INTEGRATING HUMAN FACTORS INTO THE HUMAN-COMPUTER INTERFACE: HOW BEST TO DISPLAY METEOROLOGICAL INFORMATION FOR CRITICAL AVIATION DECISION-MAKING AND PERFORMANCE

Michael R. Witiw
Certified Consulting Meteorologist, Sammamish, Washington
Richard C. Lanier
FAA-NASA Ames Research Center, Moffett Field, California
C'Anne Cook
C'Anne Cook, Inc.
Washington D.C. and Melbourne Beach, Florida
and
Kerry A. Crooks
University of Florida, Gainesville, Florida

ABSTRACT

Weather is the single largest contributor to delays and a major factor in aircraft accidents and incidents. Real-time weather information has become critical for hazardous weather avoidance. Technological advances like the Geostationary Operational Environmental Satellites (GOES) have had a profound impact on now-casting and forecasting of meteorological variables. New predictive algorithms based

Michael Witiw completed an Air Force career as an aviation meteorologist and was on the faculty of Florida Institute of Technology's School of Aeronautics for seven years where he also earned his Ph.D. He is currently a member of the ICAO's Technical Consultant Program in the area of Aeronautical Meteorology.

Richard Lanier, an aviation human factors specialist, completed a career as a Navy pilot then earned a Ph.D. from the University of Central Florida. Prior to coming to the FAA he was on the faculty of Florida Institute of Technology's School of Aeronautics.

C'Anne Cook is an aviation human factors specialist. She earned her M.S. from Florida Institute of Technology in Aviation Human Factors and is an instrument rated pilot. Currently she is a consultant in the Washington, D.C., and Central Florida areas.

Kerry Crooks is the Assistant Vice President of Public Relations at the University of Florida. While an Air Force officer he was an Assistant Flight commander and Instructor/Flight Examiner Navigator. He holds a PhD from the University of Florida and has lectured on aircraft safety and survival.

upon GOES data are now available for fog, icing, turbulence and microbursts. In this paper we examine how to present the microburst prediction product to the aviator and have developed a color-coded display of microburst potential. Advance information on this hazard has been shown to influence the decision-making flight behavior of pilots.

INTRODUCTION

During July 1982, Pan Am Flight 759 departed New Orleans with showers over the east end of the airport and along the take-off path. The airplane struck a line of trees about 2,400 feet beyond the end of the runway at an altitude of 50 feet. The plane exploded and there was a subsequent ground fire. Eight persons on the ground and 145 on board were killed.

Three years later Delta Flight 191 approached Dallas-Ft. Worth with 156 passengers and 11 crewmembers. As the crew approached the airport, they recognized a thunderstorm cell lying along the approach path producing rain and lightning. They continued the approach. The aircraft touched down in a field some 6,000 feet short of the runway. It exploded into a fireball. Although the aircraft captain had initiated the go-around, it was too late.

In 1994, in Charlotte, a U.S. Air DC-9 crashed following a missed-approach resulting in 37 fatalities. A rapidly building thunderstorm had just moved over the approach end of the runway.

In all three of these cases, the National Transportation Safety Board (NTSB) determined that the probable cause of the accident was the airplane's encounter with a microburst-induced wind shear and the resultant downdraft and decreasing headwind. Typically, the pilot would have difficulty recognizing the phenomenon and reacting to it in time. Consequently, the airplane's descent was not sufficiently arrested, resulting in impact with the ground.

In 1982 the NTSB identified microburst-induced wind shear as a serious hazard and the limitation of technology in recognizing this phenomenon. During the next several years, low-level wind shear detection systems such as the Low Level Wind shear Alert System (LLWAS) and Terminal Doppler Weather Radar (TDWR) were developed.

While most major airports have installed some type of wind shear detection equipment, a key component of their effectiveness is the timely transmission of their data to controllers and pilots. Ultimately, it is the pilot who decides if and when to alter the approach or divert to an alternate. Complicating the decision process is a lack of knowledge about microbursts and how best to respond to the potential danger they present. More importantly, this weather phenomenon appears very quickly and response time is limited. Hence, in addition to detection, there is a need for a short-term prediction capability, both on the ground and in the cockpit. This prediction capability now exists. The question of how to present the predictive information raises several interesting questions for human factors design (Lanier et al., 1999).

BACKGROUND

Wind shear is a sudden shift in wind direction, velocity, or both. Its most violent manifestation occurs in a microburst, which is a concentrated downburst of cool air from a convective cloud. Near the Earth's surface, these downdrafts result in complicated wind patterns frequently characterized by intense wind shear. Low, slow flying aircraft (e.g. aircraft in the approach and departure stages) and all general aviation (GA) aircraft flying low are particularly vulnerable to microbursts. They can cause an airplane to lose aerodynamic lift and air speed, and to plunge into the ground before the flight crew can take corrective action. This has happened on a number of occasions. Wind shear has been identified as the cause of more than 30 major aircraft accidents with the NTSB database reporting an overall aviation total of nearly 250 accidents attributed to wind shear. Additionally, there are numerous GA accidents that have been attributed to weather in a generic manner because it is not known exactly what occurred. In some of these cases, given the presence of severe convective activity in the area, microbursts may have been responsible. Microburst-induced wind shear is particularly hazardous in the approach and departure phases of flight when aircraft are at or near performance limits. As the aircraft passes through the microburst it encounters strong headwinds accompanied by a significant increase in aerodynamic lift. This is quickly followed by severe downdrafts, then strong tailwinds resulting in rapid loss of lift. This rapid sequence of events can exceed both the aircraft and crew's limits.

After the 1985 Dallas accident, the United States Congress mandated the Federal Aviation Administration (FAA) initiate a research and training effort aimed toward curbing the microburst wind shear hazard. In 1986 the FAA and the National Aeronautics and Space Administration (NASA) launched a joint program to develop the essential technology for detecting and avoiding microbursts. The FAA undertook an aircrew-training program focused on wind shear recognition and procedures for recovering from its effects. The FAA also initiated the development of ground-based wind shear detection systems, the best of which is TDWR which measures wind velocities in terminal areas and generates real-time aircraft hazard displays that are updated every minute. TDWR is now installed in over 40 airports and more are planned. Other wind shear monitoring equipment that is already in place includes the LLWAS and airborne systems include forward-looking Doppler radar. In addition, verbal warnings to pilots from Air Traffic Control (ATC) alert pilots to this hazard.

These are all good systems and they work well together, especially when they are linked with specialized meteorological training of all users (including pilots), flight training in severe meteorological conditions, and conscientious communication between all involved (pilots, ATC, and dispatch).

The value of knowledge about wind shear and microbursts has been recognized by the FAA through Advisory Circulars and changes in the Federal Aviation Regulations (FAR). Since the fall of 1997, aeronautical knowledge of microbursts, including the need to show competence in wind shear and microburst awareness, identification, and avoidance, has been required for all airline transport pilots (ATP) applicants. However, pilots not included in this category are neither required to receive this training, nor are they required to demonstrate microburst knowledge or competence in microburst avoidance for any other certificates.

In spite of recent efforts in training and improving technology, microburst incidents continue. It is worth investigating whether such continued problems are the result of inadequate training, lack of technology, or some combination. Climatological data show microbursts occur with regularity, a high degree of severity, and, increasingly, with predictability.

In 1999, the United States House of Representatives Transportation and Infrastructure Subcommittee held a hearing on severe weather flight operations. Witnesses included members of industry, ATC, FAA, Airline Pilots Association (ALPA), NTSB, and the National Weather Service (NWS) among others. The testimony of Richard Detore (1999), Chief Operation Officer for U.S. Aerospace Group was typical:

> Enhanced weather information for the pilot is useless if it does not get to the pilot. Even the best communications between controller and pilot do not provide the level, amount, and speed with which this critical information must flow. It is still an outsider's view and subject to the pilot's comprehension.

He offered his opinion that onboard access to real-time weather information and graphics will add to the pilot's situational awareness. During conditions of fatigue, overload, absorption, inexperience and preoccupation, the pilot is subject to a loss of situational awareness. Providing easy to interpret weather graphic data into the cockpit will greatly enhance the pilot's ability to fly safely (Detore, 1999).

There is an immense amount of weather information available and many experts to interpret the data. The National Oceanic and Atmospheric Administration (NOAA) and the NWS are responsible for installing, operating, supporting and maintaining a national meteorological communications system that serves aviation. However, NWS products are delivered almost exclusively in small text files with very limited graphic capability. At the terminal level the FAA is responsible for collecting and disseminating weather information. Some of the weather technologies the FAA relies upon include TDWR and LLWAS, in addition to automated surface observing systems (ASOS) and the Airport Surveillance Radar (ASR) 9 airport surveillance radar system. In the cockpit, airborne weather avoidance systems measure the intensity of weather activity. Additionally, prior to flight, weather is disseminated to pilots via such systems as Direct Users Access Terminal Service (DUATS) in the United States and Meteorological Information Self-briefing Terminal (MIST) in the United Kingdom.

These are fine technologies. They provide real-time weather data. In the cockpit, with the exception of airborne radar, weather information depends upon the interpretation of one individual who communicates it to another. A good portion of the problem lies in how weather information is filtered into the cockpit. It is secondhand information that is no longer as timely to the consumer as it was to the provider.

SURVEY OF PILOTS' NEEDS

At the Florida Institute of Technology (Florida Tech), Melbourne, Florida, a study was conducted, evaluating a range of general and commercial aviation pilots for knowledge of meteorological conditions and predilection for use of meteorological information in forming decisions concerning flight conduct. Three methods were used: direct interview at Florida Tech, an online participant survey through the Aircraft Owners and Pilots Association (AOPA) web services, and a written evaluation sent to commercial pilots. Pilot experience ranged from less than 100 flight hours with a private Visual Flight Rules (VFR) rating through more than 9,000 hours with an ATP rating. The survey was designed to determine pilots' depth of knowledge concerning microbursts, their experience with microbursts, and other flight behaviors regarding weather data. This information was to help with the design of new computer-based pilot decision aides.

Survey results revealed that the majority of pilot respondents preferred automated services for weather information. A surprisingly large percentage (53%) did not routinely update their weather. When asked, "would you alter your flight plan based on a relative certainty of microburst development," pilots with less than 500 total hours established a more conservative threshold. Their responses indicated a strong likelihood of flight path alteration if the predicted microburst probability was less than 50%. Pilots with more than 2,000 flight hours reported they would not alter their flight path unless the probability was greater than 76% (Cook, Lanier, & Witiw, 1999).

These findings are significant if you are developing a human factors-driven product design. The survey helped to determine that visual automated displays are preferred, meaning they carry more weight with the user and are referred to more consistently. A goal would be to intensify attention to weather updates with in-flight predictive information of potential microburst-induced wind shear. If the product is to be employed as an advisory indicator, in order for it to be credible to all pilots, it should have predictive certainties of microburst-induced wind shear that exceed 76% accuracy.

THE ROLE OF GEOSTATIONARY OPERATIONAL ENVIRONMENTAL SATELLITES

New technological advances such as the GOES are having a profound impact on now-casting and forecasting of weather phenomena. Today, real-time satellite imagery provides extremely accurate observational data. As part of an integrated system of earth and space environmental sensors, GOES provides almost uninterrupted real-time observational data to all kinds of users in aviation alone. Experimental GOES aviation products are now being developed to detect and forecast fog, wind, icing, turbulence, microbursts, and volcanic ash movement.

Our focus is on using the GOES experimental microburst product developed and tested by NOAA/National Environmental Satellite Display and Information Service(NESDIS) and the 45th Weather Squadron at Cape Canaveral, Florida, and the surrounding area (Ellrod & Nelson, 1998; Wheeler & Roeder, 1998). This initial area was chosen for validation because of Space Shuttle operations. Validating the microburst product became important after a microburst caused damage at a shuttle-landing site at Cape Canaveral during a landing window. Thankfully the Space Shuttle had been diverted for other reasons.

The GOES microburst product indicates values of the Microburst Day Potential Index (MDPI). The MDPI compares equivalent potential temperature (the temperature a parcel of air would have if all the moisture in it were condensed out and the parcel was brought to a pressure of 1,000 hectopascals) near the surface with that of the middle troposphere (approximately 5,000 meters). The difference between the minimum and maximum values provides an objective assessment of buoyancy or stability in the air column. A value of 30 or greater is associated with a high likelihood of microbursts for that day, in that area.

The graphical display of the MDPI developed by NOAA/NESDIS can be somewhat confusing and of limited use to the aviator. The goal of this research is to explore the development of this tool into a usable hazardous weather information product. In doing so, the human factors issues involved in building an effective end-user graphic display must be addressed. We take these data, integrate them with supplemental weather data, such as in situ atmospheric soundings and present them in a format that makes the most sense to the end-users—pilots, controllers, and dispatchers.

Initial validation of this product was made in August 1998 and the results are promising. Microbursts occurred 88% of the time they were forecast. No microbursts occurred when not predicted. There are times when the GOES image is lacking in data. However limited readings, combined with numerical models and observations, allow for smoothing when complete GOES data are not available. Climatological studies have allayed initial concerns about the product (Cook, Lanier, Witiw, & Brown, 1998; Sanger, 1999). Further evaluation found the GOES microburst products do a credible job in identifying environmental conditions that are conducive to microburst formation (Ellrod, Nelson, Witiw, Bottos, & Roeder, 2000).

In the summer of 2000, Cook (2001) conducted an experimental evaluation of the GOES products at Florida Tech. Thirty-six pilots participated, 22 of who held ATP licenses. Three groups were all given a basic weather briefing containing identical content. The first group received the weather briefing only. A second group was given airborne weather radar in addition to the weather briefing. The third group received continually updated experimental microburst data (via a graphic weather display) as well as the weather briefing. Data were reformatted from the microburst potential displays making them more user-friendly for pilots. The study found that GOES prediction data strongly influenced pilot performance, resulting in earlier diversions and fewer attempts to fly into areas of forecast high microburst potential.

OPTIMIZING THE HUMAN-COMPUTER INTERFACE

To make this very important predictive observational data a useable tool for aviation; it is necessary to put GOES data in a more pilot-friendly, high impact form. To accomplish this goal, numeric data from the satellite is transformed into a color gradient. The product is then designed to update with every new GOES hourly reading using numeric smoothing to fill in the blank spots. In the future, meteorological models will be used for smoothing where GOES data are not available. This graphic is more in keeping with what is expected in weather displays as far as color shading where red indicates thunderstorms or freezing rain. Color fade represents graded potential.

Developing format or interpretative value of a display is the role of the human factors engineer. Some of the issues to be addressed include information processing, cognitive and physical workload, decision-making (relevance, uncertainty, and source attribution), communications, and channel techniques.

Display interpretation is always important for performance effects but especially true during times of heavy workload with severe decision-making consequences. Secondly, interpretation issues are important now because of the development of the automated synthesis of many sources of information—GOES, Next Generation Radar (NEXRAD), historical models, and real-time observations, to name a few. The optimum goal is to integrate all these sources into a single piece of information for the aviator in real-time or predictive imagery, to send it direct, and to provide the training required for best use. We have considered several types of in-the-cockpit alerts including an auditory warning system. We believe that a simple color-coded image may be most effective, as pilots are familiar with such coding on radar displays and other depictions of weather hazards.

The GOES-derived predictive data for in-flight systems will be presented as a portion of an integrated flight information display. Other items in the display may include additional observed weather data (from other GOES products), navigational information, and facilities status. The predictive presentation will be pictorial, with color-coding of microburst development potential for the terminal and en route phase of flight. The visual presentation will use green, yellow or red shading to denote the predicted likelihood of occurrence; similar to the graphic presentations used with weather radar depictions. Empirical testing has shown this visual presentation technique to be the most influential for aviation decision-making (Lee, 1991). The preflight information will be presented automatically, online, and consistent with the subjective responses and observed behaviors found in the survey. This automatic distribution will hopefully be incorporated with the current Flight Service Station (FSS) development initiative, Operational And Supportability Implementation System (OASIS).

The effects of advance or preview information on the cognitive weighting of subsequent factors in the decision making process has been established (Wickens, 1992). The presentation of timely information has also been shown to have a specific effect for pilot's decisions and performance of flight through hazardous weather (Lee, 1991).

CONCLUSIONS

Weather has been a major factor in many aircraft accidents and incidents as are evident in historical NTSB records. In recent years, predictive and real-time weather technology has advanced to the degree that accurate weather observations and warnings can be displayed to the pilot in flight in a timely manner. However, at the present time, cockpit weather information is limited to either airborne weather radar or filtered information communicated to the cockpit via ATC or dispatch. With that in mind, we specifically examined one type of weather hazard, severe low-level wind shear associated with microbursts, to determine how best a prediction can be presented to an aircrew.

While designing the predictive microburst induced wind shear display, we incorporated results of the survey completed at Florida Tech. From this survey, we learned that pilots do not routinely update their en route weather; and that there is a pilot preference for visual automated displays (which, in practice, are referred to more frequently than other flight status sources). Our research also showed that it was essential for a predictive product to have a high degree of accuracy. Pilots with a low number of hours would likely alter their flight path if the probability of a microburst was less than 50%; but pilots with a high number of hours (most of your commercial work force) require a greater degree of certainty—76% or greater. For a predictive product to be credible to all pilots this higher threshold of certainty needed to be met or exceeded.

Evaluation of microburst forecast products generated from GOES data in August 1998 indicates that microbursts occurred 88% of the time they were forecast and none occurred when not predicted. This fulfilled the certainty requirement of the predictive display being developed. Experimentally, it was found that GOES prediction data strongly influenced pilot performance, resulting in earlier diversions and fewer attempts to fly into areas of high microburst potential. Pilot decision-making during adverse weather conditions was affected positively and safely.

We have seen that current meteorological satellite technology can provide aviators with continually updated, near event-time predictions of adverse weather events. The major challenge is to design the appropriate pilot-technology interface. The GOES microburst predictive display described in this paper was designed to meet critical human factors design concepts. It accommodates user preferences, biases, and usability criteria. The end result is to facilitate safe flight through better decision tools.

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