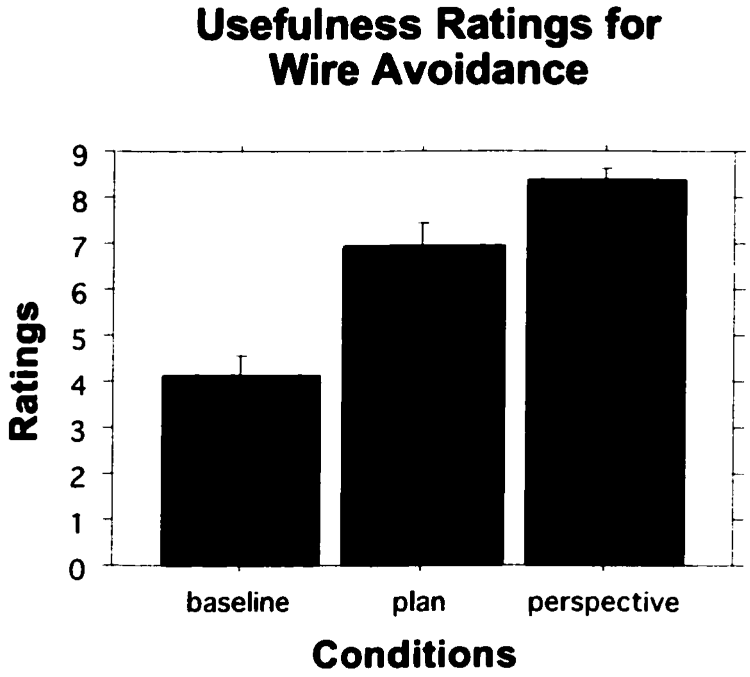

Figure 14. ANOVA table and bar plot of how useful pilots felt the displays were for helping them avoid wires in each condition. Error bars depict standard error. Differences seen here were significant.

ANOVA Table for useful for reaching target

	DF	Sum of Squares	Mean Square	F-Value	P-Value	Lambda	Power
Subject	17	106.370	6.257				
useful for reaching target	2	97.148	48.574	18.871	<.0001	37.741	1.000
useful for reaching target * Subject	34	87.519	2.574				

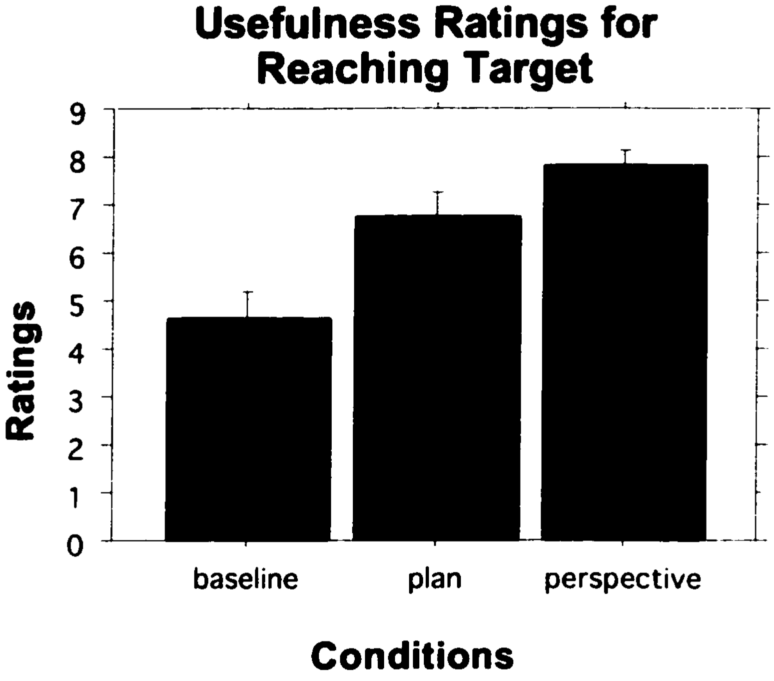

Figure 15. ANOVA table and bar plot of how useful pilots felt the displays were for helping them reach their target in each condition. Error bars depict standard error. Differences seen here were significant.

condition, *t*(17)=-3.293, *p*=.0043, and the perspective view map condition was rated higher than the plan view map condition, *t*(17)=-2.587, *p*=.0192. Another step-like trend was seen for the amount of mental demand pilots felt the conditions imposed upon them. There was once again a significant effect of map condition, *F*(2, 32)=5.436, *p*=.0093 (see Figure 16). However, this time, significance was seen between the plan and perspective view map conditions, *t*(17)=2.161, *p*=.0453, and between the baseline and perspective view map conditions, *t*(17)=2.687, *p*=.0162. Although participants gave the plan view condition slightly lower ratings than the baseline condition for mental demand, this difference was not significant.

Significant differences were also seen between the two map displays for ratings of the adequacy of the range of the maps, *F*(1, 17)=14.655, *p*=.0013 (see Figure 17), the amount of time pilots spent using the maps, *F*(1, 17)=7.263, *p*=.0153 (see Figure 18), and how often the information on the maps was used, *F*(1, 17)=5.000, *p*=.0390 (see Figure 19). A comparison of overall ratings for each of the maps also returned significant results. The perspective view map was given significantly higher ratings than the plan view map, *F*(1, 17)=6.614, *p*=.0198 (see Figure 20).

In terms of overall pilot performance ratings, a significant effect for map condition was once again seen, *F*(2, 34)=9.450, *p*=.0005 (see Figure 21). Pilots thought they performed significantly better in the perspective view map condition than they did in the plan view map condition, *t*(17)=-3.156, *p*=.0058,

ANOVA Table for mental demand

	DF	Sum of Squares	Mean Square	F-Value	P-Value	Lambda	Power
Subject	16	220.078	13.755				
mental demand	2	40.745	20.373	5.436	.0093	10.872	.818
mental demand * Subject	32	119.922	3.748				

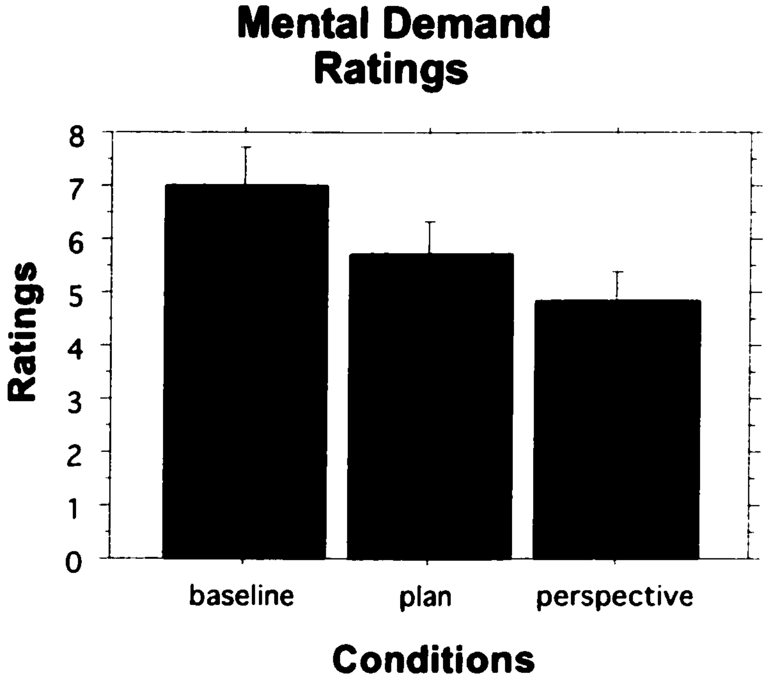

Figure 16. ANOVA table and bar plot of the amount of mental demand pilots felt the displays imposed in each condition. Error bars depict standard error. Differences seen here were significant.

ANOVA Table for range of map

	DF	Sum of Squares	Mean Square	F-Value	P-Value	Lambda	Power
Subject	17	146.000	8.588				
range of map	1	44.444	44.444	14.655	.0013	14.655	.963
range of map * Subject	17	51.556	3.033				

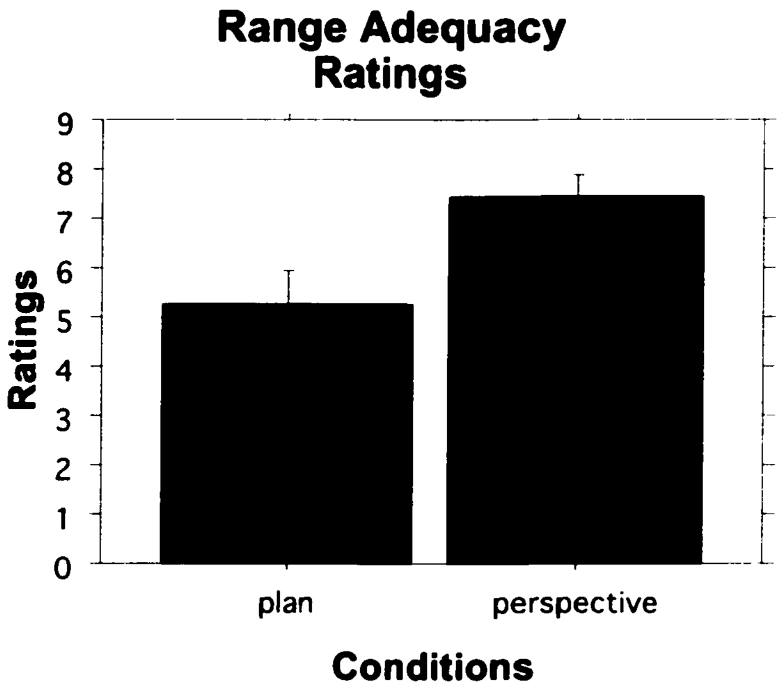

Figure 17. ANOVA table and bar plot of how adequate pilots felt the range of the map displays was in each condition. Error bars depict standard error. Differences seen here were significant.

ANOVA Table for time using map

	DF	Sum of Squares	Mean Square	F-Value	P-Value	Lambda	Power
Subject	17	69.250	4.074				
time using map	1	10.028	10.028	7.263	.0153	7.263	.724
time using map * Subject	17	23.472	1.381				

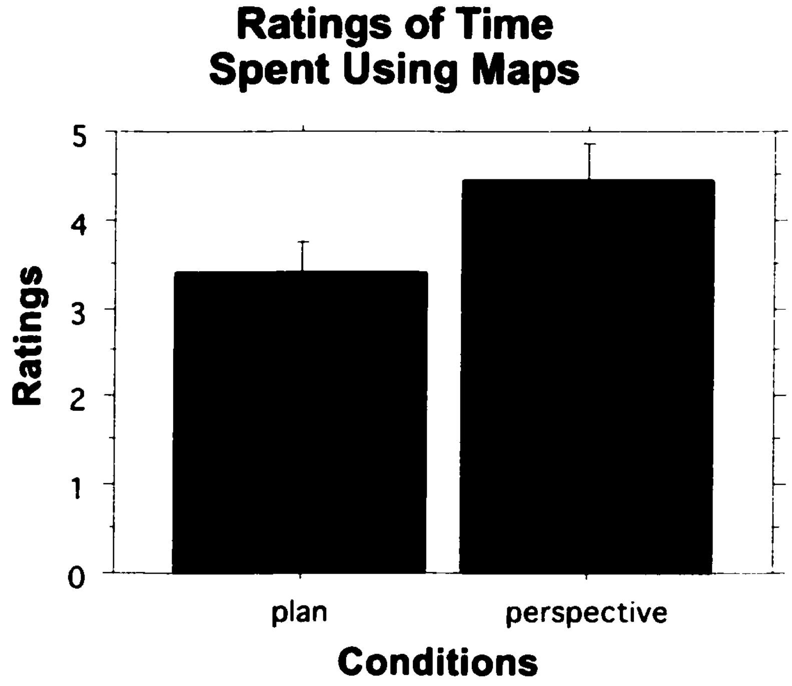

Figure 18. ANOVA table and bar plot of how much time pilots felt they spent using the map displays in each condition. Error bars depict standard error. Differences seen here were significant.

ANOVA Table for use for hazard avoidance

	DF	Sum of Squares	Mean Square	F-Value	P-Value	Lambda	Power
Subject	17	118.139	6.949				
use for hazard avoidance	1	6.250	6.250	5.000	.0390	5.000	.552
use for hazard avoidance * Subject	17	21.250	1.250				

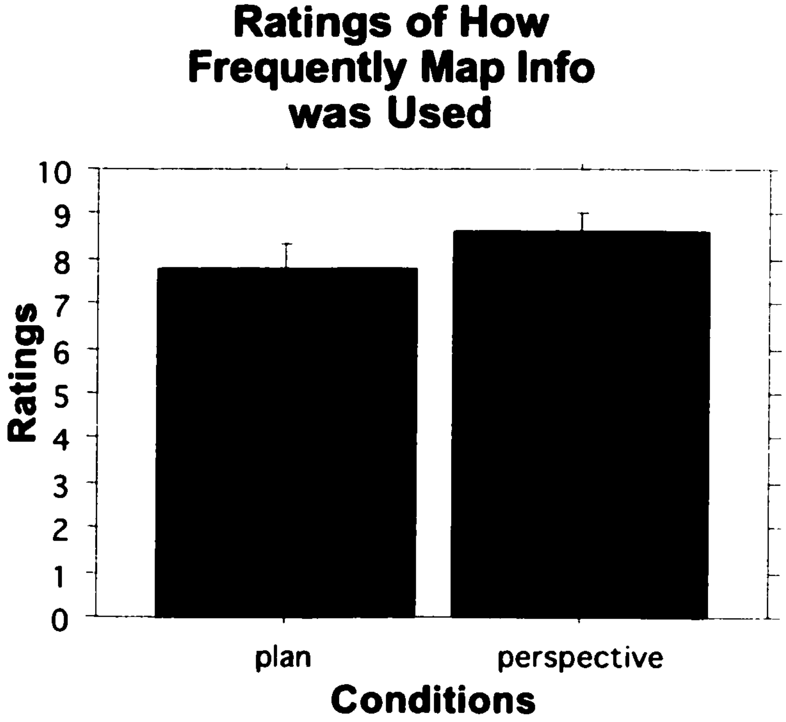

Figure 19. ANOVA table and bar plot of how frequently pilots felt they used the information on the map displays in each condition. Error bars depict standard error. Differences seen here were significant.

ANOVA Table for map overall

	DF	Sum of Squares	Mean Square	F-Value	P-Value	Lambda	Power
Subject	17	48.000	2.824				
map type	1	13.444	13.444	6.614	.0198	6.614	.681
map type * Subject	17	34.556	2.033				

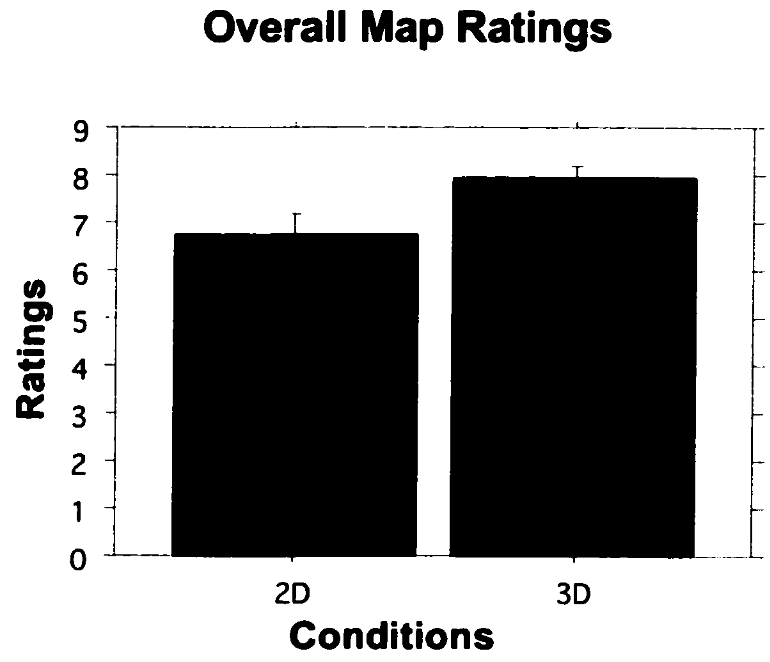

Figure 20. ANOVA table and bar plot of the overall ratings pilots gave each of the maps. Error bars depict standard error. Differences seen here were significant.

ANOVA Table for performance rating

	DF	Sum of Squares	Mean Square	F-Value	P-Value	Lambda	Power
Subject	17	194.667	11.451				
performance rating	2	44.778	22.389	9.450	.0005	18.899	.978
performance rating * Subject	34	80.556	2.369				

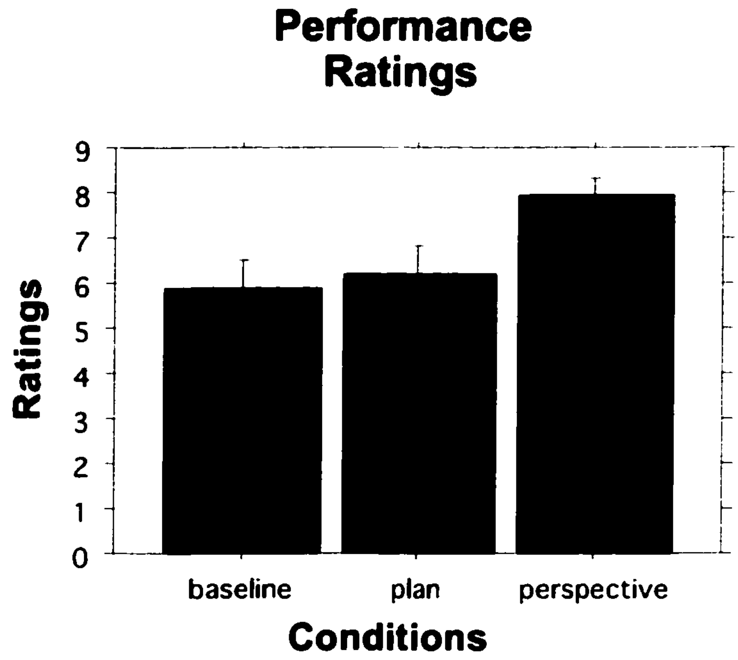

Figure 21. ANOVA table and bar plot of how well pilots felt they performed in each condition. Error bars depict standard error. Differences seen here were significant.

and better in the perspective view map condition than in the baseline condition, *t*(17)=-3.730, *p*=.0017. However, they did not think they performed any better in the plan view condition than they did in the baseline condition, which was consistent with the performance data seen in the study.

Discussion

Map conditions affected flight performance relative to wire strike avoidance in some significant ways. Participants maintained the highest degree of vertical separation in the perspective view map condition. They maintained their most consistent altitude in this condition as well. Perhaps it is not surprising, then, that this was also the only condition where no wires were hit by any of the participants. Participants flew closer to the wires in the baseline and plan view conditions. However, in each of these conditions, they were not as consistent at maintaining their altitudes as they were in the perspective view condition. These patterns replicated those found in McCann and Jones (2001), reaching significance in the present study.

Again, it is interesting that the pilots in the plan view condition would fly at lower relative altitudes (which in this study resulted in the greatest number of wires hit in any condition). Highlighted wire hazards appeared on the plan view map to warn pilots of their proximity to the wires, and pilots indicated on the questionnaires that they used the plan view map. In addition, appropriate altitude information that was lacking from the plan view map in McCann and Jones (2001) was incorporated here. It was the lack of this altitude information that was hypothesized to have been responsible for the flight trend that placed the pilots at a lower altitude, closer to the wires (relative to the perspective view condition). However, no improvement was seen. The combination of these trends into probability data clearly showed pilots were less likely to hit wires in the perspective view map condition than they were in the plan view or baseline conditions. It appears that providing the pilots with an equivalent amount of information (concerning their altitude relative to the wires) in the map conditions is not enough to equate performance between these two map conditions. It seems as though the form in which the information is presented is critical.

Precisely what role information format may have played and why the relative altitude indicator presented in this study failed to boost performance in the plan view condition is a topic that requires further examination. Not only did the indicator fail to boost performance to statistically significant levels, but participants flew slightly lower over the hazards on average, and struck almost twice as many wires in the plan view condition than they did in the baseline condition. This number was not large enough to result in the plan view being deemed significantly worse than the baseline condition, but the trend is definitely something that should be taken into consideration for the design of future plan view map displays. One hypothesis for why the digital information may not have helped pilots in the plan view map condition was because of the abstract (non-spatial) form of the information. Boles and Wickens (1987) argued that people find it more difficult to integrate both spatial and numeric information than to integrate more than one source of spatial information, and therefore, particularly if speed is important, a "pure" format (specifically an analog display) should be considered for an integration task. Therefore, a coplanar 2D display with some sort of graphical profile view, similar to ones employed in various other studies, might have been a better way to provide this information to the pilots.

Another hypothesis regarding information format is that perhaps the benefits of the perspective display seen here were not solely the result of the form of the relative altitude indicator, but of differences between the form of the 3D map and 2D map in general. Perhaps there was something about the form of the 3D map in general that made it better suited for this task. For example, these results could have been seen because of the ecological benefits of the 3D display. With the perspective view comes a greater natural view and compatibility with the world as the pilot experiences it from the helicopter. The pilots do not have to mentally convert what they see on the map to what they see out the window. In addition, this makes feedback to the pilots concerning flight control and their inputs more immediate. Pilots do not have to spend any additional effort thinking about or interpreting the visual consequences to their actions. For example, with the perspective view map, pilots would not have to interpret where they were or resort to a scan of several instruments after a change in altitude to determine precisely their new position relative to obstacles (as would be the case with the plan view map). (See Andre et al., 1991, for a further example of research into ecological benefits.)

Also relating to display form, and in accordance with the proximity compatibility principle (Wickens, 1992), it could be that wire avoidance is an integrated task that requires an integrated display for successful completion. For example, avoiding wires requires that the pilots have a clear picture of what their aircraft is doing and where it is located in all dimensions, particularly in relation to wire hazards, as they fly through an airspace. If they have a single mental image of the airspace (and its vertical, horizontal and depth components), they would be put at a disadvantage to have to piece together each one of these dimensions from a separate display. In addition, certain aspects of flight control relevant to wire avoidance, such as initiating a gain in altitude to maneuver up and over a hazard, would be better represented as a single display than multiple displays that required the pilot to combine separate pieces of distance and relative altitude information into one helpful unit to avoid the wire. (See Andre et al., 1991, for a further example of research into integrated or combined control inputs.)

Furthermore, studies report that pilots tend to make more vertical maneuvers with 3D displays, and possess better control of the vertical axis. This could be another reason these results, showing benefits for the 3D display, were seen in this study. If this flight-maneuvering tendency was seen in our study, it might have provided pilots in the 3D condition with an extra advantage when completing the tasks of wire avoidance required in our study.

These are not the only factors that could have produced the benefits for wire avoidance seen with the perspective view map in this experiment. In addition, although the relative altitude indicator was on the map and located very near the wire hazard that participants would be scanning for, perhaps its addition added a nontrivial amount to their visual scan. In the plan view condition, pilots would have then found it necessary to scan, at the minimum, four separate places for the information they needed to complete the task. First, the out-the-window view needed to be scanned for cars. Second, the instrument panel needed to be scanned so the pilot could assure he was maintaining a rough 200 feet above ground altitude, as recommended in the instructions. Third, the map needed to be scanned for wire hazards, and fourth, the relative altitude indicator needed to be scanned for hazard-helicopter separation information.

In contrast, the perspective display may have reduced the scan requirements to two separate locations. First, the out-the-window view needed to be scanned for cars, and second, the map needed to be scanned for hazards, hazard-helicopter vertical and longitudinal separation information, and to get a rough idea of the altitude being flown above ground. (It could be argued that an additional scan of the instruments would be needed here in order to obtain a precise value, but the instructions did not command that the pilots stay at exactly 200 feet, and it is believed that after an initial check of the instruments for what 200 feet looks like on the map, pilots could simply scan the map for this altitude information.) In other words, it is possible that the pilots could safely do more of their flying (and all of the checks and scans that it entails) with the perspective view map than they could with the plan view map. With the plan view map, pilots had so many additional places to scan for information that they may not have been able to do any of their flying using the map alone. In addition this separate indicator could have lead to additional mental processing, at least compared to what had to be done with the perspective view format. This scanning and processing could have added valuable time to the initiation of a response. Minutes or seconds added to the time pilots need to operate the cockpit controls necessary to maneuver the helicopter out of the way of a hazard might make the difference between clearing the hazard and colliding with the hazard.

Another hypothesis relating to general display form is that the preview of what was ahead was more extensive on the 3D map than it was on the 2D map. This was not an objective measure, but rather a subjective observation made by comparing the look ahead available in each map condition for each wire hazard in the database at the moment the wire appeared on the screen (see Figure 22). This was a benefit of 3D map formats that was not discussed a great deal in the literature. In fact, the better global awareness that can be achieved with the 2D map might lead one to assume that, if anything, preview

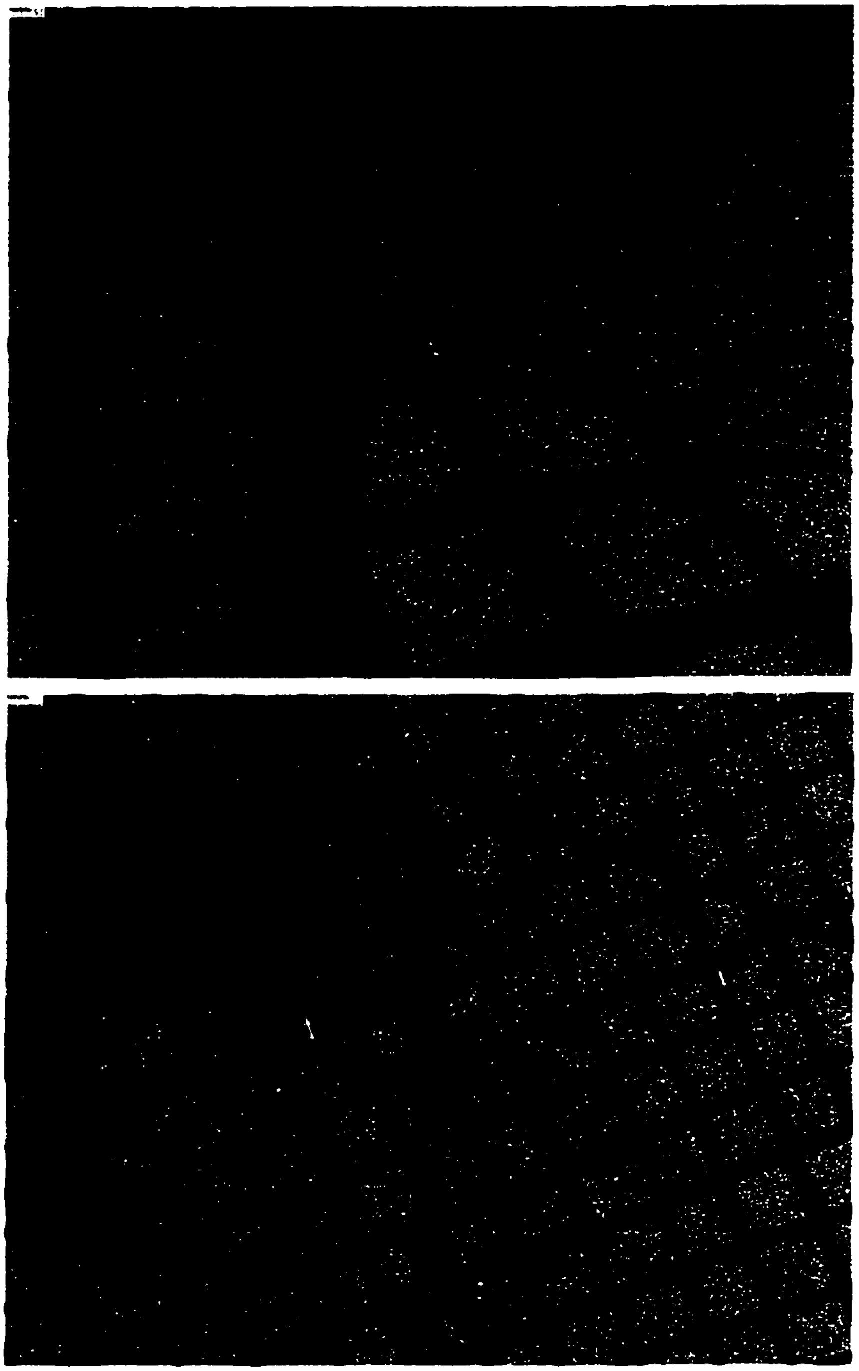

Figure 22. An example of the differences in preview pilots had using the 3D (top) and 2D (bottom) maps. Both snapshots were taken at approximately the same distance and altitude from the wire. With some wire hazards, pilots clearly had more advanced warning with the 3D map than with the 2D map.

might be greater with this display. However, for the displays in our study, this was not the case. There was a greater preview provided by the forward perspective of the 3D display than by the global perspective of the 2D display. This is despite the fact that preview on the 2D display was maximized to the fullest extent possible by the lower placement of the ownship icon on the screen, as previously described in the discussion of the design of the 2D layout. Having this additional preview meant that pilots with the 3D display would have a bit of advanced warning of pending wire hazards. This could allow them more time to plan an ideal avoidance maneuver and respond to the hazard threat. This explanation becomes particularly attractive when coupled with the previously discussed hypothesis regarding greater scanning and processing time with the 2D display. If the 2D display had less preview than the 3D display, leading to less time to prepare for an avoidance maneuver, yet at the same time required more time to visually scan and process information, then it could only be expected that this display would result in less successful hazard avoidance than the 3D display.

However, there is an important exception to this preview finding. In situations where hazards were hidden in the distance by hills, the greater preview or look-ahead capabilities that the 3D view provided may not have been useful for advanced detection of hazards. It is difficult to determine post-experiment which hazards could not have been detected with advanced preview. Seven of the 21 hazards encountered appeared to be located in a hilly area. However, the combination of exact height flown, and the pilot's position over the road (that is, whether the pilot flew left, right, or directly centered over the road) could have made a great difference in determining whether a particular pilot could have obtained a glimpse of any particular hazard located in hilly terrain. Researcher observations noted a greater advantage of preview with the 3D map, and few instances of trouble with hills. However, these observations were made subjectively, and unfortunately, no data were recorded to support these observations.

Each of these factors could have worked on their own, or worked in combination with any number of the other factors to give the 3D display an advantage over the 2D display that lead to the results seen in this study. Determining which of these factors played a role in these experiments is an area for future research.

There are two somewhat opposing theories that may encompass all of the hypotheses that could explain the outcomes in this study. The first theory is that the pilot is unable to extract the appropriate information from the 2D map, which in turn leads to the type of performance decrement relative to the 3D display seen in this experiment. The hypotheses or factors that this theory encompasses include (a) pilot's inability (with the 2D display in this study) to easily integrate both spatial and numeric information, (b) the lack of ecological benefits with the 2D display, (c) the absence of vertical maneuvers and lack of control of the vertical axis with the 2D display, relative to the 3D display, and (d) the 2D map's lack of adherence to the proximity compatibility principle regarding the task at hand. Each of these factors could make it difficult or impossible to extract the pertinent information from the 2D map before a wire strike is imminent.

For example, if pilots have a difficult time integrating both spatial and numeric information, some of this information may not be sufficiently extracted from the display. This could lead to wire strikes, resulting in the type of performance decrement seen with the 2D display (relative to the 3D display) in this experiment.

Likewise, with ecological benefits reduced or absent in the 2D display, pilots may have had difficulty mentally converting what they saw on the map to what they saw out the window. They could have had some difficulty interpreting the visual consequences of their actions. They also could have come to the wrong interpretation or spent too long considering the interpretation, and therefore could have failed to extract the critical information from the display before wires were struck.

Similarly, if the proximity compatibility principle was not adhered to with the 2D map, pilots may have had to do more work mentally to piece together a picture of what their aircraft was doing and where it was located in all dimensions. This additional mental effort may have kept them from extracting the information necessary to avoid a wire before it was too late.

Finally, although it cannot be said with absolute certainty, it seems likely that a pilot's lack of control over the vertical dimension with a 2D map would result from an inability to extract pertinent information from the map. If pilots are unable to extract the critical information allowing them to maneuver around wire hazards with the 2D map, it is much more likely wires will be hit in this condition.

The second theory is that the pilot in some way or for some reason misses the information displayed on the 2D map, which in turn leads to the type of performance decrement relative to the 3D display seen in this experiment. With this theory, it is believed that pilots have the ability to *extract* the information from the 2D map, but for some reason, *miss* the information that is there. The hypotheses or factors that this theory encompasses include (a) the greater amount of visual scanning required on the 2D map with the addition of the relative altitude indicator, leading to an additional amount of mental processing relative to the 3D display; and (b) the smaller range of the 2D map compared to the 3D display, leading to a reduced amount of preview for the pilot. Both of these factors could lead the pilot to miss information on the 2D map, putting them at risk for a wire strike.

For example, if the relative altitude indicator added a significant amount to the pilots' visual scan in the 2D map condition, important hazard information on the map could be missed solely due to the amount of time that must now be spent scanning elsewhere. However, if the increased visual scan had the effect of adding to the amount of information that had to be mentally processed, then the problem is better categorized by the theory that the pilot is unable to extract the necessary information from the map. Additional mental processing, like what is seen if the proximity compatibility principle is not adhered to, may keep pilots from extracting the information necessary to avoid a wire before it is too late. Which theory this factor of increased visual scan best fits with depends on the underlying process at work.

Similarly, the smaller amount of preview of what was ahead of the pilot with the 2D map could have lead to missed information. Because the 2D map does not have the same look-ahead capabilities (i.e., there is not the same ability to "see off into the distance" with the 2D map) as the 3D map, a longer period of time will pass before hazards come into view on the 2D map. Therefore, overall, hazards on the 2D map will be displayed for a shorter period of time than hazards on the 3D map because of the 2D map's reduced preview. Hazards displayed for a shorter period of time will be more likely to be missed, especially in the multitasking environment of low-level helicopter flight where many other things demand the pilot's attention.

Not enough information can be gleaned from the data collected in this study to be able to determine with absolute certainty which one of these theories was the cause of the results seen. However, participant comments suggest that the latter theory is almost certainly responsible. Specifically, the preview hypothesis was noted as a concern earlier in the discussion, and was commented on frequently in the participant questionnaires. Participants rated the range as being significantly less adequate for the 2D map than it was for the 3D map. It was also a factor commented on frequently in the open-ended question section. When participants were asked what they did not like about the 2D map, 11 of the 14 comments focused on the inadequate preview of this map type. When they were asked what features they would like to see added to the maps that would help them in avoiding wire hazards, nearly half of the comments (7 of 15) focused on more adequate range for this map type. Comparatively, only 2 of the 17 comments made regarding this question for the 3D map focused on adding selectable scale functions. Four of 15 comments praised the range on the 3D map when participants were asked what they liked about this map type. Participants clearly felt they had a harder time avoiding hazards with the 2D map than they did with the 3D map because of the 2D map's inadequate preview.

An additional contributing factor that is suspected, but cannot be verified, concerns the speed the participants flew and the resultant degree of effectiveness of the color-coding logic. The color-coding logic was programmed to provide pilots with a warning sufficient enough to allow them to respond to a hazard threat. Pilots were additionally instructed to try to fly the helicopter simulator under 140 knots (out of the "red" range on the simulated airspeed indicator), and were told that it was preferable to fly under 115 knots (in the "green" range on the airspeed indicator). They were told that flying in the “red” range over 140 knots made the simulator unstable and increased their risk of crashing the math model running the simulation. It was additionally pointed out that an artifact of the simulator was that the helicopter would seem very sluggish and slow to respond compared to an actual helicopter. Participants were told that visual cues may lead them to believe they were flying slower than they were, and that it was therefore easy to end up flying faster than intended. Despite these warnings, it was believed that many participants flew through the routes at a faster speed than intended. Task instructions were to fly to the scene of the accident as quickly as possible, and when this instruction was combined with sluggish visual cues, a faster than intended actual speed may have been inevitable. Additionally (and understandably), there is evidence from a few of the participant comments that some participants may have believed that their performance was being rated on speed as well. In addition, two comments on the participant questionnaire indicated the color-changing logic on the alerting system might be a bit too abrupt. If pilots were flying faster than anticipated, this may have been the case. If so, the problem would be exaggerated with the 2D display, where a smaller amount of preview was already a potential problem for pilots. These combined factors (reduced preview and faster than anticipated travel speed) could have lead to the performance decrement seen with the 2D map relative to the 3D map in this study. Unfortunately, speed data was not collected in this experiment, and at this point there is no way of knowing with certainty if pilots approached the hazards at a rate of closure that would allow them enough time to properly maneuver and take evasive action. This is an unfortunate artifact of the simulation that would not be expected to transfer to an actual helicopter.

It is interesting to note that the trouble participants in other studies seemed to have had with determining the precise position of objects or overestimating the target elevation with the 3D display was not seen with the display of wire hazards in our study. It is hypothesized that this is because, as discussed, pilots used 3D map information to fly reliably higher over hazards in this condition. If their task involved making more precise maneuvers around these hazards, these perceptual difficulties may have emerged.

In terms of subjective ratings gathered from the questionnaires, participants in this study seemed to rate the displays in a way that somewhat more accurately reflected their performance than participants in McCann and Jones (2001). Although participants in this study showed some of the same general trends of rating the 2D condition superior to the baseline condition despite the fact that the performance data showed that this was not the case, there was usually a step-like pattern seen with those ratings. Differences were seen between all conditions for ratings of usefulness of the displays for avoiding wires, for usefulness of the displays for reaching the target, and for the amount of spatial situational awareness the pilots felt they had in each condition.

For ratings of overall situational awareness, the 2D and 3D conditions were both rated as superior to the baseline condition. Although ratings were higher for the perspective view map condition than they were for the plan view map condition, the difference was not significant. These ratings seem to contradict the performance data by citing differences between the baseline and plan view conditions where they do not exist. Pilots seem to be saying that having a plan view map for this task is better than having no map at all. Indeed, it may be the case that any map will provide the pilot with a better sense of global awareness (which makes the finding seem much less contradictory), and in that sense will be considered more useful for avoiding wires, but caution should be taken if using this information for map design. Pilots may believe the map to be more useful, but the performance data shows a detrimental trend to using the plan view map, and statistically, it is clearly no better than having no map at all for wire avoidance. However, for overall performance, the amount of control pilots felt they had, and the amount of mental demand they felt each condition required, superior performance ratings were given to the perspective view map display. Meanwhile the baseline and plan view map display were given nearly equivalent ratings for these questionnaire items. Overall, pilots in this study seemed to have a better sense of how they performed with each map display than did pilots in the previous study. Their ratings generally seemed to match the performance data more closely.

Other significant differences were seen between the two map conditions for ratings of how adequate the range of the maps was, ratings of the amount of time spent using the maps, and ratings on the use of the map information. These significant differences indicate that pilots generally found the 2D map inadequate in terms of the range of the display, compared to the 3D map. Comments made in response to the open-ended questions supported these ratings, as was previously discussed (see page 100 for the discussion, and Appendix D for a full list of participant comments).

Additionally, participants reported using the 3D map in general more than the 2D map, and they stated that they used the information on the 3D map more than information on the 2D map. How (or if) these factors are related can be speculated upon; however, without further information from the pilots, the true relationship may never be known with certainty. For example, it could be that pilots reacted negatively to the inadequate range of the 2D map, or found the map ineffective, and for that reason stopped using the map, which in turn led the pilots to report using the *information* on the 2D map less than information on the 3D map. However, it could also be that the inadequate range of the 2D map lead pilots to miss information on this map because it would be displayed for a shorter time. Then, because the information was going unused, pilots might have stopped using the 2D map as much as the 3D map. So, it is not clear whether unused or missed information caused pilots to use the 2D map less, or whether using the 2D map less led the pilots to not use or to miss the information displayed on the map. It is also not known with certainty if the shortened range of the 2D map was a factor leading participants to not use the map or to miss information on the map.

Overall, all of the ratings the pilots provided seemed to match the performance data fairly closely. However, the one item for which this was not the case was a question concerning the participants' perceived flight patterns. Participants were asked if they felt they flew differently in the baseline (no map) condition compared to the other two map conditions. Of the comments participants provided, 10 of 17 stated that the participant flew at a higher altitude in the baseline condition than in either of the other two map conditions. This contradicts the performance data, which shows that the pilots in the baseline condition flew, on average, lower over the hazards than in the perspective view map condition. However, the key to making sense of this seemingly contradictory information might be noting that the performance data shows them flying lower *over hazards*. At this time, it is unknown how participants' flight patterns looked over the routes as a whole in each condition. It could be the case that participants flew higher overall in the baseline conditions, but dropped down over hazards, perhaps to get a better view of potential accidents near the hazards. Perhaps they flew lower in the perspective view map condition overall, but with the aid of the map, were able to maintain a greater degree of vertical separation over the hazards in that condition. It would be extremely useful to extract and examine this data in the future, to determine more specifically what the pilots' flight patterns were. In this way, a confident statement could be made about why the perspective view map led to better flight performance in terms of wire avoidance.

Areas for future research

As mentioned, determining what led to poorer performance with the 2D display as compared with the 3D display is an important area for future research. Many helicopters have already incorporated 2D maps into their cockpits, and adding wire hazard symbology similar to the kind just discussed would be an easy implementation. 3D displays, in comparison, would be more costly to integrate, but would certainly be well worth the cost in terms of lives saved and helicopters kept from destruction if the 3D display does indeed improve performance. Clearly, however, if performance can be boosted with the 2D map by means other than what has already been attempted in these studies, it would be the most cost effective and timely means of getting this information to the pilot, since 2D maps already exist in cockpits in many cases.

Other related research may include experimentation with flashing cues or auditory warnings to initially alert pilots to look at the map for hazard information. Flying a helicopter is still a very "eyes out" task, meaning that pilots must spend a great deal of time looking outside the cockpit at the surrounding environment to accomplish their tasks safely. Moving maps have been shown to help pilots accomplish their tasks safely. However, they do take away from the time allotted to scanning the outside environment. While some studies have looked to head up displays (HUDs) as a solution to this problem, it is not the ideal solution where cost and quick implementation are important factors. Therefore, visual cues or auditory alerts may be quick and inexpensive additions that prove beneficial to pilot performance and safety.

Additional research could be conducted based on the results of this study. The study could be replicated with an analog indicator or some type of coplanar display that could replace the digital relative altitude indicator. With this change, it could be determined whether the form of the indicator was responsible for the performance outcomes seen with the 2D map in this study. The study could also be replicated using an eyetracker to determine the pilots' visual attention strategy. In this way, one could quantitatively establish whether pilots are actually attending to the 3D display more than the 2D display. Also, an examination of the visual attention paid to the 2D display, including a look at the relative altitude indicator dwell times, could provide insight to whether this display indicator is adding more information than can easily be processed to the pilot's visual scan. Finally, the study could be replicated with a greater range or degree of scale on the 2D map, or perhaps even adjustable ranges on both maps. A greater range on the 2D map could help with the problem of too little preview. Results from this type of study could help determine whether greater preview contributed to the performance benefits seen with the 3D display in the current study.

Conclusion

Results of this study indicated that there were clear benefits for wire hazard avoidance with the 3D map, relative to the 2D map and baseline (no map) conditions. The addition of relative altitude information to the 2D map did not result in the anticipated boost in performance. Several hypotheses were presented above that could potentially explain these results. The improvement in wire avoidance found with the 3D map could have been the result of either the spatially integrated form of the relative altitude information in the 3D display, or the general 3D aspect of the display itself. With regard to the form of the relative altitude display, spatially integrating the relative altitude information, as in the 3D display, may have helped improve wire avoidance in ways digitally presenting the same information did not. It was found that presenting the relative altitude information in a digital form, as in the 2D display, did not benefit pilots. It has been noted (Boles & Wickens, 1987) that people find it more difficult to integrate both spatial and numeric information (which was the situation that was created with the addition of the digital relative altitude information to the 2D map) than to integrate one source of spatial information (which was the situation with the 3D map). With regard to the general 3D aspect of the display itself, it could have been that the ecological benefits of naturalness and greater compatibility with the world removed the need to mentally rotate what was seen for pilots with the 3D display, and lessened the need for interpretation, which may have led to better performance. In addition, in following with the proximity compatibility principle, the integrated nature of the display was another factor thought to have improved pilot performance with the 3D display, because it matched the integrated nature of the wire avoidance task. It also could have been that the improved control over the vertical axis that pilots seem to have with this type of display would have helped them maneuver over wires, and could have been an additional reason a performance benefit was seen with the 3D display format. Another factor considered was that the addition of digital information to the 2D display may have added to the pilot's visual scan in a way that hindered performance relative to the 3D display. Finally, it was thought that preview may have been greater with the 3D display, providing benefits to the pilots by allowing them greater look ahead and planning time. Any one or any combination of these factors could have lead to the performance benefits seen with the 3D display in this study.

It was further noted that all of these factors can be categorized into one of two theories. The first theory is that the pilot is unable to extract the appropriate information from the 2D map, which in turn leads to the type of performance decrement seen in this experiment. The factors that this theory encompasses include (a) pilot's inability (with the 2D display in this study) to easily integrate both spatial and numeric information; (b) the lack of ecological benefits with the 2D display; (c) the absence of vertical maneuvers and lack of control of the vertical axis with the 2D display, relative to the 3D display; and (d) the 2D map's lack of adherence to the proximity compatibility principle regarding the task at hand.

The second theory is that the pilot in some way or for some reason misses the information displayed on the 2D map, which in turn leads to the type of performance decrement seen in this experiment. With this theory, it is believed that pilots have the ability to *extract* the information from the 2D map, but for some reason *miss* the information that is there. The factors that this theory encompasses include (a) the greater amount visual scanning required on the 2D with the addition of the relative altitude indicator, leading to an additional amount of mental processing relative to the 3D display; and (b) the smaller range of the 2D map, leading to a reduced amount of preview for the pilot compared to the 3D display. Though both theories are quite plausible, it is the latter theory, and specifically, the lack of preview seen with the 2D map, in combination with a faster-than-anticipated forward speed (resulting in less warning time with the color-coding logic) that was thought to be the most likely explanation for the performance decrement seen with the 2D map (relative to the 3D map) in this experiment.

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Appendix A. Signed Approval Forms

San José State
UNIVERSITY

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To: Karen Jones
NASA Ames Research Center
MS 262-2
Moffett Field, CA 94035

From: Nabil Ibrahim,
AVP, Graduate Studies & Research

Date: May 1, 2001

The Human Subjects-Institutional Review Board has approved your request to use human subjects in the study entitled:

"Moving Map Technology in a Wire Hazard Environment."

This approval is contingent upon the subjects participating in your research project being appropriately protected from risk. This includes the protection of the anonymity of the subjects' identity when they participate in your research project, and with regard to any and all data that may be collected from the subjects. The approval includes continued monitoring of your research by the Board to assure that the subjects are being adequately and properly protected from such risks. If at any time a subject becomes injured or complains of injury, you must notify Nabil Ibrahim, Ph.D., immediately. Injury includes but is not limited to bodily harm, psychological trauma and release of potentially damaging personal information. This approval is in effect for one-year and data collection beyond April 30, 2002 requires an extension request.

Please also be advised that all subjects need to be fully informed and aware that their participation in your research project is voluntary, and that he or she may withdraw from the project at any time. Further, a subject's participation, refusal to participate, or withdrawal will not affect any services the subject is receiving or will receive at the institution in which the research is being conducted.

If you have any questions, please contact me at
(408) 924-2480.

The California State University:
Chancellor's Office
Bakersfield, Chico, Dominguez Hills,
Fresno, Fullerton, Hayward, Humboldt,
Long Beach, Los Angeles, Maritime Academy,
Monterey Bay, Northridge, Pomona,
Sacramento, San Bernardino, San Diego,
San Francisco, San Jose, San Luis Obispo,
San Marcos, Sonoma, Stanislaus

Appendix B. Instructions to Pilots

Instructions to Pilots

About the Study

This study takes place in the Rotorcraft Part Task Lab (RPTL). You will have a series of three missions to complete, in which you are acting as an EMS helicopter pilot looking for an accident scene.

About the simulator

The RPTL helicopter is operated via controls adjoining the seat in the cab. The collective is on the pilots' left hand side, and the cyclic is on their right hand side.

Monitors will display information to the pilot in the simulator. The uppermost monitor displays the outside world. The lower monitor on the right hand side of the cab displays an electronic moving map, on the missions where that feature is available to you. The lower monitor on the left side of the cab displays the helicopter's instruments.

The experimenter will communicate with you through a headset, throughout the experiment.

Pilot Goals/Setup

We ask you to perform a mix of experimental and practice sequences. The first will be a practice effort in which you will be allowed to fly around freely, in order to become familiar with the handling qualities of the simulated helicopter. During this practice flight, we would like you to fly the vehicle as long as you like, until you are comfortable with your ability to control the vehicle. Please feel free to practice as many maneuvers as you like.

We will then ask you to perform 3 missions. Each mission will be preceded by a practice trial that will allow you to acquaint yourself with the technology available for that mission.

In each mission, you are to act as an EMS pilot who is searching for an automobile accident site. The search area is in the vicinity of the Hunter-Liggett military reservation, in the Big Sur region of coastal California. At the beginning of each mission, we will start you out by pointing your aircraft in the direction of one particular road. You should then follow that road while constantly scanning for the traffic accident. You may occasionally be given verbal instructions concerning flight direction when forks in the road are encountered. To identify the accident site, you should look for a cluster of cars that are at odd angles in the road, and are in physical contact with one another. The accident will always be located at some point along the road you are tracking. Please fly in a manner consistent with your ability to identify the accident scene as quickly as you can, as if you are aware of a severely injured automobile passenger who needs to be evacuated as quickly as possible. Thus, the goal is to report to base that the accident scene has been located. At that point, the mission will end. Thus, you should fly the route as quickly, and at as low an altitude, as possible. We would like you to remain below 200 ft., except if necessary to avoid hazards. In addition, although timeliness is important, it is critical that you keep the helicopter at a speed that is within the limits of this particular aircraft design, as indicated by the instrument gauges. Flying too far outside of these limits can cause problems with the simulation.

Of course, you are not going to be of any use to the injured passenger if you don't arrive safely at the accident scene. As with any low-level flight environment, you should be on the alert for wire hazards. On one of your missions, the only way to detect wires will be to see them in the out-the-window view on the upper monitor. When encountering wires, you should of course safely fly up and over them. If you do not clear the hazard and come into contact with the wires, you will see a flashing message in the out the world scene that says "WIRE STRIKE." On the remaining two missions, you will be provided with one of two moving map displays whose purpose is to help you detect and avoid these hazards. We will now describe these moving maps in more detail.

<u>Plan view</u>: On one of your missions, you will be provided with a 2D plan view map. Consistent with most of the moving maps on the market today, this provides a "track-up" view of the environment directly around your helicopter from a "Gods-eye" perspective (i.e., directly above your aircraft). The map will include a color depiction of all the wires that physically cross the road you are following, and therefore could impinge on your flight path. Importantly, the color of the depiction will change, depending on your relative position with respect to the hazard. If you are sufficiently far away from the hazard, or if you are at a safe altitude above it, the wire will appear green. If you are starting to approach the wire at an altitude that could result in an impact, the wire depiction will switch to yellow (warning condition), and if you don't proceed to climb to a safer altitude, the hazard will eventually switch to red (imminent danger condition). Additionally, the plan view map will be equipped with a relative altitude indicator, which will be centered on the left edge of the display. This instrument

will display your altitude relative to the wires (above or below) seen on the plan view map, measured in feet.

Perspective view. In the "perspective condition," a 3D perspective view of the environment is provided on the moving map. That is, the eye-point of the map view will correspond to a location just above and to the right of your ownship position. The map view will not slew along with momentary changes in your pitch attitude, but it will follow changes in yaw. As with the plan view map, the perspective map will also depict all wire hazards that actually cross the road, and the same logic as far as coloring the hazards will apply.

Each of your 3 missions will be preceded by a brief "practice mission", designed to familiarize yourself with the moving map display (when one is provided), and the color coding of the hazards. There will be two hazards on each practice mission. We encourage you to vary your approach altitude when coming up on these practice hazards, in order to familiarize yourself with the color coding, and how (and when) the colors change.

When you have found the accident site, we ask that you identify it verbally to the experimenter, by saying that the scene has been located. The simulation will then end. At the end of the experiment, we will ask you to fill out a brief questionnaire about the study, the various technologies you were exposed to, and the strategies you used to carryout your missions.

Appendix C. Experimental Questionnaire

Post Experiment Questionnaire

Please rate each of the following items on a scale from 0 to 10. As a general guideline, **0** is **Not Acceptable**: The display in question, or feature of the display, is not acceptable even with extreme pilot compensation for display inadequacies.

5 is **Somewhat Acceptable**: the display is adequate with significant pilot compensation for display inadequacies.

10 is **Completely Acceptable**: the display does not require any pilot compensation for display inadequacies (fully equivalent or better than standard helicopter).

1. Please rate the SPATIAL SITUATION AWARENESS you felt you had over the course of the three missions (0 = little awareness, 10 = a great deal of awareness)

NO MAP MISSION
0 1 2 3 4 5 6 7 8 9 10

2D MAP MISSION
0 1 2 3 4 5 6 7 8 9 10

3D MAP MISSION
0 1 2 3 4 5 6 7 8 9 10

2. Please rate each of the display conditions in terms of usefulness for AVOIDING WIRE HAZARDS (0 = not at all useful, 10 = extremely useful):

OUT-THE-WINDOW VIEW with NO MOVING MAP

0 1 2 3 4 5 6 7 8 9 10

2D MAP

0 1 2 3 4 5 6 7 8 9 10

3D MAP

0 1 2 3 4 5 6 7 8 9 10

3. Please rate the hazard color coding scheme (GREEN,YELLOW,RED) in terms of usefulness for AVOIDING HAZARDS (0 = not at all useful, 10 = extremely useful):

2D MAP

0 1 2 3 4 5 6 7 8 9 10

3D MAP

0 1 2 3 4 5 6 7 8 9 10

4. Please rate the CONTROL you felt you had over the aircraft in each of the three missions (0 = poor control, 10 = excellent control)

NO MAP MISSION

0 1 2 3 4 5 6 7 8 9 10

2D MAP MISSION

0 1 2 3 4 5 6 7 8 9 10

3D MAP MISSION

0 1 2 3 4 5 6 7 8 9 10

5. Please rate the MENTAL DEMAND (EFFORT) associated with each of the three missions (0 = very little effort, 10 = a great deal of effort):

NO MAP MISSION

0 1 2 3 4 5 6 7 8 9 10

2D MAP MISSION

0 1 2 3 4 5 6 7 8 9 10

3D MAP MISSION

0 1 2 3 4 5 6 7 8 9 10

6. Please rate each of the display conditions in terms of usefulness for REACHING THE TARGET SITE (0 = not useful at all, 10 = extremely useful)

NO MAP

0 1 2 3 4 5 6 7 8 9 10

2D MAP

0 1 2 3 4 5 6 7 8 9 10

3D MAP

0 1 2 3 4 5 6 7 8 9 10

7. Please rate your overall SITUATIONAL AWARENESS for the wire hazards in each of the three missions (0 = very low situation awareness, 10 = very high situation awareness):

NO MAP MISSION

0 1 2 3 4 5 6 7 8 9 10

2D MAP MISSION

0 1 2 3 4 5 6 7 8 9 10

3D MAP MISSION

0 1 2 3 4 5 6 7 8 9 10

8. Please rate how well you thought you performed each of the three missions (0 = very poor performance, 10 = very good performance):

NO MAP Mission

0 1 2 3 4 5 6 7 8 9 10

2D MAP Mission
0 1 2 3 4 5 6 7 8 9 10

3D MAP Mission

0 1 2 3 4 5 6 7 8 9 10

9. Please rate the 2D MAP display OVERALL (0=not acceptable, 10=completely acceptable)

0 1 2 3 4 5 6 7 8 9 10

10. Please rate the 3D MAP display OVERALL (0=not acceptable, 10=completely acceptable)

0 1 2 3 4 5 6 7 8 9 10

11. Please rate how adequate you felt the RANGE of the map was in terms of maintaining situation awareness of the wire hazards:

0 1 2 3 4 5 6 7 8 9 10

12. Please rate the amount of time that you flew using the moving maps (as compared to the out the window view) (0=not at all, 10=all the time):

2D MAP

0 1 2 3 4 5 6 7 8 9 10

3D MAP

0 1 2 3 4 5 6 7 8 9 10

13. Please rate how often you exploited the information on the moving maps to avoid the wire hazards? (0 = never used the information, 10 = used the information all the time).

0 1 2 3 4 5 6 7 8 9 10

14. Please rate the placement of the displays (0=poor location, 10=good location)

INSTRUMENTS

0 1 2 3 4 5 6 7 8 9 10

MOVING MAPS

0 1 2 3 4 5 6 7 8 9 10

Would you like either of these displays to be located in a different place?

If so, where?

15. What did you like most about the…?

2D MAP

3D MAP

16. What (if anything) did you dislike about the…?

2D MAP

3D MAP

17. What features would you like to see added to the maps, that might help further in avoiding wire hazards?

2D MAP

3D MAP

18. Are there any features on the maps that you would remove?

2D MAP

3D MAP

19. Did you feel that you flew differently in the baseline condition, compared to the other two map conditions? If so, how (higher, lower, etc.)?

Please feel free to make any additional comments on the back.

Appendix D. Participant Comments and Answers to Experimental Questionnaire Questions

Would you like either of these displays to be located in a different place? If so, where?

- Instruments- not offset, DIRECTLY in front of me, attitude gyro being the center
- All three monitors closer together- maybe use a HUD
- Moving map would be better a bit higher and more in line with peripheral vision
- Moving map should be closer to the window view (maybe next to it on the right)
- In actual cockpit, the maps should be as near to the outside view as possible. Should be incorporated with existing GPS moving maps or Night Vision Goggles
- The moving map should not be as low, but located on the "outside" side of the pilot flying. I.e., on a two pilot helo, place it on the left side of the instrument panel for the left pilot and on the right side for the right pilot. That way a scan (internal to external) will flow more naturally without causing the pilot to become focused on the center consol. The instruments should be placed on the inside and above (slightly) the moving map. On a multi-functional display, let the individual pilot decide where he/she wants it.
- Yes. Center of all flight instruments in a real helicopter are under attitude gyro just above the cyclic. In the approximate position of compass of present engine/flight instrument display now.
- Ok- keep map on right, with the cyclic.
- A bit higher towards the main visual display
- Integrate the moving map into the instrument display to avoid the need to switch screens frequently. More info could be provided on the map display to negate the need to reference the instruments
- Instruments belong on centerline of pilot's view- the map could be left or right of the instruments
- In the view of the screen (i.e., higher in the cockpit/closer to my view of outside)
- Heads-up in the upper right or lower right field of view.
- Would prefer height over wires on outside view. Would prefer moving map on right and at same height as outside (side by side)
- Slightly higher/closer to the 'out-the-window" screen

What did you like most about the 2D map?

- For orientation, not so good but helpful to ID the approaching wires. I liked the "ft." counter more than the colored portion
- I liked the relative wire altitude most. It saves a lot of time by letting you know whether you have to climb or not. And if you know your next set of wires is 100 ft. or more lower, you know its ok to descend and get a closer look on the road.
- Good orientation with wires (in terms of position/location) and altitude from wires
- 2D was better for circling back to see a certain part of the road
- the color-coding of the wires and the wire display – very easy to glance at and assess quickly
- 2D map was easier to transition to since most aircraft I fly have 2D moving maps (ex. GPS/weather radar). Makes situational awareness easy
- Ease of use. Not as distracting as 3D. Changing colors was good! Navigation function was useful for situational awareness
- I used the number display on the map more than the color-coding
- I could see hazards over hills and to both sides. I also liked the digital display of height above hazard.
- Gave a better idea of upcoming curves of roads and approximate distance to where wires crossed the road.
- Quantitative info. - i.e., the exact altitude above or below the obstruction
- Good information that is easy to assimilate and use
- Easily understandable view – typical of my experience
- The ability to navigate (which way will the road turn next?), the quantitative value for wire clearance
- The positive/negative relative altitude to the wires
- Good for look ahead warnings of wires
- The relative altitude indicator
- Height above wires data
- I rated the 2D map higher because of the vertical reference above wires information, not because of the vertical reference.
- The numbers that showed obstruction clearance in altitude

What did you like most about the 3D map?

- For orientation, not so good but helpful to ID the approaching wires. Plus it gave an added display of the terrain ahead

- I loved the out-look. It gave me a great heads up that a wire was coming and if I was at an ok altitude to approach it.
- Wire location and look forward to next wire
- It was very clear where the wires were a factor. Also, the terrain was more realistic and helped a bit with the altitude and course change.
- The color-coding of the wires and the wire display – very easy to glance at and assess quickly. Plus the map seemed to give a better perspective ahead on the road **except** in a very hilly situation, in which case, the 2D was better
- Changing colors was good! Navigation function was useful for situational awareness
- Gave advanced warning of hazards
- Gave spatial relationship of wires to topographical rises/depressions. I had a better sense of when to adjust altitude to follow the terrain and when to adjust to minimize the risk of a wire strike.
- Qualitative info combined with contoured map.
- I especially liked the ability to look ahead at the projected hazards. The color-coding and relative height were easy to interpret.
- Greater range
- The range of the wires available on the screen and the color codes
- Was an excellent tool for look ahead warnings and corrective actions.
- Color lines were very visible (same as 2D actually). Much preferred the "tethered view" than vertical of 2D.
- The fact that you had plenty of heads-up notice when an obstruction was coming up

What (if anything) did you dislike about the 2D map?

- I could see the road with my own eyes further than the map. So no help except for the wires.
- It gave me a limited view. When looking out the window some towers may not be easily visible and the 2D does not give you good outlook to see the green (colored) marker for the wire. Also, it may just be the simulator, but it felt like there was a slight lag. The window looked like I had passed the wire, but the 2D showed me still in front of it. The 2D is a great tool and I would never turn it

down to have it in a helicopter. Probably the only reason I have negative comments is because I tried the 3D first.

- Not enough range
- I was a bit confused about what its purpose was, as it was the first attempt!
- Scale- too small. Should extend to the visual horizon at least. Also the road should be a little better defined against the background. Also reading the numbers for relative wire height was difficult. Maybe a graphical scale would be better.
- Didn't give enough advance notice of upcoming wires; no distance reference (i.e. range circles), and had to constantly reference road visuals to judge the distance to the next wire crossing
- No contouring – no audio – depict wires sooner
- Difficult to correlate height info to actual hazards. Had trouble getting a feel for the distance scale.
- Limited range, and some wires were clearly a hazard if the simulator didn't already know my path
- The fact that I had no idea at what range the relative altitude to the wires was
- Less useful for applying corrective action – display seemed to be late (or I was just late to react)
- Range seems a bit small
- Don't like vertical view as well as "tethered" of 3D
- Too short of range. Not enough notice. Screen fell out of my scan because it wasn't being used enough.

What (if anything) did you dislike about the 3D map?

- Can't see road direction over a hill at [low] altitude
- The scale of the 3D was somewhat better than the 2D, but the hills tended to confuse the route of the road.
- 3D map was good but took a little more getting used to. I tended to concentrate more on this map and less outside which distracted me from looking for the accident. Because of colors used in wire detection, the use of 3D seemed overkill.
- Perspective was interesting but it didn't really add anything useful. Pilot needs to LOOK outside
- No digital height above hazard. Had many of the same limitations of visual display, i.e., couldn't see obstacles until clearing ridgeline, couldn't see hazards on either side. The moving helo

blades on the model helo were also slightly distracting; my eyes are drawn to motion on the instrument panel so I was constantly looking down only to see it was the icon drawing my attention.

- It seemed as if the initial green indication gave me a false sense of security even though I understood its initial parameter. Twice I had to maneuver somewhat excessively when I noticed the colors change from green to yellow to red. At 150 knots, a more gradual color warning may be better. I.e., indicate a potential collision sooner.
- Would have liked distance reference to know how far in advance wires were
- It would be nice to have altitude reference of wires, so as approaching wires they didn't go from green suddenly to yellow then read and have to do last minute panic climb
- No digital altitude clearance display, and no audio
- Still looks very "simulated." Not enough additional info available to allow greater focus on this display alone
- Inability to navigate (i.e., road turns just over ridgeline)
- The fact that I did not know exactly how much I needed to climb to be "green"- was red under the wires or am I going to strike the wires?
- Should have also incorporated distance above reference target like the 2D
- No relative altitude indicator
- Didn't have height above wires
- Not knowing how much more I needed to climb.

What features would you like to see added to the 2D map that might help further in avoiding wire hazards?

- Just like a real map/chart, exact altitudes of the towers/wires. This superimposed above the obstacle would help tell me if I am clear or not.
- Distance from obstacle. Estimated time of arrival at obstacle (at speed presently traveling)
- Range ring button- 1mi, 5mi, 10mi markers
- Altitude of poles and towers AGL
- Possibly blink the yellow or red wire markings to call the pilot's attention.

- Incorporated with GPS navigation. Audio feature and distance (if there is a database on these wires, they should have fixed lat/long coordinates)
- A minimum altitude (radar) readout to clear the wires (either aural or visual). A command display for solution.
- Adjustable range scale with an on-screen distance reference
- Aural tone for yellow and red
- A proximity warning indication! If you are within a set distance of a hazard an indication should be provided. Selectable scale with range rings. Incorporate info from instruments: airspeed, altitude, heading, power settings, etc.
- More navigation and greater range
- Larger visual range or a digital range to the wires (although the digital info required more mental effort to process)
- Perhaps an arrow to recommend straight or turn to point toward lowest point of wires to allow pilots maximum clearance available (maybe too much data for system to process) I think if a right turn signal then level turn signal were continuously available to help avoid higher points, that could be useful
- A bit more range. AGL tags next to the wires at the point where the helicopter is about to cross. Perhaps a distance-to-obstruction indicator, like the relative altitude indicator that comes on when obstruction turns yellow.
- Larger scale so that you can see further into the distance

What features would you like to see added to the 3D map that might help further in avoiding wire hazards?

- Just like a real map/chart, exact altitudes of the towers/wires. This superimposed above the obstacle would help tell me if I am clear or not.
- Distance from obstacle. Estimated time of arrival at obstacle (at speed presently traveling)
- Digital altitude readout above wires
- Altitude of poles and towers AGL
- Possibly blink the yellow or red wire markings to call the pilot's attention.
- Incorporated with GPS navigation. Audio feature and distance (if there is a database on these wires, they should have fixed lat/long coordinates)
- Digital height above hazards display

- Flight path vector cueing- avoids excessive altitude avoidance
- Altitude reference on wires based on tower height. Then could set altitude to clear them ahead of time. Minimize climbs/descents, "yanking and banking" and there can be more time spent looking outside looking for an accident.
- Absolute altitude as well as clearance altitude on opposite sides of the screen. I think the 3D map is the ticket if you can incorporate a digital altitude clearance display and incorporate a selectable or mutable audio warning function.
- Aural tone for yellow and red
- A proximity warning indication! If you are within a set distance of a hazard an indication should be provided. Selectable scale with range rings. Incorporate info from instruments: airspeed, altitude, heading, power settings, etc.
- More navigation features (basically a VFR sectional with altitude and elevation information)
- Either a known range (altitude) for red/yellow/green or an above/below indicator
- Perhaps an arrow to recommend straight or turn to point toward lowest point of wires to allow pilots maximum clearance available (maybe too much data for system to process) I think if a right turn signal then level turn signal were continuously available to help avoid higher points that could be useful. I'd be interested in a from-cockpit relative view to compare.
- Relative altitude, distance-to-the-obstruction. It would be nice to be able to zoom/un-zoom the view (to change the range).
- Alt above obstruction clearance, like in the 2D display

Are there any features on the 2D map that you would remove?

- The crosshatch or checkerboard would be more helpful in defining the route if it was smaller or a tighter check/hatch. Plus, putting a border on the road would help define the road better
- Not sure if cross-hatching of plan view is necessary. Maybe a better idea for a quick reference of ground vs. road is to have 2 color differences.
- Grid lines

Are there any features on the 3D map that you would remove?

- Moving blades on helo icon
- Maybe change display to differentiate between road and ground differently. Such as: another way for a quick reference of ground vs. road is to have 2 color differences. i.e., road black rather than just same color as crosshatched background.
- Grid lines

Did you feel that you flew differently in the baseline condition, compared to the other two map conditions? If so, how (higher, lower, etc.)?

- Yes. I may have been more conservative during the baseline run, both higher altitude and slower speed.
- Faster because I was made more aware of what to come. Higher because I knew I didn't want to descend with up-coming wires.
- Flew baseline higher – 200 ft. in case I saw wires late
- Definitely higher – had to circle at some points to get a better view
- Higher over the wires in the baseline- the flat display made it a little difficult to judge height over wires, but with a second source of information the pilot can be a little bolder about getting close. Also- higher over the road in the baseline to avoid getting lost.
- Yes. More relaxed knowing ahead of time where wires existed, but not complacent. It is a good TOOL. It makes the operation safer.. and that's what its all about. (author's note: because of "tool" comment, presumably the pilot was more relaxed with map than in baseline condition)
- I felt I stayed at a higher altitude for the 10-20 seconds before crossing a set of wires, because I already knew they were coming up. I probably had fewer last minute climbs to avoid wires.
- I definitely crossed the poles at a higher than necessary altitude (or perceived it that way) my radar altitude definitely illustrated that fact. I used the moving map display as a second set of eyes and as a cross check to what I was perceiving. I used it as a situational awareness tool, but did not trust it completely. What I mean by that is, I perceived potential hazards ahead and saw no warning, but climbed anyway to cross the poles.
- Yes. Higher and more conservatively (slower) where expected/guessed wires were thought to be near abrupt terrain changes i.e., rise/depression

- Yes- more cautiously with more dedication to scouting possible obstructions
- Yes- more conservative, as the wires were difficult to see
- I was more anxious because I perceived that it would be more difficult to see the hazards. I actually flew worse in the 2D mode. I suspect that I relaxed because I thought the display would warn me. I flew the best in the 3D mode.
- Other than being more familiar, no.
- I was more confident at lower altitudes, faster airspeeds
- Lower due to lack of awareness of approaching obstacles
- I flew higher without the maps. My evasive maneuvers took more attention from the road since they were more exaggerated.
- Yes, higher and more cautious
- Yes. I was more alert. 2D was almost a detriment because I became dependent on it/used it as a crutch, yet it failed to give me enough warning to take evasive measures.

Additional comments

- I made several 360-degree turns to get a better look at the road/vehicles that in real life I would not have. In a real helo, you have a wider field of vision. I understand the artificial aspects of the simulator, but that affected how fast/slow it took me to find the crash site.
- One of the questions was how much time I used the maps. I gave them a 2 and 3 rating. I think they are excellent tools/instruments to have but only to scan for a second- enough to get the obstacle info needed and fly visually. Of course if an extreme meteorological condition exists that leaves you with low visibility, I would rely more on it, but still not to the point where I'm looking at it through half my flight.
- 2D – fixated on digital readout and didn't see wire color change
- Would a pilot believe digital readout of wire height?
- Flash-color change to draw attention to screen
- Wire alerts seemed to definitely cut down on the mental work in the cockpit
- The real visual situation for wires is that they are much more invisible, so I think a simple (color-coded) wire display would be very useful in real life. Other invisible hazards include guy wires for transmission antennas- in any case, the display must be one that can be quickly glanced at, and give info

- It would be ideal to combine this with terrain mapping software.
- It's good to see this type of research being done for helicopters. We fly in very high-risk environments and being that we are such a small "market," most technology is developed for airplanes. All we need is to know is where the mountains and wires are
- A heads up display or monocle (would be nice) with the color warnings. A sound warning is a must, especially for high single pilot workloads (dark, low visibility, weather, distractions inside and outside the helo). This aural warning should provide a solution with a representative urgency and should be a female's voice.
- Recommend that all scenarios start at a mid-range airspeed rather than at zero. Unnecessary time spent at the beginning of each scenario getting airspeed adjusted. Time spent doing this adjustment will vary a lot with experience of pilot and pilot's adaptability to simulator. It decreases quality of data collected even if time is only secondary or tertiary measurement.
- This would be a great addition to a rotorcraft's navigation/terrain marking package. Especially if the package were to include the qualitative cues of the 3D (inclusive of the ground contour mapping) with the qualitative cues of the 2D (digital read-out). Audio would be great, maybe two types of alerts (i.e. warnings and extremes). Adding just a few more pieces of info would be good too, such as absolute altitude.
- I'm not sure I necessarily need to know how far from wires I am – I just need to know I'm not going to hit them
- It seems like this would work best in a HMD. The time spent looking down definitely detracts from the search for the scene, and the lookout for other obstructions (smoke stacks)
- i found myself ignoring the moving map display after I saw green wire warning line. I did use the vertical reference number above wires a lot to "hop" over the wires and get back down. My preference is to have a map display to the right of the outside display (so I don't have to look so far down)- thus there would be more time to keep "eyes outside" – I need a quick reference to information – where the wires are and how high I need to go to get over them. The change in color of the wire line wasn't as useful as I thought it would be. My favorite civilian scenario for a set up would be to have the outside view on the left with the vertical height over wires displayed on a HUD, and the moving map display to the right of that. For a combat scenario I would prefer the vertical map so I could stay as low as possible as long as possible- assuming a hostile environment.