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Weatherwise: Evaluation of a Cue-Based Training Approach for the Recognition of Deteriorating Weather Conditions during Flight

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Inappropriate and ineffective weather-related decision making continues to account for a significant proportion of general aviation fatalities in the United States and elsewhere. This study details the evaluation of a computer-based training system that was developed to provide visual pilots with the skills necessary to recognize and respond to the cues associated with deteriorating weather conditions during flight. A total of 66 pilots were assigned to one of two groups, and the evaluation process was undertaken at both a self-report and performance level. At the self-report level, the results suggested that pilots were more likely to use the cues following exposure to the training program. From a performance perspective, there is evidence to suggest that cue-based training can improve the timeliness of weather- related decision making during visual flight rules flight. Actual or potential applications of this research include the development of computer-based training systems for fault diagnosis in complex industrial environments.

INTRODUCTION

Continued visual flight into instrument meteorological conditions (IMC) remains one of the most significant causes of fatalities in the U.S. general aviation industry. Between 1983 and 1992, accidents related to visual flight rules (VFR) flight into IMC constituted 9.8% of the total number of weather-related general aviation accidents in the United States but accounted for 27% of the fatalities that occurred in this period (Aircraft Owners and Pilots Association, 1996).

Aircraft accidents involving VFR flight into IMC tend to be associated with pilots who are authorized to fly solely within visual meteorological conditions (VMC). A typical accident scenario involves the continuation of a flight toward deteriorating weather conditions such that visual reference to the terrain is lost. The pilot is subsequently forced to rely on instruments to maintain control of the aircraft, a task that is particularly difficult in the absence of appropriate training and experience. The result of the loss of reference to the terrain is that the pilot loses control of the aircraft, typically within 3 min of entry into IMC (Bryan, Stonecipher, Aron, 1955).

In attempting to establish the psychological basis for the decision by a visual pilot to continue a flight into IMC, two approaches have been investigated. The first of these is based on the assumption that visual pilots persist in flying into IMC because of a misplaced motivation to continue the flight. This approach is encapsulated within the *hazardous thoughts training program,* in which pilots are taught to recognize and respond to the onset of inappropriate motivators (Buch & Diehl, 1984).

Although the motivational approach has achieved some limited success within the operational environment (Harris, 1994), evidence suggests that some pilots may lack the skills necessary to recognize and respond to deteriorating weather conditions during flight. Evidence to support the skills-based approach can be derived from both anecdotal and empirical research suggesting that individual differences among pilots exist in their capacity to recognize and respond appropriately to deteriorating weather conditions (Goh & Wiegmann, 2001; Stokes, Kemper, & Marsh, 1992; Wiegmann, Goh, & O’Hare, 2002; Wiggins & O’Hare, 1995). These differences tend to be a function of operational experience, to the extent that experts outperform novices in the capacity to acquire information pertaining to weather-related decisions (Rockwell & McCoy, 1988; Wiggins, Connan, & Morris, 1996; Wiggins & O’Hare, 1995).

One of the most significant issues in pilots’ responses to deteriorating weather conditions during flight may involve the initial decision to divert from a planned operation. For example, the crash of a Cessna 152 in the South Island of New Zealand in 1992 appeared to be attributable to a failure to make a decision to divert, rather than to a deliberate decision to continue the flight into IMC (Transport Accident Investigation Commission, 1992). The apparent failure to actively engage in a decision-making process suggests that the pilot may have been unable to recognize and respond, in a timely manner, to the significance of the cues available during the flight. The result was a loss of control of the aircraft and a subsequent collision with terrain.

The aim of the present study was to investi- gate the extent to which pilots can be taught to recognize and respond appropriately to the cues associated with a deterioration in weather conditions during visual flight.

Cue-Based Training

The importance of cues in decision making has been well established in a number of domains, including firefighting (Klein, 1998), in-flight weather-related decision making (Stokes et al., 1992), chess (de Groot, 1966), and finance (Hershey, Walsh, Read, & Chulef, 1990). Generally these cues are employed both to establish the requirement for an intervention and to assist in the decision-making process by providing guidance as to the most appropriate strategy to be employed (Gaba, Howard, & Small, 1995). The capacity for cues to guide the decision-making process is particularly evident among experienced decision makers (Klein, 1998).

The application of cues as a trigger for the decision-making process constitutes an integral part of the broader strategy of fault diagnosis. Although a number of elements constitute fault diagnosis, the identification of task-related cues appears to be the principal means by which operators recognize changes in the system state (Friedman, Howell, & Jensen, 1985). According to Smith, Giffen, Rockwell, and Thomas (1986), the recognition of a change in system state occurs when the cues associated with an event differ from a frame or schema that embodies the stereotypical characteristics that might be anticipated within a given situation.

The initial activation of a frame is presumed to occur when an operator directs attention toward salient cues and triggers the associated frame from memory (Smith et al., 1986). However, one difficulty that has emerged as part of this process appears to be some operators' inability to develop an accurate and reliable association between the salient cues and the frame (Stokes, Kemper, & Kite, 1997). This is the basis for misdiagnoses and may lead to a situation in which the operator fails to appreciate the significance of the changes that occur in the operational environment.

Given the significance of salient cues as a trigger for fault diagnosis, it might be argued that the same principle applies in the context of complex decision making. For example, the decision-making process begins with an assessment of the change that has occurred within the system state. In the case of weather-related decision making, the recognition of a change in the system state, and the association with the appropriate frame, would be expected to provide pilots with an understanding of the likely consequences associated with proceeding with the flight.

In establishing a relationship between salient cues and a related frame, the theoretical basis is provided for a training initiative that has the potential to enhance learner performance in probabilistic environments. Empirical support for this proposition can be drawn from Sniezek, Dudycha, and Schmitt (1978), who found that teaching the cues pertaining to the relationship between mathematical functions improved learners' performance during a probability learning task. Similarly, Klayman (1988) observed that enabling learners to "discover" the cues associated with a task resulted in subsequent improvements in the learners' ability to predict the behavior of a computer-controlled graphic display. However, despite the promise afforded by a cue-based approach to training, the principles have yet to be examined in the context of aeronautical weather-related decision making.

From a theoretical perspective, it was assumed that the timeliness with which weather-related decisions are made could be improved by exposing pilots to weather-related cues and developing a frame that embodied the pattern of cues that would trigger the requirement for a weather-related decision.

Program Development

To test the potential impact of cue-based training, we developed a computer-based training program to facilitate the recognition and application of a series of cues that could be employed as triggers for in-flight weather-related decision making. The weather-related cues were identified following a cognitive interview with expert pilots who were asked to describe a situation in which they made what they considered an inappropriate weather-related decision (Wiggins, 1999; Wiggins & O'Hare, 2003). As part of the interview, experts were asked to identify any cues in the environment that would have indicated that the conditions were deteriorating (Wiggins, 1999). A total of nine cues were identified by the participants, and the application of these cues was evaluated using an Internet-based survey in which participants were asked to make a series of judgments concerning 10 images of in-flight weather conditions (Wiggins & O'Hare, 2003).

Among the experts in the study, the mean frequency of cues considered in deciding that VFR flight would no longer be possible ranged from 2.78 to 5.46 (Wiggins & O'Hare, 2003). These data provided the basis for a rule of thumb, to the effect that a deterioration in three or more weather-related cues during a flight would be sufficient to trigger the requirement for a diversion from planned flight. Having evaluated the nine cues as indicators of deteriorating weather conditions during flight, we integrated the cues and the rule of thumb into the training system, forming the basis for the computer-based training program.

Program Structure

The training system consisted of four stages, the first of which was designed to highlight the difficulty involved in assessments of in-flight weather conditions. Specifically, users were asked to assess a series of in-flight weather-related images and determine the extent to which the weather conditions depicted were above or below the minimum requirements for visual flight. Feedback was subsequently provided concerning the accuracy of the judgments.

The second stage of the system was designed to introduce the user to the nine weather-related cues that were identified as part of the cognitive interviews (see Figure 1). A tenth cue, horizon, was also included following discussion with subject matter experts during the initial development of the computer program. However, this cue was not the subject of evaluation in the present study.

The weather-related cues were introduced to the users by the presentation of an image of in-flight weather conditions. Information pertaining to the specific cues was accessed by passing the cursor over various features of the image, such as the terrain or the cloud base. This process revealed a series of visual examples of situations in which the cues were associated with a deterioration in weather conditions below the requirements for visual flight.

To reinforce the significance of weather-related cues during the decision-making process, we asked users to indicate, in a series of images involving a deterioration in weather conditions during flight, the extent to which they perceived each of the cues to be significant. Throughout this third stage a rule of thumb was advocated, to the effect that simultaneous deterioration in three or more cues during a flight would act as a trigger for the decision-making process.

The final stage of the training program involved the identification of the point during a sequence of in-flight video recordings at which the weather conditions deteriorated below the requirement for VFR flight. This task represented an application of the weather-related cues in a dynamic environment and provided an opportunity for users to receive feedback concerning the appropriateness of their decisions.

Evaluation

The evaluation phase consisted of exposure to a number of video clips of weather conditions that simulated progress along a planned flight. At the beginning of the flight, participants could peruse the flight plan and map and conduct a simulated inspection of the aircraft.

Once the flight had been initiated, the meteorological conditions deteriorated progressively, and the pilot was asked to make a series of decisions as to whether the flight should continue or be diverted. In each case the two options (continue or divert) were presented simultaneously on the computer screen, and the participant was asked to select one. The decision-making process was limited to 10 s, and the flight would progress automatically if a decision was not made within this time. This strategy was designed to simulate the time constraints imposed in flight during the decision-making process.

There were five decision points throughout the flight; of these, Decision Point 3 was designed as the optimal stage at which the decision to divert ought to have been made. Decision Point 3 was the first occasion on which at least three of the weather-related cues had deteriorated simultaneously. This was confirmed by a group of three subject matter experts, who determined that the visibility, terrain clearance, cloud darkening, and cloud concentration cues for Decision Point 3 had all deteriorated since the preceding video clip.

It was hypothesized that in comparison with a control group, participants who were exposed to the training program would better recognize the requirement for a weather-related decision and

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would thereby initiate a diversion at or before the optimal decision point during the flight.

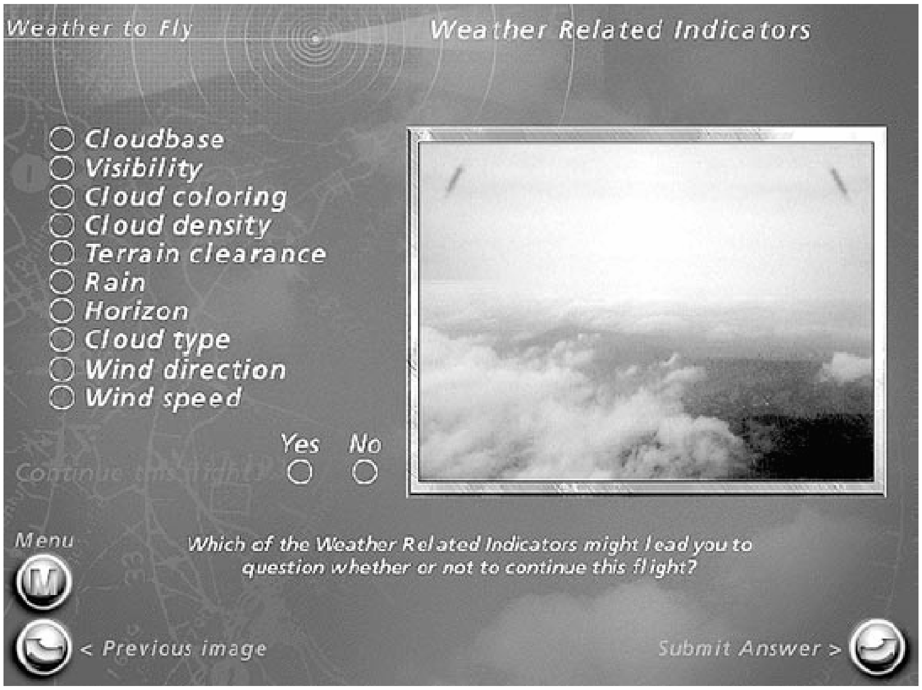

Figure 1. An example of the weather-related cues interface from the training system.

METHOD

Participants

The study participants were 66 licensed private pilots (11 women, 55 men). They ranged in age from 19 to 47 years (*M* = 24 years), were recruited from throughout Australia, and had accumulated fewer than 150 h as the pilot in command of cross-country flights. They were not financially compensated for their participation.

The pilots were randomly divided into two groups: a cue recognition group (44 participants) and a control group (22 participants). No significant differences were evident between groups in terms of cross-country flying experience, $F(1, 64) = 1.31$, $p > .05$; experience as pilot in command, $F(1, 64) = 0.11$, $p > .05$; instrument flying experience, $F(1, 64) = 2.41$, $p > .05$; or total flying experience, $F(1, 64) = 0.53$, $p > .05$.

Design

The study had a one-way, between-subjects design. Participants in the cue recognition group had access to the training program prior to completing the evaluation phase. Those in the control group did not complete any of the preliminary phases of the program prior to completing the evaluation phase.

Stimuli and Materials

The stimuli used in the computer-based training program were developed with the assistance of the Federal Aviation Administration (which now distributes the program under the name Weatherwise.) Once a beta version of the program had been developed in house, professional designers were engaged to produce the computer program using Authorware™ and Director™ (Macromedia, San Francisco, CA).

The materials included a data evaluation sheet, on which participants were asked to indicate their level of operational experience, their assessment of the applicability of the material, their perceptions of the usability features of the computer program, and the relative importance that they attributed to each of the nine cues as an indication that VFR flight may not be possible along a planned route. Information pertaining to the relative importance of the weather-related cues was recorded prior to and following exposure to the computer program using a Likert scale ranging from 1 (*not at all important*) to 5 (*very important*).

Procedure

Participants were tested individually, either in a laboratory or in a quiet room. They were recruited by approaching individual flying schools and by advertising in aviation-related newsletters and magazines. Each participant was provided with an information sheet and a consent form and began the study by completing the first stage of the data evaluation sheet.

No time limit was imposed on those participants who were exposed to the training system. Participants in this group were encouraged to progress only when they felt comfortable with the material provided.

During the process of evaluation, participants were exposed to two stages of the simulated flight: a preflight and a flight stage. The pre-flight stage included a simulated preflight inspection, topographic map, flight plan, information pertaining to the weather conditions, and information pertaining to various airports en route. This information was displayed in a menu-based system through which access was consistent with the navigation principles employed during the subsequent flight stage. No time limit was imposed on participants during the preflight stage, and they were encouraged to progress only when they felt comfortable with both the usability aspects of the program and the information available.

RESULTS

Training Time

Overall, participants in the cue recognition group spent a mean of 27.11 min (*SD* = 2.98 min) examining the information during the training phase of the study.

Self-Report Assessment

Participants were asked to indicate whether they might be inclined to apply the particular concepts and principles that were embedded in the program. In the case of the training system, the fundamental embedded concepts were the weather-related cues. Therefore, the assessment involved the participants' consideration, prior to and following exposure to the program, of the extent to which they would be inclined to utilize the cues during flight.

The responses concerning the potential application of the cues were made using a Likert scale, and the results were examined using a 2 · 2 (Group · Trial) mixed-methods multivariate analysis of variance incorporating two levels of group (cue recognition and control) and two levels of trial (pretest, posttest) as the independent variables and the ratings of the cues as the dependent variables. The results revealed a main effect for group, $F(9, 56) = 2.09$, $p < .05$, and a main effect for trial, $F(9, 56) = 6.65$, $p <$ 01, although no interaction was evident, $F(9, 56) = 1.91$, $p > .05$.

Subsequent univariate tests revealed that the main effect for group was attributable to the responses for the darkening cloud, $F(1, 64)=8.84$, $MSE = 1.03$, $p < .01$, and terrain clearance cues, $F(1, 64) = 4.69$, $MSE = 1.05$, $p < .04$. For the darkening cloud cue, the mean Likert scale response of participants in the cue recognition group ($M = 4.22$, $SE = 0.11$) was higher than that of the control group ($M = 3.66$, $SE = 0.15$). Similarly, participants in the cue recognition group recorded a relatively higher mean response for the importance of terrain clearance ($M = 4.34$, $SE = 0.11$), as compared with the control group ($M = 3.93$, $SE = 0.15$).

Univariate tests for trial revealed main effects for each of the nine cues: cloud base, $F(1, 64) = 4.67$, $MSE = 0.29$, $p < .05$; visibility $F(1, 64) = 6.58$, $MSE = 0.25$, $p < .05$; darkening, $F(1, 64) = 6.58$, $MSE = 0.31$, $p < .05$; concentration, $F(1, 64) = 23.30$, $MSE = 0.24$, $p < .001$; rain, $F(1, 64) = 8.57$, $MSE = 0.23$, $p < .001$; terrain clearance, $F(1, 64) =17.64$, $MSE= 0.31$, $p < .001$; cloud type, $F(1, 64) =14.01$, $MSE=0.59$, $p < .01$; wind direction, $F(1, 64) = 32.78$, $MSE = 0.31$, $p < .001$; and wind velocity, $F(1, 64) = 15.89$, $MSE = 0.34$, $p < .001$. In each case perception of the importance of the cues in assisting in- flight weather-related decision making increased posttest (see Table 1).

Performance Assessment

The main assessment criterion was performance during a simulated flight at the conclusion of the program. A chi-square analysis was used to determine the extent to which differences occurred in the frequency with which members of the control and cue recognition groups would divert at, or before, the optimal decision point. Because of the sample size, some cells were collapsed so that responses before the optimal decision point were coded in one group, whereas responses at or after the optimal decision point were coded as second and third groups, respectively.

TABLE 1: Likert Scale (1–5) Responses for Importance of Weather Cues

	Mean (*SE*)	
Cue	Pretest	Posttest
Cloud base	4.16 (0.12)	4.37 (0.11)
Visibility	4.03 (0.11)	4.27 (0.09)
Darkening	3.80 (0.11)	4.07 (0.09)
Cloud concentration	3.62 (0.10)	4.05 (0.08)
Rain	3.33 (0.10)	3.59 (0.10)
Terrain clearance	3.92 (0.12)	4.35 (0.09)
Cloud type	3.23 (0.13)	3.76 (0.12)
Wind direction	2.62 (0.12)	3.22 (0.12)
Wind velocity	2.79 (0.13)	3.22 (0.13)

A subsequent chi-square analysis revealed a statistically significant relationship between the frequency with which pilots in the cue recognition and control groups continued beyond the optimal decision point, $\chi^2(2) = 14.63$, $p < .01$.An inspection of the contingency table indicated that 54% of the control group participants continued beyond the optimal decision point, as compared with 11% of participants in the cue recognition group (see Table 2). These results suggest that exposure to the training program may have the capacity to improve performance in terms of preventing pilots from continuing beyond the optimal decision point during in-flight weather-related decision making.

DISCUSSION

The primary aim of this study was to investigate the extent to which a cue-based approach to training could be employed to facilitate the acquisition of the skills necessary to efficiently recognize and respond to deteriorating weather conditions during flight.

In the context of this study, it was assumed that relatively inexperienced pilots had not yet developed frames (Smith et al., 1986) encapsulating the critical weather-related cues that determine that VFR flight would no longer be possible along a planned route. The aim of the training program was to enable learners to interact with these critical cues and develop a frame that encapsulated these cues. The validity of this training system was examined on the basis of a combination of self-report assessment and assessments of performance during a simulated in-flight decision-making task.

The self-report data showed an across-the board increase from pretest to posttest in the rated importance of all nine critical weather cues for both the control participants and the participants who completed the cue recognition training. This increase could be attributable to their having completed the simulated crosscountry flight or could simply have been attributable to so-called demand characteristics of the experiment. Because the flight task involved carefully discriminating among different weather conditions, it is possible that simply completing the task would lead participants to elevate their perceptions of the importance of the cues depicted. However, there was an additional effect of participating in the cue recognition training, which increased the perceived importance of two of the critical cues (cloud darkening and reduction in terrain clearance), as compared with the control group participants' ratings.

These data thus suggest a specific change in the perceptions attributable to participation in the cue recognition training in addition to general effects attributable to participation in the study as a whole or in the simulated flight component.

The differences that emerged among participants on the basis of the self-report assessment were consistent with the results that emerged from the performance assessment. The performance assessment was undertaken using a simulated in-flight scenario in which participants "flew" a flight and made a series of decisions concerning whether to divert or continue the flight in the face of deteriorating weather conditions. The frequency with which participants continued beyond the optimal decision point was compared, and the results indicated that control group participants were significantly more likely than cue recognition group participants to continue beyond the optimal decision point. On this basis it can be argued that exposure to the training system resulted in an improvement in the timeliness of the decisions made during a simulated cross-country flight.

TABLE 2: Points at which Participants (*N* = 66) Decided to Divert during the Evaluation Flight

	Decision Point		
Group	Preoptimal	Optimal	Postoptimal
Cue recognition	12	27	5
Control	2	8	12

Limitations of the Study

Although the training system has yielded a number of positive outcomes, assessment of the program was based on a simulated assessment of in-flight decision making. The extent to which performance in a simulated environment reflects performance within the operational environment is a matter of debate. However, it should be noted that the simulated flight in the training system was based on real weather data and followed an actual route within the United States. Furthermore, a time limit was imposed on the decision-making process to reflect the limited time available to formulate weather-related decisions during actual flight.

From an experimental perspective, it might be possible to examine the decision-making performance of pilots during actual flight, but ethical considerations preclude exposing pilots to the significant level of risk that an in-flight assessment of weather-related decision making might impose. The level of risk could be minimized by including a safety pilot aboard the aircraft, but it might be argued that performance bias could be triggered to the extent that behavior would improve beyond the level that would normally occur in the operational environment.

Implications for Practice

On the basis of the results, there is sufficient evidence to suggest that computer-based training systems can facilitate the recognition and response to faults within complex technological environments. These faults may range from large-scale system failures, such as might be evident in a nuclear reactor, to relatively less complex faults, such as the recognition of an inoperative instrument landing system. In each case there is a need to associate the situation specific cues to a frame of reference within long-term memory. By actively establishing the frame at a relatively early stage of the user's development, one can obviate the need to develop the skills through trial and error.

Previous attempts to integrate computer-based training systems in aviation have generally focused on the development of procedural (Koonce, Moore, & Benton, 1995; Taylor et al., 1997) and/or perceptual-motor skills (Koonce & Bramble, 1998; Mattoon, 1994) among users. However, computer-based training systems also have the capacity to develop cognitive skills such as fault recognition and diagnosis (Marinelli, 1994). The results arising from the present study provide support for this assertion and suggest that greater effort needs to be directed toward the development of interactive computer-based training systems that focus on the development of task-specific cognitive skills.

In considering the development of taskspecific skills, we note that effective and efficient decision making within complex environments is also dependent on an appropriate motivation to successfully complete the task. Whereas the training system described in the present study focuses on the development of skills pertaining to fault diagnosis, it might be argued that future initiatives ought to consider the integration of a motivational component and examine the extent to which timely fault diagnoses can assist the broader decision-making process. In particular, one might argue that the timely recognition of a deterioration in the system state, combined with an appropriate motivation to complete the task, may provide the ideal conditions under which successful decisions can be made, especially among less experienced practitioners.

Finally, at an applied level, the training system represents a highly cost-effective means of improving human performance in the operational environment. It can be used either individually or within a group setting, and it is likely to be more appropriate for those users who are relatively less experienced in the operational environment.

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