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N. R. Johnson

D. A. Wiegmann

J. Goh

C. D. Wickens

COCKPIT TECHNOLOGY AND WEATHER RELATED DECISION MAKING: AN INTEGRATIVE REVIEW

Johnson, N.R., Wiegmann, **D.A., Goh, J.** and **Wickens, C.D.**
Aviation Human Factors Division, Institute of Aviation
University of Illinois at Urbana-Champaign
Savoy, IL

This paper provides a synthesis of the empirical studies to date that have investigated weather-related pilot decision making. Of particular interest is how new cockpit technologies such as synthetic vision systems and graphical weather information systems interact with flight experience, risk perception, risk-taking tendencies and self-confidence in affecting pilots' decision to continue flight into adverse weather. A conceptual framework for integrating and interpreting the results of these various studies is also be proposed.

Introduction

Visual flight rules (VFR) flight into instrument meteorological conditions (IMC), or unqualified flight into adverse weather, continues to be a major safety hazard within general aviation (GA). In an analysis of GA accidents between 1990 and 1997, Goh and Wiegmann (2002) found that the fatality rate of VFR into IMC accidents was approximately 80%. This compared to a fatality rate of approximately 19% for other types of GA accidents during the same period. These statistics reflect similar trends found by the National Transportation Safety Board (1989) for United States GA accidents that occurred during the 1970s and mid-1980s, as well as GA accident trends in other countries (e.g., United Kingdom and New Zealand; O'Hare & Smitheram, 1995). In a recent analysis, Knecht, Harris and Shappell (2004) found that the GA fatality rate per million passenger miles was 223 times that of commercial aviation for the period 1990-1998. In addition, the authors' analysis revealed that IMC was implicated in 32% of these GA fatalities. In sum, these findings clearly indicate that VFR flight into IMC continues to be a major safety hazard within general aviation.

Visual flight rules flight into IMC is often characterized by pilots' decisions to continue a flight into adverse weather conditions, despite having been given information or presented with cues that indicate they should do otherwise (NTSB, 1989). One possible explanation for VFR flight into IMC is based on the predictions made by prospect theory (Kahneman & Tversky, 1982). The hypothesis put forward by O'Hare and Smitheram (1995) and O'Hare and Owen (1999), predicts that pilots framing the decision to continue flight into deteriorating weather in terms of losses (e.g. loss of time, money, effort) will be risk-seeking and continue with the flight. Conversely, those pilots who frame the decision in terms of gains (e.g. personal safety) will be risk-averse and divert the flight when faced with deteriorating weather. This hypothesis was supported by analysis of GA accidents in New Zealand over the period 1988 to 2000 (Owen, O'Hare and Wiegmann, 2001). The authors' found that weather-related accidents occurred significantly farther from the departure point than other types of accidents (loss of control, collision with terrain and mechanical failure). Efforts to demonstrate a similar pattern in laboratory studies have been unsuccessful however.

There is a growing body of evidence that errors in situation assessment may lead to pilots' decisions to continue flight into deteriorating weather. Goh and Wiegmann (2001) and Wiegmann, Goh and O'Hare (2002) found that VFR pilots who continued simulated flights into adverse weather generally misinterpreted weather information, overestimating weather parameters. That is, pilots who continued flight had more positive views of cloud ceiling and visibility than those pilots who did not continue the flight. Pilots involved in VFR into IMC accidents also generally have less experience diagnosing and flying in adverse weather (Goh & Wiegmann, 2002). Burian, Orasanu & Hitt (2000) found that pilots in their study who were in the 25th percentile and below in terms of total flight hours were more likely to press on into deteriorating weather than those in the 75th percentile and above. The authors suggested that some pilots, particularly those with less experience, "do not trust what their eyes are telling them and so proceed on blindly"(p. 25). Therefore, at least in some situations, VFR flight into IMC can be viewed as a failure in recognition-primed decision making (RPD; Klein, 1993). Consequently, training and technological inventions that focus on improving pilots' situation awareness (SA) and weather evaluation might improve pilot decision making, thereby reducing accidents due to VFR flight into IMC.

Contrary to the above evidence, however, are findings indicating that some pilots occasionally choose to continue flight into adverse weather even after they have become aware of the hazardous conditions (Burian, Orasanu & Hitt, 2000). Pilots who continue flight into adverse weather tend to be overconfident in their abilities and also underestimate the risks of VFR flight into IMC (O'Hare, 1990). Indeed, results from the Goh and Wiegmann (2001) study partially support this hypothesis in that pilots who chose to continue a simulated flight into adverse weather were more confident in their skills compared to those who chose to divert and generally underestimated the risks of crashing due to the weather.

Some researchers have found that prior exposure to adverse weather improves pilots' situation assessment abilities (Wiggins & O'Hare, 1995; O'Hare, Owen & Wiegmann, 2001) but also reduces their perceptions of risk. In a simulator study involving a 180° turn out of IMC, Goh and Wiegmann (2004) found that pilots who flew the turn in a low-turbulence condition had reduced perceptions of risk compared to pilots who flew in a high-turbulence condition. In subsequent encounters with adverse weather, those pilots with reduced risk perception may be more willing to fly into deteriorating weather or enter into flight conditions that exceed their abilities.

Novacek, Burgess, Heck and Stokes (2001) found that pilots who possessed more extreme risk-taking personalities were also more likely to make riskier/poorer weather-related decisions when using a NEXRAD display than those pilots who were generally risk averse. Collectively, these findings suggest that efforts to improve pilots' weather related decision making should not only address situation awareness and assessment but also the potential impact of such efforts on risk-taking behavior.

Unfortunately, only a few empirical studies to date have been conducted to examine the impact that different types of technology aboard aircraft have on GA pilots' decisions to continue VFR flight into IMC. In one such study, O'Hare, Owen and Wiegmann (2001) investigated GA pilots' use of a global positioning system (GPS) during a cross-country flight in deteriorating weather conditions. The authors found that pilots flying an airplane equipped with a global positioning system (GPS) were more accurate in their position assessments and had a greater confidence in their location than pilots who flew without GPS equipment. In addition, the pilots with GPS were more likely to continue flight into IMC or remain airborne longer than pilots without GPS. The results of the study also showed that pilots who continued flight into IMC had lower estimates of the risks involved, compared to pilots who diverted, corroborating the previous findings of Goh and Wiegmann (2001).

In another study, Beringer and Ball (2003) investigated how variations in the data resolution of an on-board graphical weather information system (GWIS) affected pilots' judgment of weather severity and decisions to continue a simulated cross-country flight. The GWIS used NEXRAD (NEXt-generation-RADar) data to give pilots graphical information on the location and intensity of local area precipitation. The NEXRAD data was presented in 8km, 4km or 2km resolutions. The authors found that pilots with the highest resolution NEXRAD display (2km) spent the most time looking at the GWIS display, delayed their decision to divert the longest and came closest to the thunderstorm cells compared to the other two lower-resolution pilot groups. Based on these results and further data from post-flight static image judgments, the authors suggested that the high-resolution NEXRAD displays are likely to encourage pilots to continue flight while attempting to maneuver around or between the significant weather cells.

These findings suggest that as weather and other navigation displays become more advanced and sophisticated they may shift pilots' decision making processes from that of *strategic* decision making to that of *tactical* decision making. A pilot using such a display strategically may attempt to avoid a hazard altogether, whereas a pilot using a display tactically may attempt to negotiate a path through a weather hazard area such as a broken line of thunderstorms. In general, the distinction between the two types of decision making is that tactical decision making will be reactive to immediate environmental events while strategic decision making will be proactive and include planned avoidance of potentially hazardous events (Latorella and Chamberlain, 2002). Such shifts in decision strategies could have severe negative ramifications for generally less-skilled GA pilots.

A particular advance in cockpit technology that could affect these GA pilots in the near future is the synthetic vision system (SVS). SVS displays provide the pilot with an ego-centric, synthetic realization of terrain and other potential hazards (for example, traffic or towers) in front of the aircraft to better support flight in challenging terrain or low visibility conditions. Typically, the SVS display will include flight path guidance in the form of a highway in the sky (HITS; Alexandra, Wickens and Hardy, 2003; Williams, 2002; Berringer, 2000). It is hoped that synthetic vision technology will help prevent controlled flight into terrain (CFIT) and low-visibility loss of control (LVLOC) GA accidents.

Takallu, Wong and Uenking (2002) examined the use of SVS technology to help counter LVLOC accidents. In their flight simulation study, non-instrument rated GA pilots were required to execute basic flight maneuvers after entering into IMC. The maneuvers (180° turn, straight climb, straight descent, straight and level flight) were performed with either standard instruments or a SVS display (without HITS). The authors found that pilots flying with the SVS generally committed fewer violations of the altitude, heading or airspeed tolerances that were specified prior to the flight maneuvers. The improved performance of pilots while using the SVS display was attributed to enhanced spatial awareness that the display afforded.

To the best of our knowledge, there have been no further studies that investigate VFR pilots' use of SVS displays while encountering deteriorating weather. There is however, the opportunity to examine issues with SVS technology that may be relevant to weather related decision making that have been raised in a number of different studies. Although it has commonly been found that a HITS SVS display supports flight path tracking (e.g., Iani & Wickens, 2004; Prinzel, Comstock, Glabb, Kramer, Arther & Barry, 2004) there is evidence that there may be performance trade-offs. For example, the clutter associated with over-laying traffic information, traditional aircraft instrumentation and the HITS may inhibit traffic detection, in particular traffic that is neither expected or salient (Wickens, Ververs and Faden, 2004). In addition, the compelling nature of the HITS SVS may cause pilots to shift a disproportionate amount of visual attention to the SVS display, or at least make it more difficult to switch attention away from the SVS display to perform a concurrent task.

While not specifically looking at an SVS display, Wickens , Goh, Helleberg, Horrey and Talleur (2003) found that a cockpit display of traffic information (CDTI) affected pilot detection of a "rouge" aircraft that was only visible in the outside world. By drawing pilot attention away from the outside world, the CDTI made it more difficult for pilots to detect the rouge aircraft.

In contrast to the hypothesis that a HITS SVS display may be so compelling as to reduce outside-world scanning performance, is the hypothesis that such a display may lead to an increase in concurrent task performance by alleviating the workload associated with the primary flight control task. This hypothesis is supported by the finding that pilots flying with a HITS SVS display were more sensitive to weather changes presented in a secondary cockpit display than pilots without the HITS (Iani and Wickens, 2004). For integration with the issues raised in this paper, it should be noted that weather-event detection occurred from the in-cockpit display and not from any visual cues in the outside world (pilots were flying in IMC).

The manner in which scanning mediates the relationship between display and performance also needs to be considered. While Wickens et al. (2003) found a coupling between reduced outside world scanning and poorer performance in traffic detection, the relationship is not always consistent. Williams (2002) for example, found that despite the fact that the time pilots spent scanning the outside world decreased with a HITS SVS, their ability to detect outside world traffic was not reduced significantly.

The above studies, while not directly addressing VFR flight into IMC, highlight some general issues with pilot use of synthetic vision systems that are worth considering in a weather related decision making context. If pilots' scanning behavior is altered by the new technology, resulting in less time spent looking outside the cockpit, it is reasonable to expect that pilots' weather situation assessment may become poorer. Also, if the HITS appears to present the pilot with enough flight path information to navigate without reference to the outside world, it may encourage certain pilots to fly into deteriorating weather believing they can use the technology exclusively. On the other hand, if pilot flight control workload is reduced with the HITS SVS display, it is reasonable to expect that weather-related decision making may improve as more mental resources are available to integrate the in-cockpit weather information and the outside world weather cues.

The specific parameters of advanced displays that impact pilot-decision making, however, have yet to be systematically identified. Hence, little is known about how to design displays to achieve their desire effect (e.g., improved weather evaluation) while *also* minimizing any detrimental impact they have on decision making (i.e., induced risk taking). It should be noted, however, that the impact that advanced cockpit displays have on decision making and risk-taking behavior is likely to be affected by individual differences in pilot personalities and experiences. As stated previously, flight experience (including overall flight time, cross country flying, and recency), self-confidence, and risk-taking tendencies can all influence pilots' weather-related decision making (Goh & Wiegmann, 2002). Hence, more research is needed to examine the impact that advanced displays have on decision making in the GA cockpit, while also considering individual differences in pilots' experiences and risk-taking tendencies.

Conceptual Framework

In order to help guide further research and integrate the various issues affecting weather-related pilot decision making, a conceptual framework is presented in Figure 1. When encountering adverse weather in flight, a number of factors can influence a pilot's decision to continue flight into the deteriorating conditions. The preconditions that may affect decision making include pre-flight planning procedures and pilot characteristics such as confidence in their ability and risk taking tendencies. Inadvertent flight into IMC can be facilitated by pilots' poor situation assessment or in-flight planning or by distraction. Intentional flight into IMC could be seen as a result of pilots' low risk perception, personal motivation or perhaps social pressures. After entering into IMC, pilots typically have little time before the effects of spatial disorientation can produce catastrophic consequences.

Both technology-centered and human-centered interventions have the potential to affect pilots' weather related decision making at different stages in this model. GWIS displays for example, afford improved situation awareness and give the pilot another resource for in-flight planning. However, the use of this technology must also be considered in conjunction with pilots' self-confidence in their abilities, tendencies for risk-taking and perceptions of risk. Consequently, human-centered interventions like risk-management training need to be considered in helping reduce incidences of VFR flight into MC.

In addressing the issue of spatial disorientation, SVS displays could provide an intuitive tool for pilots to remain spatially orientated and avoid LVLOC accidents after entering IMC. However, effective training would need to be in place to help ensure the technology is used for its intended purpose (assisting in executing a 180° turn out of IMC) rather than as a means to support continued flight into conditions the pilot is not trained or qualified to fly in.

Ongoing Research

A study is currently in progress at the University of Illinois that examines how GWIS and SVS displays affect pilots' weather-related decision making. Of specific interest is how the particular properties of these two technological interventions (e.g. SVS display with and without HITS) influence pilots' decisions to continue simulated flight into deteriorating weather. In addition, the interaction of pilot personality factors with the technology will be examined. The results of the study will have implications for the design of displays for improving weather-related decision making while also minimizing risk-taking behavior.

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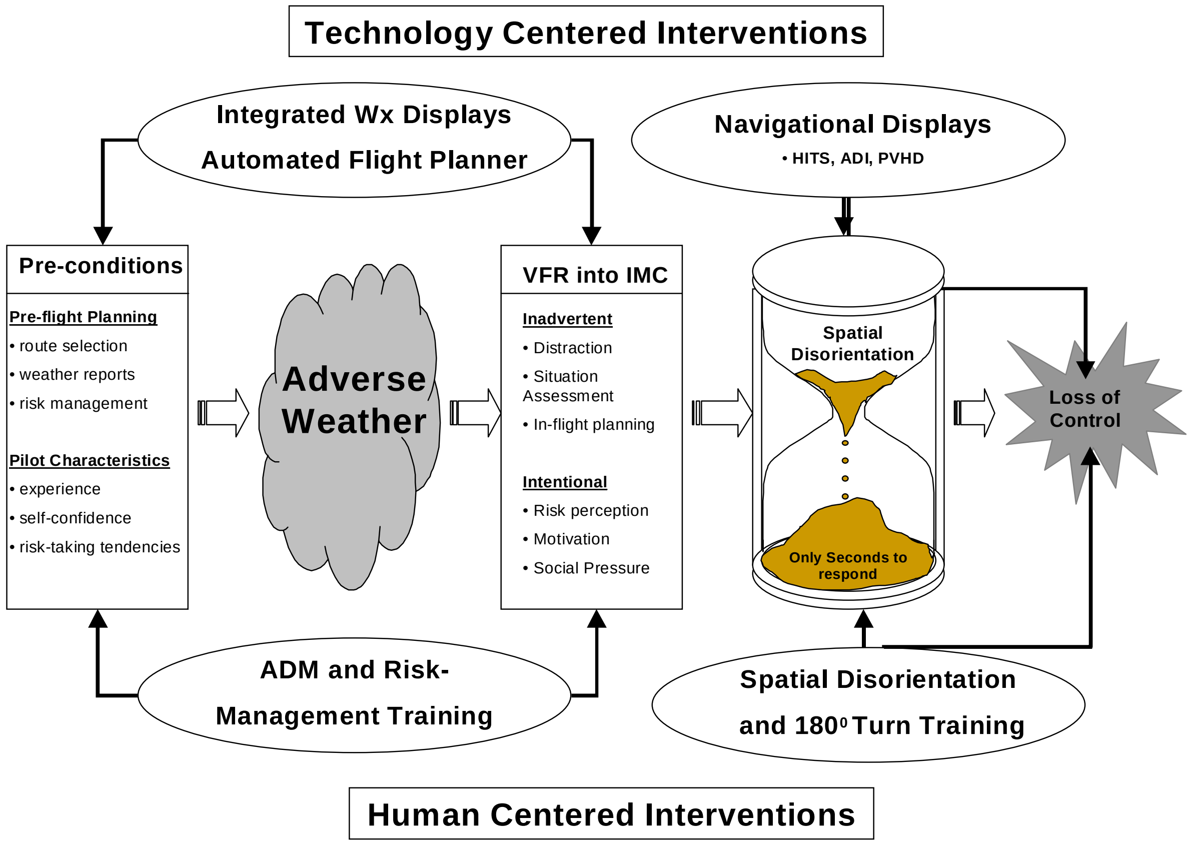

Figure 1. *Conceptual framework for integrating issues relevant to pilots' weather related decision making.*