



**Aviation Human Factors Division
Institute of Aviation**

**University of Illinois
at Urbana-Champaign
1 Airport Road
Savoy, Illinois 61874**

**Effects of Advanced Cockpit Displays on
General Aviation Pilots' Decisions to
Continue Visual Flight Rules (VFR) Flight Into
Instrument Meteorological Conditions (IMC)**

**Nicholas R. Johnson, Douglas A. Wiegmann,
& Christopher D. Wickens**

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ABSTRACT

Thirty pilots flew a simulated VFR cross country flight with one of three levels of display support: a control display with standard instruments, a synthetic vision systems (SVS) display depicting terrain and a highway in the sky (HITS), and a configuration in which the same SVS/HITS display was augmented by an electronic moving map depicting weather. The flight path directed for all three groups penetrated bad weather (IMC) near the destination airport. Results revealed that nearly all pilots in the control condition avoided penetrating the IMC clouds. Significantly more pilots in both SVS conditions penetrated the clouds before diverting to a lower altitude. Their failure to notice the deteriorating weather outside the cockpit was documented by a dominance of head down scanning for the pilots in these two groups who penetrated the weather. Even pilots who did avoid the clouds, looked outside only 1/3 as frequently as those in the control group. The presence of the moving map weather display did not mitigate these manifestations of attentional tunneling. Possible solutions related to display design and training are discussed.

Introduction

Visual flight rules (VFR) flight into instrument meteorological conditions (IMC), or unqualified flight into adverse weather, continues to be a significant safety hazard within general aviation (GA). Although VFR flight into IMC accidents typically only account for a small proportion of total number of GA accidents, they account for a disproportionate percentage of GA fatalities. For example, the National Transportation Safety Board (NTSB) found that while VFR into IMC accidents made up only 4% of the total number of accidents from 1975 to 1986 they resulted in 19% of the total GA fatalities (NTSB, 1989). These statistics point to the fact that the *fatality rate* of VFR into IMC accidents is significantly greater than that of other types of accidents. Indeed, the NTSB determined that 72% of VFR flight into IMC accidents resulted in fatalities, whereas only 17% of other accident types caused fatalities (NTSB, 1989). In addition, Goh and Wiegmann (2002) reported that the fatality rate of VFR into IMC accidents was approximately 80% compared to approximately 19% for that of other types of GA accidents during the period between 1990 and 1997. These statistics reflect similar trends found by the Transportation Safety Board of Canada (1990) as well as GA accident trends in other countries (e.g., United Kingdom and New Zealand; O'Hare, 1990). Collectively these findings indicate that VFR flight into IMC continues to be a major safety hazard within general aviation.

Clearly then, safety initiatives are required to help reduce the number of VFR flight into IMC accidents. One approach is through the use of new cockpit technology to either help pilots avoid adverse weather or recover from hazardous situations should they encounter IMC. VFR flight into IMC is often characterized by pilots' inadequate evaluation or misinterpretation of weather information (Goh & Wiegmann, 2001; Wiegmann, Goh & O'Hare, 2002). Consequently, advanced cockpit displays that focus on improving pilots' situation awareness and weather assessment might improve pilot decision-making. Technologies such as on-board graphical weather information systems (GWIS; Latorella and Chamberlain, 2002) can provide routine weather information and weather radar images via data-link from ground-based stations. Based on a more thorough understanding of the current weather situation and trends than they would otherwise have without the GWIS, pilots may make better en route decisions that avoid hazardous weather altogether.

Another approach using technology to reduce the number of VFR into IMC accidents is to provide pilots with displays that help prevent both loss of terrain awareness and spatial disorientation should they fly, inadvertently or otherwise, into low or zero visibility weather conditions. Synthetic vision systems that provide pilots with an in-cockpit, 3-dimensional representation of terrain in front of the aircraft (Prinzel, Comstock, Glaab, Kramer, Arthur & Barry, 2004; Schnell, Kwon, Merchant & Etherington, 2004; Alexander Wickens and Hardy, in press.) can potentially increase terrain awareness and help prevent spatial disorientation while pilots maneuver out of IMC. However, the benefits of synthetic vision systems need to be considered with their potential negative effects on pilots' risk taking tendencies, self-confidence and attention management. There is evidence that some pilots who continue VFR flight into adverse weather tend to be over confident in their abilities and underestimate the risks associated with continued flight into IMC (O'Hare, 1990; Goh & Wiegmann, 2001). Hence there is the possibility that synthetic vision displays may increase pilots' risk taking behavior, encouraging

them to continue flight, knowing they can navigate through significant weather hazards. A second concern with synthetic vision displays is that the 3D immersed perspective of such displays can cause pilots to look extensively at the display at the expense of time spent sampling the outside world (Wickens, 2005). This attentional tunneling can have significant detrimental effects on pilots' situation awareness, possibly causing them to miss vital weather cues that are only visible in the outside world.

So while technological advances such as in-cockpit weather displays and synthetic vision systems potentially enhance flight safety, concerns that these technologies may create new and undesirable problems need to be addressed. This report investigates the effects of two technological interventions, the synthetic vision system display and a graphical weather information system, on weather-related pilot decision-making during a simulated VFR cross-country flight, in order to examine the extent to which either or both mitigates or exacerbates the tendency continue flight into deteriorating weather. In the following, we focus first on the research on why pilots fly VFR into IMC, and then describe research on how advanced display technology may influence these judgments.

VFR Flight into IMC

Several explanations for pilots' decisions to continue VFR flight into IMC have been proposed. One possible explanation is based on the predictions made by prospect theory (Kahneman & Tversky, 1982). The hypothesis put forward by O'Hare and Smitheram (1995) predicts that pilots framing the decision to continue flight into deteriorating weather in terms of prospective 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 prospective gains (e.g. personal safety) will be risk averse and divert the flight when faced with deteriorating weather. This hypothesis was supported by results from of a laboratory study where pilots monitored a simulated VFR cross-country flight into deteriorating weather (O'Hare and Smitheram, 1995). The authors found 75% of the pilots who were presented with adverse weather information that focused on safety gains, diverted the flight. In contrast, only 33% of the pilots who were presented weather information emphasizing the costs and inconveniences associated with diverting, chose to do so. Although the decision frame was externally manipulated in this study, the authors suggested that in the real-world flight environment, decision frames may be induced by the proximity of the pilot's goal, such as the destination airport. As goal achievement gets closer, there may be a natural shift from the gains to the losses frame as deteriorating weather is encountered. Such a shift can result in the *sunk-cost effect* (Arkes & Blumer, 1985), where pilots become less likely to abandon their planned course, the closer to their destination they become because of the resources already committed to the flight.

Support for the role of sunk costs in VFR into IMC occurrences also comes from analyses of GA accident data that examines accident location with respect to departure and destination points. O'Hare, Owen and Wiegmann (2001) found that weather-related GA accidents in New Zealand from 1988 to 2000 occurred significantly farther from the departure point (92.5 nautical miles - NM) than loss of control accidents (49.7 NM) and accidents due to mechanical failures (78.1 NM). Analysis of GA accidents in Australia by Batt and O'Hare (2005) revealed a similar

pattern. The authors found that 66% of VFR into IMC occurrences occurred during the second half of the flight. By contrast, 55% of the occurrences of weather avoidance, that is diverting or returning to the departure airport, occurred in the first half of the flight.

Although accident data analysis provides general support for the role of decision framing in pilots' weather related decision-making, two flight simulation studies have failed to provide similar support. O'Hare and Owen (1999) specifically tested the hypothesis that sunk costs may affect pilots' decisions to continue flight into deteriorating weather. During a simulated VFR cross-country flight, pilots encountered deteriorating weather either early or late in the flight. The prediction based on sunk costs was that pilots who encountered the adverse weather late in the flight would be more likely to continue their flight than those who encountered the adverse weather early in the flight. However, this hypothesis was not supported by the results of the simulation where the majority of pilots in both conditions chose to divert the flight. In the second cross-country flight simulation study (Wiegmann, Goh and O'Hare, 2002), pilots also encountered adverse weather either early or late in the flight. The authors found that contrary to the predictions of the sunk cost hypothesis, pilots who encountered the adverse weather early in the flight actually continued further into the weather before diverting than those pilots who experienced the adverse weather late in the flight. Further evidence gathered during this study suggested that pilot decisions to continue VFR flight into IMC may be attributable, at least in part, to poor situation assessment rather than risk seeking behavior as proximity to their goal increases.

Wiegmann, Goh and O'Hare (2002) found that VFR pilots who continued the simulated flight into adverse weather generally misinterpreted weather information. Specifically, 44% of pilots who encountered the deteriorating weather early in the flight overestimated the cloud ceiling compared to only 6% of pilots who encountered the weather late in the flight. Those pilots in the early group flew longer into the deteriorating weather (median 5.94 NM) than those in the late group (median 2.75 NM). These results suggest that errors in assessing weather conditions may influence pilots' decisions to continue flight into deteriorating weather. The authors suggested that the erroneous assessment of deteriorating weather conditions by the early group in this simulation may have been caused by the disparity between the encountered weather and the weather information obtained during the pre-flight briefing. In contrast, pilots in the late group, were less likely to anchor their weather assessments to information provided in the pre-flight briefing, given the time elapsed before the deteriorating conditions were encountered.

The hypothesis that pilots' weather-related decision-making can be explained by errors in situation assessment is also supported by results from another simulation experiment by Goh and Wiegmann (2001). In this study, pilots flew a simulated VFR cross-country flight where they encountered adverse weather approximately three quarters of the way to their destination airport. The results of the study showed that those pilots who continued the flight had significantly higher estimations of visibility than pilots who chose to divert the flight.

A likely underlying factor in poor situation assessment is pilots' lack of experience in interpreting changing weather information. Pilots with little flight experience will not have had the same exposure to weather hazards as pilots with comparably more flight time. As such they will not have had the same chances to identify and interpret weather changes that may present a

safety hazard to the flight. Analysis of NTSB accident data from 1990 to 1997 revealed that GA pilots involved in VFR into IMC accidents had significantly fewer flight hours than those involved in other types of accidents (Goh and Wiegmann, 2002). Furthermore, based on analysis of Aviation Safety Reporting System submissions, 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 importance of experience is central to Klein's (1993) recognition primed decision-making (RPD) model. According to the RPD model, expertise or experience allows individuals to quickly diagnose a situation and generate an appropriate solution. In the case of an experienced pilot encountering deteriorating weather, once the relevant cues of reduced visibility and/or lowering cloud ceilings were perceived and interpreted, the decision to avoid the deteriorating weather should quickly follow. Results from Wiegmann, Goh and O'Hare (2002) support this idea. In their experiment, more experienced pilots tended to divert sooner than less experienced pilots. Burian et al. (2000) 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 of recognition-primed decision-making.

There is also evidence however that pilots' sense of overconfidence and their lack of appreciation for the risks involved, may account for some decisions to continue flight into adverse weather. For example, results from a simulation study by Goh and Wiegmann (2001) indicated that pilots who chose to continue a flight into adverse weather were more confident in their skills compared to those who chose to divert and generally underestimated the objective risks of crashing due to the weather. This evidence is consistent with O'Hare's (1990) findings that GA pilots generally exhibited low levels of risk awareness and high levels of self-belief in their flying abilities and judgments. Furthermore, the UK Civil Aviation Authority (1988) has cited pilots' "excessive optimism", "reluctance to admit limited capability" and "lack of appreciation of real dangers" as factors contributing to weather-related accidents.

A factor that may lead to differences in pilots' risk perceptions and self-confidence is their specific flight experience. Based on research in the area of self-efficacy (Bandura, 1988), Goh and Wiegmann (2004) suggested that the difficulty and outcome of pilots' weather-related flight experiences can lead to two different effects on risk perception and confidence. An easier flight task experience is more likely to lead to success in that task and consequently to lowered estimates of the risks involved and increased confidence. Conversely, difficult flight tasks that are more likely to lead to failure in the task could increase the perceived risk involved and decrease their self-confidence. The authors' ideas were supported by results from their simulation study in which pilots flew a 180° turn out of IMC in either an easy condition (no turbulence) or a difficult condition (high turbulence). Goh and Wiegmann (2004) found that after the maneuver, pilots who flew the turn in the difficult condition had increased perceptions of the risks involved of flying into adverse weather compared to those pilots who flew in the easy condition. These results suggest that pilots who have encountered adverse weather and successfully navigated out of or through it, may subsequently have a lower perception of the risks involved of flying regions of deteriorating weather and have a greater belief in their abilities to handle the situation.

Another way in which pilots' flight experience may lead to their decisions to continue flight into adverse weather is through "frequency gambling" (Reason, 1990). Frequency gambling refers to pilots' expectations of success based on previous behavior that had led to success in a similar risky situation. Beard and Geven (2005) report, for example, an Aviation Safety Reporting System case where a pilot's frequency gambling led to a low visibility loss of control incident after take off (ASRS #615534). The pilot reported that when flying with another pilot, he had frequently taken off into marginal weather before subsequently making a go/no-go decision. Although the authors do not provide any comprehensive analysis of accident or incident data, this example nonetheless highlights a specific way in which pilots' experience can potentially affect their weather-related decision making.

In sum, these research findings suggest that efforts to improve pilots' weather-related decision-making need to not only address deficiencies in pilots' situation assessment and awareness, but also be evaluated in terms of their potential impact on pilots' risk-perceptions and self-confidence.

Technological Interventions

The use of new cockpit technology can potentially improve pilots' situation awareness and consequently support better weather related decision-making. Innovations and improvements in ground to aircraft data link capabilities have led to a range of on-board weather services becoming available to general aviation pilots. Global positioning system (GPS) maps, convective weather radar displays and graphical or textural displays of routine weather information (METARs) provide the pilot with information that was previously either not available at the same level of accuracy (GPS), not available in-cockpit (METAR information) or not available at all (radar imagery).

With the abundance of new information available in the cockpit, pilots can have greater certainty in their position relative to weather hazards, a greater awareness of what those weather hazards are (for example, precipitation, low visibility or low cloud ceilings), how these hazards are changing over time and potentially make safer decisions to avoid hazardous conditions. However, there is also the possibility that the influx of new information could cause pilots to be over confident in their position relative to weather hazards and lead them to believe they can navigate through or in close proximity to those hazards (Beringer & Ball, 2003). When combined with a lack of appreciation for the inherent uncertainty in some of the information displayed (for example, radar images can be up to 15 minutes old before being refreshed), such over confidence could have dire consequences.

Unfortunately, only a few empirical studies to date have been conducted to examine the impact that these different types of technology aboard aircraft have on GA pilots' weather-related decision making. In one such study, O'Hare, Owen and Wiegmann (2001) investigated GA pilots' use of a GPS map during a cross-country flight into deteriorating weather conditions. The authors found that pilots flying an airplane equipped with the GPS map were more accurate in their position assessments and had a greater confidence in their location than pilots who flew

without GPS equipment. Importantly however, the pilots with GPS were more likely to continue flight into IMC or remain airborne longer than pilots without GPS.

Novacek, Burgess, Heck and Stokes (2001) investigated instrument-rated pilots' use of a graphical weather information system (GWIS) display during a simulated flight in IMC. The GWIS display used next-generation radar (NEXRAD) data to give pilots graphical information on the location and intensity of local area precipitation. In addition, the display provided graphical METAR information. The authors gave pilots a NEXRAD display resolution of either 4 km² or 8 km² and examined pilots' choices in either continuing flight into or avoiding areas of heavy precipitation. The results of the simulation showed that pilots with the lower NEXRAD imagery resolution (8 km²) tended to make better decisions (avoiding the hazard) than those with the higher resolution display in one of the two decision-making scenarios used. The authors hypothesized that the lower resolution NEXRAD display introduced a greater uncertainty into the weather information and thus prompted pilots to fly more conservatively around the hazardous weather compared to pilots with the high resolution display.

In a similar study, Beringer and Ball (2003) investigated how three levels in the data resolution of an on-board GWIS using NEXRAD imagery affected pilots' judgment of weather severity and decisions to continue a simulated VFR cross-country flight. The NEXRAD data were presented in 8 km², 4 km² or 2 km² resolutions. The authors found that pilots with the highest resolution NEXRAD display (2 km²) 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. A possible explanation for such behavior is that the reduction in uncertainty of the high-resolution display compared to the lower resolution displays allowed pilots to see courses through the precipitation area that were far more direct than those that would have to be flown to avoid the hazard entirely. Thus the high-resolution displays may allow pilots to perceive what appear to be efficient and safe paths through the hazardous area to the intended destination. However, the time-delayed nature of the NEXRAD images and the dynamic nature of convective weather activity means that such direct paths may not in reality exist.

The findings of O'Hare, Owen and Wiegmann (2001), Novacek et al. (2001) and Beringer and Ball (2003) suggest that as weather and other navigation displays become more sophisticated and detailed 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.

An alternate approach to the use of technology to prevent weather related GA accidents is to provide pilots with better tools to escape low visibility conditions should they fly into them, inadvertently or otherwise. The aim of such technology is to improve pilot's terrain awareness, prevent spatial disorientation and provide a safe route out of IMC. A particular advance in cockpit technology that offers this support is the synthetic vision system (SVS; Prinzel et al., 2004; Schnell et al., 2004). 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. Often, the SVS display will include flight path guidance in the form of a highway in the sky (HITS; Prinzel et al., 2004; Schnell et al., 2004; Alexander, Wickens and Hardy, in press; Williams, 2002; Beringer, 2000). It is hoped that synthetic vision technology can help prevent controlled flight into terrain (CFIT) and low-visibility loss of control GA accidents (Hughes & Takallu, 2002).

SVS Displays and Attentional Tunneling

While SVS displays may enable the non-instrument rated pilot to fly out of IMC conditions and support terrain awareness, little is known about how pilots may use the technology while encountering deteriorating weather. Given the simulated VFR picture that SVS displays render in the cockpit, VFR pilots may be tempted to press on into low visibility conditions knowing that the display provides the necessary aircraft attitude and terrain information for continued flight. The impact that such displays have on pilots' perceptions of risk and self-confidence are important issues to address. A second concern is that the SVS display may affect pilots' visual scanning of the outside world. VFR pilots are responsible for maintaining separation from clouds and it is reasonable to expect that if their monitoring of the outside world decreases, the risk of inadvertently flying into adverse weather will increase. Emerging concepts for SVS displays do not generally include presentation of 3D weather information. To the best of our knowledge though, there have been no studies that investigate VFR pilots' use of SVS displays in the context of weather-related decision-making.

There is however, the opportunity to examine issues with SVS technology and attentional tunneling 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 SVS display supports flight path tracking and terrain awareness (e.g., Prinzel et al., 2004; Schnell et al., 2004; Glabb & Takallu, 2002) there is evidence that the realistic ego-referenced perspective of such a system may impact pilots' attention allocation. Specifically there is concern that the compelling nature of the SVS display may cause pilots to look extensively at the display, at the expense of time spent scanning the outside world (SAE, 2005). Such attentional tunneling can have major safety consequences where critical or unexpected events in the outside world, such as other traffic or changing weather conditions, are not presented on the SVS display.

The Aircraft Owners and Pilots Association (AOPA), suggest that pilots should spend twice the amount of time scanning the outside world as they do inside the cockpit (AOPA, 1993). The Aeronautical Information Manual advises that visual scanning inside the cockpit should account for no more than a quarter to a third of the time spent scanning outside the cockpit (FAR/AIM, 2003). These figures suggest then that pilots should be spending approximately 67% to 75% of

their time attending to the outside world. However there is little data on whether this ratio is practical or optimal given pilots' critical need for information within the cockpit (Talleur and Wickens, 2003).

In two studies high fidelity simulator studies investigating pilots' use of a cockpit display of traffic information (CDTI), Wickens and colleagues found that pilots typically spent around 60% of their time looking at the traditional instrument panel and distributed their remaining scanning between the outside world and the CDTI. Wickens, Goh, Helleberg, Horrey & Talleur (2003) observed that pilots spent 33% of the time looking outside the cockpit and Wickens, Helleberg & Xu (2002) found similarly that pilots spent around 40% of the time scanning the outside world. These results are in approximate reversal to the suggested ratio of outside world to in-cockpit scanning times (AOPA, 1993; FAR/AIM 2003).

The manner in which visual scanning mediates the relationship between display characteristics and performance is an important issue to address. Visual scanning measures offer insight into how a given display influences the allocation of attention to relevant areas of interest (AOIs) and how that attention allocation affects performance on tasks supported by those AOIs. For example, the typical traffic detection task for a VFR pilot requires identifying aircraft in the outside world and avoiding those aircraft. If an in-cockpit display causes pilots to reallocate visual attention from the outside world to that display, it is reasonable to expect that pilots' traffic detection efficiency may be reduced in so far as the display does not support traffic detection.

Several studies within an aviation context have revealed situations where increases in the amount of attention allocated to a particular AOI has lead to performance degradation in tasks supported by other AOIs that received proportionately less attention. Alexander and Wickens (2005) examined the effectiveness of a synthetic vision system suite on flight performance and traffic awareness during simulated flight in VMC. The SVS consisted of a primary flight display with a HITS for guidance but no terrain representation and an integrated hazard display that contained various 2-dimensional and 3-dimensional representations of terrain and traffic hazards. While the emphasis of the experiment was on the impact of hazard display type on traffic awareness and detection, participants flew one trial in which an unexpected event occurred. During this trial, the HITS guided pilots through a radio tower that was only visible in the outside world. Of 24 pilots in the simulation, 10 flew right through the tower. Of those 10 pilots, 4 did detect the tower but failed to avoid it but the remaining 6 failed to even notice the tower. Using eye tracking data, the authors found that on average, pilots spent 67% of the time attending to the PFD and only 6% scanning the outside world (the remaining time was spent attending to the hazard display). When looking at the difference in scanning behavior between the 18 pilots who detected the tower and the 6 who failed to detect it, the authors found that while both groups spent approximately the same time attending to the PFD, the non-detectors spent 7% less time than the detectors looking at the outside world. The implication of these results is that performance on the outside-world obstruction detection task suffered when pilots spent less time attending to the outside world.

Thomas and Wickens (2004) and Wickens, Alexander, Horrey, Nunes and Hardy (2004) examined the effect that a HITS SVS display had on pilots' allocation of attention during an

approach to landing. The authors were specifically interested in how pilots' distribution of visual attention between the SVS display and the outside world influenced their response to two unexpected events. The unexpected event trials consisted of a rogue blimp in the vicinity of the flight path the pilot was provided with by the HITS, and a misalignment between the HITS final approach path to the synthetic runway on the SVS display and the real-world runway. Both cases were only detectable by pilots through viewing the outside world. The authors found that all 4 of the pilots without the HITS detected the blimp and conducted avoidance maneuvers. However, 2 of the 4 pilots flying with the HITS failed to detect the blimp. Results from eye tracking analysis showed that the two non-detectors spent 77% of the time looking at the HITS SVS display and only 1% of the time looking out the window (the remaining time being distributed across the other elements of the SVS display). By contrast, the four pilots flying with the SVS display that did **not** have a HITS (and noticed the blimp) spent 8% of the time looking out the window.

During the offset runway trial, at 5 of 12 pilots failed to detect the discrepancy between the HITS pathway and the real-world runway. Scanning data indicated that detectors of the runway offset spent 62% of the time attending to the HITS SVS display and 13% to the outside world. Similarly to the rogue blimp event, the non-detectors had increased dwell times to the HITS SVS display (81%) and reduced dwell times to the outside world (3%). The authors also looked at the overall scanning patterns averaged across both unexpected events for the two best detectors (pilots who detected both blimp and runway offset) and the single worst performer who failed to detect either event. The comparison revealed that the "good" detectors spent 11% more time attending to the outside world than the "poor" detector (16% vs 5%). A reciprocal decrease in time spent attending to the SVS display by the good detectors compared to the poor detector was also found (55% vs 65%).

In another study, Alexander, Wickens and Hardy (in press) investigated pilots' detection of another surprising event while flying an approach to landing with an SVS display. During the trial, a runway incursion necessitated pilots fly a missed approach. While the HITS pathway automatically reconfigured for the missed approach, the path produced guided pilots right through a blimp that was only visible in the outside world. During this trial, 14 out of 17 pilots failed to detect the blimp in the flight path and flew through it. Visual scanning was not measured in this study however, nor were data collected from a control group to fly the missed approach without the tunnel. It may however be inferred that such a group would have been looking primarily outside, since there would be no in-cockpit guidance of progress along the missed approach path, and therefore the blimp would have been noticed.

The studies discussed above, whose results can be integrated to reveal a consistent pattern of attentional tunneling (Wickens, 2005), highlight the problems pilots have in detecting unexpected events that are only visible in the outside world when flying with SVS displays. The analysis of visual scanning data also support the hypothesis that attentional tunneling to the SVS display causes pilots to look outside less, and that this is likely responsible for their missing unexpected events in the outside world.

However, other studies reveal that less visual scanning to a particular AOI does not necessarily result in poorer performance during routine or expected detected tasks. For example, Williams (2002) examined pilots' use of a HITS SVS display and found that while scanning of

the outside world reduced from 41% to 14% with the display compared to traditional cockpit instruments, there was no significant reduction in outside world traffic detection (although here pilots knew that traffic was not depicted on the HITS display). Wickens, Helleberg and Xu (2002) investigated the effect a CDTI had on routine traffic detection performance and found that although the CDTI reduced outside world scanning from 40% to 26%, detection of traffic not displayed on the CDTI was not adversely affected.

These results, in addition to that of Wickens and Thomas (2004) suggest that some minimal amount of outside world scanning (perhaps around 10%) may be sufficient to detect unexpected events, even though this level of time spent looking at outside world is significantly less than that advised by aviation organizations (AOPA, 1993; AIM/FAR 2003) and found during simulated VFR flight without a SVS display (Wickens, Helleberg & Xu, 2002, Wickens et al., 2003)

A further consideration that should be taken into account is that concurrent task performance during some flight scenarios may benefit from pilots' use of SVS displays, given the potential for the SVS display to alleviate the workload associated with the primary flight control task. This hypothesis is supported by results from a flight simulation study by Iani and Wickens (2004). During approach to land, pilots flying in IMC were presented with an unexpected weather change on an electronic weather map and given the opportunity to fly an optimal safe flight path around the weather. The results from the simulation showed that pilots flying with the 3D HITS were more sensitive to the weather changes presented in the weather display than pilots without the HITS. The authors suggested that the ease with which pilots could fly the approach course using the HITS, gave them a larger amount of available attention to monitor the weather map. For integration with the issues affecting VFR flight, it should be noted that pilots were flying in IMC and hence weather event detection occurred on the in-cockpit display and not from any visual cues in the outside world.

Summarizing the work of Wickens and colleagues, it is clear that in-cockpit technology can adversely affect not only pilots' visual scanning but also the task performance that is based on that visual scanning. The compelling nature of the SVS display, and in particular, the HITS contributes to pilots allocation large amounts of their attention to the display at the expense of other areas of interest. This attentional tunneling to the SVS display and consequent failure to look at the outside world has been demonstrated to have a detrimental impact on pilots' detection of unexpected events in the outside world such as traffic and runway offsets.

The studies reviewed above, while not directly addressing VFR flight into IMC, highlight important 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 an alternative hypothesis is 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.

To the best of our knowledge, there have been no studies that specifically investigate the impact that synthetic vision and graphical weather display technologies have on pilots' decisions to continue VFR flight into deteriorating weather. The research presented in this thesis was undertaken in an effort to examine the effect these displays have on pilots' situation assessment, self-confidence, risk taking and workload in a weather-related decision making context.

To investigate the impact that SVS and GWIS displays had on weather-related decision-making, pilots flew a simulated cross-country flight over central Illinois into deteriorating weather with one of three display configurations. A control group flew the simulated flight with standard analog instruments while two experimental groups utilized flat panel digital displays. One experimental group (SVS) was provided only with a synthetic vision display. The other experimental group (SVS/MMM) was provided with a synthetic vision display along with a moving map display that contained surface weather information. All three groups flew the same flight path and encountered the same deteriorating weather conditions approximately three-quarters of the way to their destination airport.

Based on the findings of the reviewed literature, the following hypotheses are to be tested.

(1) Group Performance Hypotheses:

- I. Pilots flying with the two types of synthetic vision display will be more likely to continue flight into the deteriorating weather than pilots in the control group.
- II. Eye Tracking Analysis should reveal pilots in the two experimental groups spending a greater proportion of time attending to their in-cockpit instruments (SVS displays) than the outside world compared to pilots in the control group.
- III. Given the specific weather information provided to pilots flying with the moving map - weather display, these pilots will be less likely to continue flying into deteriorating weather than pilots with only the synthetic vision display, and this will be reflected by pilots' scanning to the weather map.

(2) Individual Differences Hypotheses:

- I. Pilots in the two experimental conditions who elect to continue flight further into deteriorating weather will spend a greater proportion of the time attending to the SVS displays than those who elect not to continue.
- II. Pilots in the SVS/MM group who elect not to continue flight into deteriorating weather will spend a greater proportion of the time attending to the weather display than those who elect not to continue.
- III. Pilots using the SVS displays who elect to continue flight into deteriorating weather will have increased confidence in their abilities to fly safely to their destination and lower perceptions of the risks involved, compared to pilots who elect not to continue.

Methods

Participants

Thirty pilots (28 male, 2 female) from the Institute of Aviation at the University of Illinois participated in the flight simulation. Twenty-nine pilots held their private pilot certificates and of these, five held instrument ratings. The remaining pilot was a student pilot nearing completion of their private pilot certificate. All pilots had completed at least 5 cross-country flights and accumulated at least 10 cross-country flight hours. Pilots' total flight experience ranged from 57 to 205 hours (mean = 120.1 hours) while their IFR experience ranged from 0.9 to 50 hours (mean = 22.1 hours). Pilots' ages ranged from 18 to 26 years (mean = 20.5 years). All were compensated \$9 per hour for their participation in the experiment, which typically lasted 2.25 hours.

Equipment

Participants flew a Frasca 142 fixed-base simulator configured as a Cessna 172 aircraft. Pilots flying the simulator were presented with a 180 degree field of view (FOV) depiction of the outside world, projected onto three screens. The outside world scenery consisted of generic (non-photorealistic) representations of terrain, rivers, interstate and state routes, cities, airports, radio towers and specific VFR navigation landmarks used in the experiment. 3D objects were created using Multigen-Paradigm Creator Pro, while terrain was generation using Terrex TerraVista. Graphics were run with Multigen-Paradigm Vega on three Evans & Sutherland simFusion computers.

The Synthetic Vision System and Moving Map displays were housed on an 18" flat panel LCD display located in front of the right hand seat of the cockpit. The FOV at 26.5" from the screen was 30° wide x 28° high.

Eye movement data was collected using an Applied Science Laboratories (ASL) Model 6000 control unit, an Ascension Technology Corporation "Flock of Birds" head tracking unit and an ASL Model 5000 head mounted optics unit. Eye movement data was collected at 60Hz.

Task

Participants flew a VFR cross-country flight from Champaign, IL to Rochelle, IL using one of three display configurations. Weather conditions at takeoff from Champaign were 10 statute miles (sm) visibility and 5000 feet above ground level (AGL) cloud ceilings. Three-quarters of the way to Rochelle the weather began to deteriorate to below VFR minimums with visibility and cloud ceilings being reduced to 2 sm and 1500 feet AGL respectively by the time pilots reached their destination. Pilots would fly into the cloud ceiling approximately 7 minutes after the weather began to deteriorate. Pilots were free to either divert to an alternate airport or continue flight to Rochelle after encountering the deteriorating weather.

Procedure

At the beginning of the experiment, pilots completed a statement of consent form and a short questionnaire. This questionnaire required participants to provide demographic and flight experience information including age, gender, number of years flying, total flight hours, total instrument hours (simulated and actual), total cross-country flight hours, number of cross-country flights, and total time in the last 30 and 90 days. Participants then read the experimental instructions and were briefed on the particular display they would be using.

The instructions explained to participants that they were going to make two cross-country VFR flights, the first of which was a short, 15 minute practice flight from Champaign to Rantoul to familiarize themselves with the simulator, the outside world view and the particular display they would use. In the experimental flight, they were to fly from Champaign to Rochelle, approximately 120 nautical miles (NM) and 60 minutes flight time away. For this flight, no communication with Air Traffic Control was required. Participants were told to imagine making the trip for the purposes of logging cross-country flight time.

Pilots were instructed to treat the flight as they would a real world flight. Prior to the experimental flight they were given weather information (Terminal Area Forecasts, winds aloft and routine weather reports - METARS), a Temporary Flight Restriction, Navigation log and Chicago Area Sectional Chart to review. Weather along the flight route was forecast to be above VFR minimums but deteriorating later in the day with low cloud and limited visibility moving across the flight path from the north-east. Conditions to the west of the route were forecast to be above VFR minimums all day. No convective weather activity was present at the time of departure or forecast for the day of flight and winds were light (5-10 knots) from the north-east.

Participants were instructed to take as much time as necessary to review the pre-flight material. In addition to the pre-flight briefing, pilots were specifically instructed to monitor for traffic, weather changes and mechanical malfunctions and reminded that all Federal Aviation Regulations would apply to the flight as they do in the real world.

The simulation was stopped when participants either landed at Rochelle, were clearly diverting to an alternate airport (as judged from their flight path) or became lost.

Following the flight, participants were asked to complete a questionnaire where they assessed flight conditions, the impact of the display they used on flight technical performance and in-flight decision-making and provided subjective feedback on risk evaluation. Pilots were then debriefed and made aware of the purposes of the study.

Design and Displays

A between-subjects manipulation of display type was used in this study. Pilots were assigned to one of three display condition groups:

1) Synthetic Vision System and Moving Map Displays (SVS/MM)

The SVS display provided pilots with regular flight instrument information (attitude, altitude, airspeed, vertical speed and heading) superimposed on a synthetic representation of terrain they were flying over as shown in Figure 1. The 3D terrain portrayal in the SVS display was identical to that portrayed in the outside world view. A Highway in the Sky was provided in the SVS display for navigation and began on the runway at Champaign and ended 200 feet AGL on approach to runway 07 at Rochelle. Pilots were made aware that the SVS display contained no weather information.

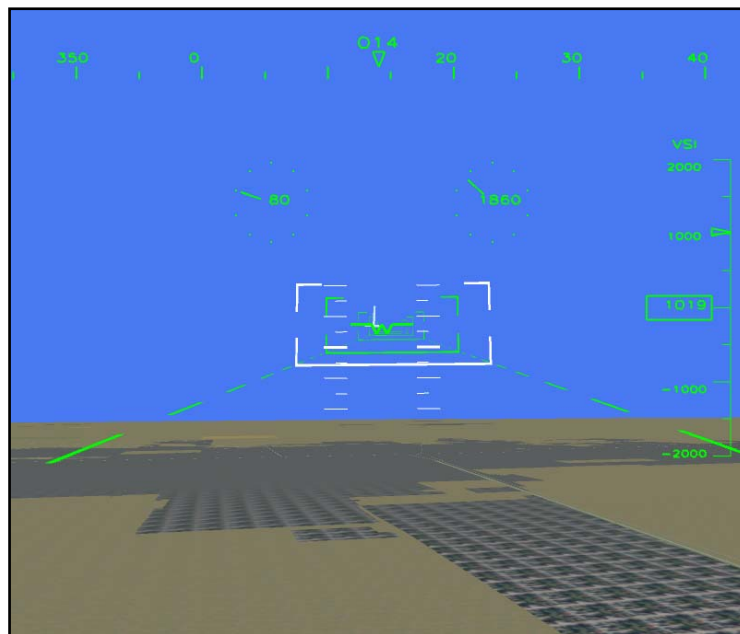


Figure 1. SVS Display used by participants in the SVS/MM and SVS conditions

The Moving Map display shown in Figure 2 provided pilots with their position along the planned course and locations of airports in the vicinity of the flight path. In addition, each airport location was supplemented with routine weather information (METARS) and was color-coded for the corresponding flight condition: green for VMC, blue for Marginal VMC and red for IMC. Weather information was updated at 15 minute intervals throughout the flight, giving pilots four updates before reaching Rochelle.

2) Synthetic Vision System Display only (SVS)

The SVS display was identical to that used in the SVS/MM condition and again, pilots were made aware the display provided no weather information.

3) Traditional Flight Instruments (Control)

Traditional flight instruments consisted of analog airspeed, attitude, altitude, heading and vertical speed indicators. No radio navigation receivers were able to be used by pilots in this display condition.

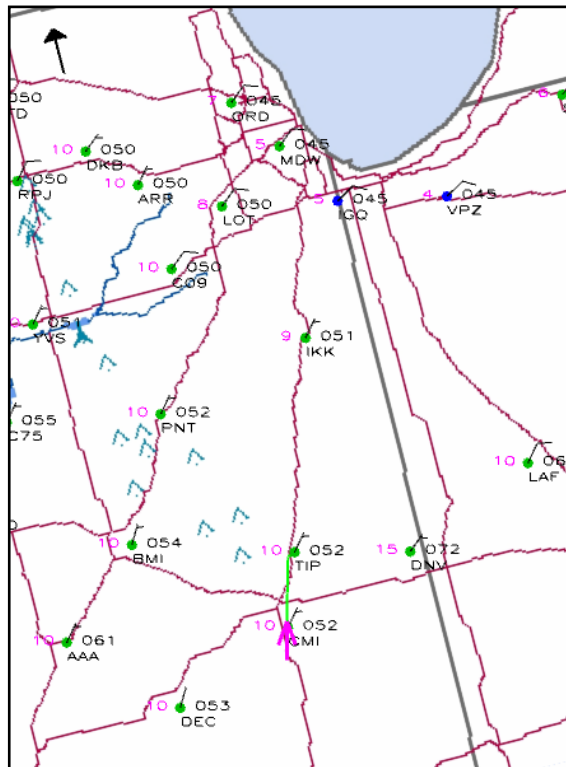


Figure 2. Moving Map display used by participants in the SVS/MM condition

To ensure that groups did not differ in experience levels, participants were matched individually across groups for total flight experience.

Results

1. Decisions to Divert or Continue

The decisions of pilots to either divert to an alternate airport or continue on to their destination airport (Rochelle) are shown below in Table 1.

		Decision		Total
		Divert	Continue	
Group	SVS/MM	1	9	10
	SVS only	1	9	10
	Control	0	10	10

Table 1. Breakdown of decisions to divert or continue to destination by group.

One pilot from each of the SVS conditions chose to divert to an alternate airport, although these decisions occurred at different points of the flight. The pilot in the SVS/MM condition initially chose to descend below the lowering cloud ceilings and chose to divert within 5 NM of Rochelle airport after the Moving Map displayed the weather conditions at the airport as IMC. The pilot in the SVS only condition chose to divert after initially encountering the lowering cloud ceiling and reduced visibility.

While the vast majority of pilots chose to continue the flight, their response to the deteriorating weather can be examined in terms of whether they decided to either follow the SVS Highway in the Sky (HITS) into IMC or to *avoid* the clouds by diverting or descending below the clouds at first encounter. These decisions are summarized below in Table 2.

		Decision		Total
		Avoid	Continue	
Group	SVS/MM	5	5	10
	SVS only	3	7	10
	Control	9	1	10

Table 2. Breakdown of decisions to continue into or avoid clouds by group.

All pilots in the control condition, except one, descended below the clouds when encountering the deteriorating weather. In the SVS only condition, 3 pilots elected to descend below the clouds, while the remaining 7 flew on into zero visibility IMC by following the tunnel. Pilots with the SVS and MM display were split evenly in their responses with 5 descending below the clouds and 5 continuing on into them.

Chi-square analysis reveals a significant difference in the proportion of pilots continuing in each group ($\chi(2)=7.6$, $p<0.05$). Chi-square comparisons showed a significant difference in the number of pilots continuing between the SVS only and control groups ($\chi(1)=7.5$, $p<0.01$) and a marginally significant difference between the SVS/MM and the control group ($\chi(1)=3.8$, $p=0.051$). The comparison between the two SVS groups did not show a statistically significant difference.

2. Flight Technical Error (FTE)

Flight technical error or flight path tracking error was measured by both lateral and vertical root mean square errors from the flight path for all pilots. Given that some pilots chose to leave the HITS during the encounter with deteriorating weather, RMSE were calculated up the point where the weather began to deteriorate. Two pilots' data were excluded from these FTE calculations however. One pilot in the control condition became lost which resulted in an extremely large lateral RMSE and one pilot in the SVS and MM condition deliberately flew out of the HITS to ascertain the actual cloud ceiling by visual inspection.

Given that pilots in the control condition relied only on visual landmarks in the outside world, large differences in lateral FTEs would be expected between pilots in the control condition and pilots in either SVS condition. Table 3 summarizes the results of FTE analysis for pilots in the three display conditions.

Group	RMSE – Lateral (meters)	RMSE – Vertical (meters)
SVS/MM	14.90	6.61
SVS Only	13.30	5.63
Control	2482.54	35.77

Table 3. Mean Lateral and Vertical FTEs

One-way ANOVAs (condition: SVS/MM, SVS only, control) on log-transformed data revealed a significant difference in lateral flight path tracking ($F(2,25)=259.1$, $p<0.01$) and vertical flight path tracking ($F(2,25)=54.5$, $p<0.01$) between experimental groups.

Planned comparisons revealed significant differences between the control condition and each of the two SVS conditions ($p<0.01$) while there was no statistical difference in FTEs between the two SVS conditions.

3. Time Flown into the Deteriorating Weather

Analysis of the time flown into the deteriorating weather was performed only on those pilots who descended or diverted, as it was impossible to assign such a time value to those pilots who did not ultimately descend or divert. This analysis revealed no significant differences between groups. Two of the pilots in the SVS/MM condition descended preemptively; that is before they encountered the deteriorating weather visually in the outside world. These two pilots clearly used the weather information in the Moving Map display to determine they would fly into the lowering clouds ceilings if they continued at the assigned flight altitude of 4500 feet MSL. However all other pilots across all three groups appeared to descend at around the same time and the low sample size in each condition (pilots avoiding in each group) did not provide enough power to detect significant differences.

4. Visual Scanning Measures

For analysis of pilots' visual scanning, eye tracking data were taken from just after climb out from the runway at Champaign to the beginning of the final approach leg at Rochelle. The two periods that were excluded from analysis made up approximately 2 minutes of the 60 minutes total flight time and were excluded because the tasks of taking off and landing are qualitatively different from the task of primary interest (e-route decision making).

Eye tracking measures were then extracted from either the 45 minute segment of flight before the weather deteriorated or the approximately 7 minutes during which the deteriorating weather was encountered.

The allocation of visual attention as measured by percent dwell time (PDT) to the various areas of interest (AOIs) is show in figure 3. The AOIs included the primary flight display used in the given condition (PFD), the Moving Map display (MM), the outside-world (OW). In the two experimental conditions, the PFD was the SVS display while in the control condition, the PFD was the set of traditional analog instruments. Time spent outside the SVS, MM and OW AOIs would include scans to the sectional chart for navigation and other cockpit instruments (for example, engine indicators, fuel flow indicators and the throttle block).

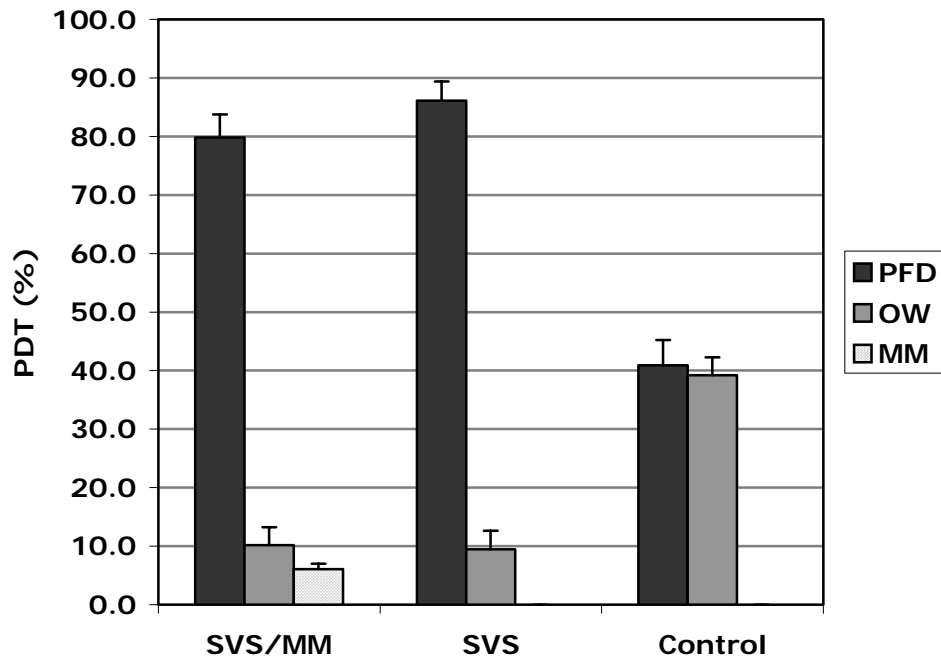


Figure 3. Percent Dwell Times (PDTs) to AOIs by pilots before encountering weather

Clearly, pilots in the both SVS conditions spent the vast majority of time attending to the SVS display and very little time looking at the outside world. Averaged across the two SVS conditions, pilots attended to the SVS approximately 83% of the time while scanning the outside world only 10% of the time. In contrast, pilots in the control condition, who by navigational necessity must seek cues in the outside world, spent almost 40% of their time looking out the window. The significant proportion of the control group pilots' scans to AOIs other than the PFD, OW and MM accounts for time spent looking at the sectional chart and flight plan that provided navigation guidance in this condition.

One-way ANOVAs revealed significant differences in mean PDTs between groups for scans to the SVS display ($F(2,27)=40.5$, $p<0.01$) and the outside world ($F(2,27)=29.9$, $p<0.01$). Planned comparisons between groups revealed significant differences between both SVS conditions and the control condition ($p<0.05$) but not between the SVS/MM and SVS conditions. Note then that the small amount of scanning to the MM weather display (about 5%) for pilots in this group, did not significantly lower either outside world or SVS panel scanning.

While there are clear differences between the scanning patterns of pilots in the three groups, analysis of eye movement data of pilots from only the SVS groups reveals further differences in scanning behavior. Figure 4 compares the percent dwell times to the SVS display and Outside-World during the 7 minute encounter with the deteriorating weather of the 8 pilots who avoided and the 12 pilots who continued flight into the clouds, collapsed over the two experimental groups.

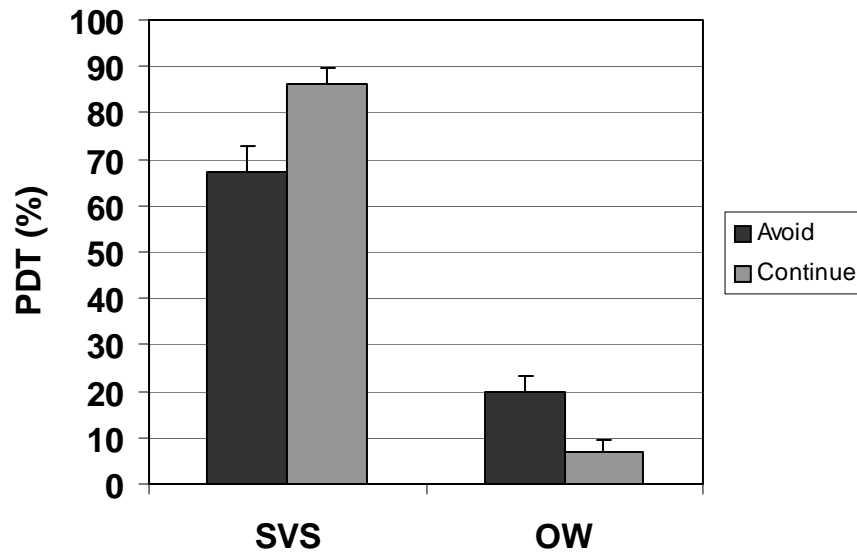


Figure 4. Percent Dwell Times (PDTs) to AOIs during weather encounter, grouped by decision

The difference in visual scanning behavior between the two pilot decision groups is readily apparent in Figure 2. Of particular interest is the fact that pilots who avoided the weather spent 19.8% of their time scanning the outside world, compared to only a figure of only 6.7% of the time by those pilots who continued into the clouds.

A two way ANOVA (between subjects: decision; within subjects: AOI) revealed a significant interaction between the two factors ($F(1,18) = 13.2, p < 0.01$) indicating that the weather avoiders looked more at the OW and less at the SVS than did the penetrators.

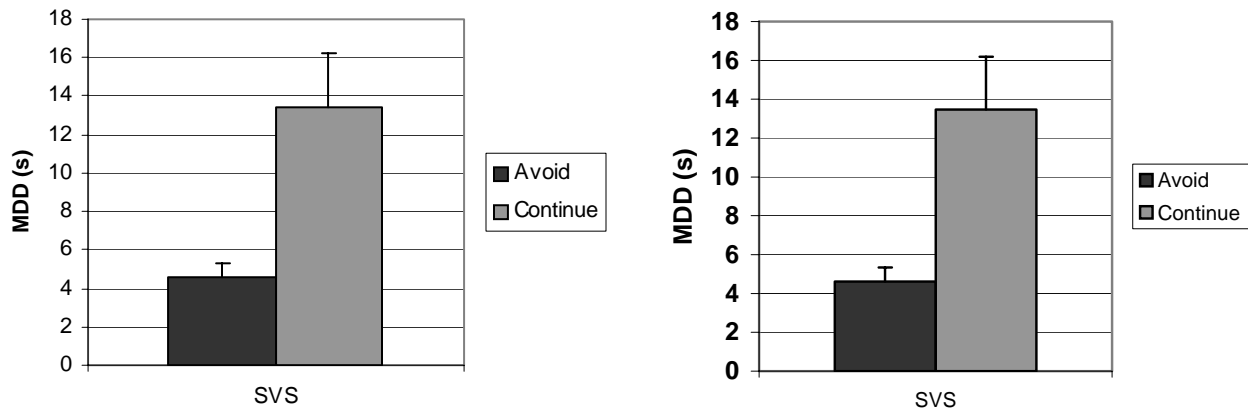


Figure 5. Mean Dwell Duration (MDD) to the SVS display and the Outside-world during weather encounter, grouped by decision

Figure 5 presents the mean **dwell duration (MDD)** to the areas of interest. That is, once the pilot moves the eyes to an AOI, this measures how long (on average) the eyes remain there before moving away. Such a measure is often correlated with percent dwell time; but the former will not distinguish several rapid scans from a fewer number of slower scans, whereas the MDD measure does so. The figure reveals that pilots who avoided the weather had mean dwells to the SVS display of less than 5 seconds, compared to pilots who continued who had mean dwells of approximately 13.5 seconds. A t-test showed this difference to be statistically significant ($t(18)=2.6, p<0.05$). A comparison of MDDs to the outside world (Figure 5b) shows pilots who continued flight into the clouds tended to have shorter dwells out of the cockpit than those who avoided the weather. This trend however, was only marginally significant ($t(18)=1.67, p=0.11$).

A second classification was performed on those pilots from both SVS groups who continued flight into the clouds. Based on pilots' answers from the post-experiment questionnaire and eye-tracking data, Table 4 shows the breakdown of those twelve pilots who chose to continue flight into the clouds into those who stated that they were aware of the deteriorating weather (eight pilots in total) and those who did not notice (four pilots in total).

		Decision		Notice Weather?	
		Avoid	Continue	Yes	No
Group	SVS/MM	5	5	3	2
	SVS only	3	7	5	2

Table 4. Breakdown of decisions to continue into or avoid clouds by group

Of those pilots who continued, three of five in the SVS/MM group claimed to have been aware of the decreasing visibility and cloud ceiling, while five of seven from the SVS only group claimed to have been aware. It should be noted however, that the questionnaire answers did not give enough detail to reveal whether these pilots noticed the weather while they were encountering it or after they had already flown into the clouds and were descending to land at Rochelle. Two pilots from both SVS groups admitted they were unaware of the deteriorating weather.

The visual scanning behavior of pilots who were either aware of unaware of the deteriorating weather are shown in Figure 6.

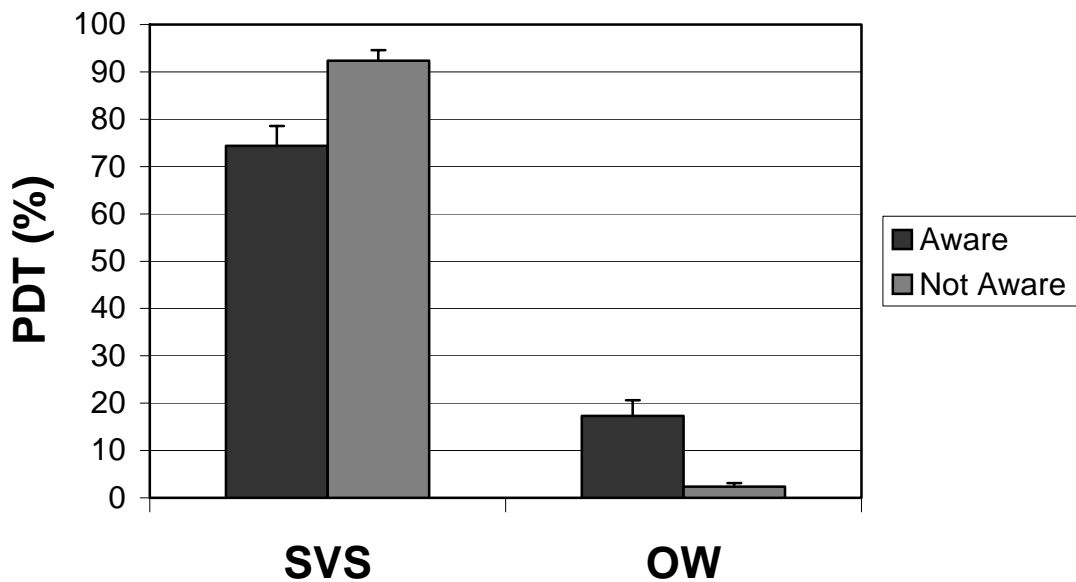


Figure 6. Percent Dwell Times the SVS display and the Outside-world during weather encounter, grouped by awareness of weather

Pilots who claimed to be aware of the deteriorating weather spent, on average 17.3% of the time scanning the outside world, compared to only 2.3% of the time that pilots who were unaware. It is also interesting to note that from the group of four pilots who were not aware of the weather, one pilot had no scans to the outside world during the time the weather deterioration was encountered.

Not surprisingly, pilots who noticed the weather spent less time (74.4%) attending to the SVS display than did those pilots who did not notice the weather (92.4%).

5. Subjective Feedback

Synthetic Vision System Display

No significant differences were found between the two SVS groups for question scores on a five point Likert scale and results for each question regarding the SVS display were collapsed across groups. Pilots were asked to compare flying with the SVS display to their previous experience flying without such a display. The middle value of the rating scale (3) was consistently described as being no different, with lower and higher values representing decrements and improvements respectively. The t-test results reported below are one-sample tests comparing the actual rating to the “no difference” rating of 3.

- Pilots reported that the SVS display with Highway in the Sky guidance improved flight path tracking (mean rating 4.45/5.00; $t(19)=12.74$, $p<0.01$).
- Pilots reported that the SVS reduced their monitoring for outside-world weather changes (mean rating 2.22/5.00; $t(19)=3.20$, $p<0.01$).
- Pilots reported that the SVS display made noticing outside-world weather changes more difficult (mean rating 2.15/5.00; $t(19)=4.07$, $p<0.01$).
- Pilots reported that flying with the SVS display increased their confidence in continuing flight into deteriorating weather (mean rating 4.50/5.00, $t(19)=8.82$, $p<0.01$).

No significant differences for these measures were found between those pilots who decided to avoid the weather and those who flew into the clouds.

Moving Map Display

Pilots in the SVS/MM condition also provided feedback on the effect the Moving Map display had on aspects of their flight performance. As above, pilots were asked to compare flying with the Moving Map to flying without the display and a “no difference” rating value of 3 was used with performance decrements and improvements rated below and above this value.

- Pilots reported that the Moving Map display did not significantly affect their monitoring for outside world weather changes (mean rating 3.20; $t(9)=0.56$, $p>0.10$).
- Pilots reported that the Moving Map display improved their assessment of weather conditions (mean rating 4.00; $t(9)=4.74$, $p<0.01$).
- Pilots reported that the Moving Map increased their confidence in continuing flight into deteriorating weather (mean rating 3.90/5.00, $t(19)=2.86$, $p<0.05$).

Discussion

The results of the current study were quite consistent with the predictions of hypothesis 1. Both SVS display conditions generated the behavior of flying VFR into IMC penetrating into the clouds, in a way that pilots in the control condition did not. Furthermore, consistent with hypothesis 2, this behavior appears to be tied fairly directly to “attentional tunneling” in that it pilots in the control condition looked outside approximately four times as much, as those with the SVS displays, a region that occupied around 80% of their visual attention. This linking between the “compelling” nature of the SVS and tunnel, and attentional neglect of the outside world (and its important events and information) is certainly consistent with the pattern of attentional tunneling revealed in other SVS studies, summarized in Wickens (2005).

It is important to note that in the current data, we cannot distinguish the extent to which both the increased downward scanning and the VFR-->IMC behavior was attributable to the tunnel (or HITS) for flight path guidance, or to the SVS terrain depiction, because we did not de-couple these two features in our experimental design. It is highly likely that some portion **is** related just to the tunnel since this, after all, was a primary source of navigational guidance, absent from the control group who were required to look outside to check for navigational features and landmarks on the ground. Furthermore, a meta-analysis of other attentional tunneling effects with advanced displays that we have carried out (Wickens, 2005) documents the contributing role of the tunnel (HITS) independently of the SVS terrain depiction. Finally, of course, we must highlight the well documented benefits that the SVS terrain depiction confers on improving terrain awareness, with its direct implications for reducing CFIT accidents (Arthur et al., 2004).

Interestingly, while the tendency toward tunneling, operationally defined by penetration of the weather, was slightly mitigated by the presence of the moving map weather display inside the cockpit (where in-cockpit displays have **not** been found to suffer the same degree of tunnel induced neglect as outside monitoring, Iani and Wickens, 2004; Wickens, 2005), this effect was very modest and not statistically reliable. This failure of the weather display to mitigate the attentional tunneling effects of the SVS may be attributed to the relatively novel nature of the weather display and the subtlety of the weather changes that were represented. This in turn, can account for why the weather display was only infrequently sampled (5% of the time).

Converging evidence that links visual attention allocation to decision behavior confirmed the individual differences hypotheses I and II. Specifically, the data revealed that those who flew into the weather looked outside relatively less (and at the SVS display relatively more) than those who diverted prior to penetration.

There was no evidence based on self reports of confidence to support the individual differences hypothesis (III) that pilots in the SVS conditions may continue flight because of their increased self-confidence in and perceived lack of risk of flying into deteriorating weather. Instead, pilots in both SVS groups reported that the presence of the display increased their self-confidence in continuing flight into deteriorating weather, regardless of their actual decision to do so in this flight simulation experiment. There was, however, limited evidence supporting the idea that pilots’ increased self-confidence and lowered perceptions of risk when flying with SVS displays impacted their decisions to continue flight. Feedback from pilots who continued flight

into the clouds indicated that eight of twelve pilots were aware of the deteriorating weather during the course of the flight. Presumably, if pilots noticed the deteriorating weather, but continued on into it, their decision to do so was based more on the capabilities of the SVS display and their confidence to use it in zero visibility conditions than their failures in situation assessment. However, the data that were collected were not detailed enough to allow determination of whether pilots noticed the deteriorating weather *before* they flew into clouds or *after* they had flown into the clouds. It is quite possible that pilots who continued flight noticed the deteriorating weather only after they had regained sight of the ground on final approach into Rochelle airport. This confound prevents any strong conclusion being made about how prominent the effects of increased self-confidence were on pilots' decisions to continue flight into deteriorating weather when flying with SVS displays.

Of course the current results do reinforce the now extensive data base suggesting that the tunnel is quite beneficial for flight path tracking, and such continuous benefits must be heavily weighed against the much less frequently observed costs of attentional tunneling observed here. Mitigation of such costs could take two generic forms. First, it is possible that enhanced representation of in-cockpit weather deterioration could be effective. This might take the form of more salient representation on the MM display, or even some form of alerting on the SVS display itself. Such an effort should probably avoid using the SVS as a platform to accurately represent 3D weather, as this action could compromise the very important benefits of using this platform for terrain representation (just as outside world weather can compromise real terrain viewing). The second approach, and not mutually exclusive of the first, is careful attention to training the scan patterns associated with SVS displays, and trying to establish some minimum OW scan percentage. The advantage of this approach is that, naturally, it will address all problems of cognitive tunneling and neglect of the outside world including those related to issues such as runway offsets, and traffic and terrain not reflected on the SVS data base.

In interpreting the current results, certain cautions and limitations of the current study should be kept in mind. First, the participants were quite inexperienced having (for the most part) only VFR qualifications. This choice was of course intentional, since the VFR-IMC error is that which has the greatest danger for those pilots. Furthermore, it is quite likely that with the tremendous ease of flying associated with the tunnel display, this display (and its resulting problems) could show an increased utilization by very inexperienced pilots. Nevertheless it is important to replicate these tendencies with those of higher experience (typical of pilots participating in some of the other revelations of attentional tunneling; Wickens, 2005).

A second limitation is that associated with nearly all simulator studies of pilot judgment; that is, the costs of wrong judgments do not have the same potentially fatal consequences as those committed in the actual airplane. For this, research will probably need to await the input of ASRS incident reports, to gain converging evidence.

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