CHANGES IN PILOT BEHAVIOR WITH PREDICTIVE SYSTEM STATUS INFORMATION

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ABSTRACT

Research has shown a strong pilot preference for predictive information of aircraft system status in the flight deck. However, changes in pilot behavior associated with using this predictive information have not been ascertained. The study described here quantified these changes using three types of predictive information (none, whether a parameter was changing abnormally, and the time for a parameter to reach an alert range) and three initial time intervals until a parameter alert range was reached (ITIs) (1 minute, 5 minutes, and 15 minutes). With predictive information, subjects accomplished most of their tasks before an alert occurred. Subjects organized the time they did their tasks by locus-of-control with no predictive information and for the 1-minute ITI, and by aviate-navigate-communicate for the time for a parameter to reach an alert range and the 15-minute conditions. Overall, predictive information and the longer ITIs moved subjects to performing tasks before the alert actually occurred and had them more mission oriented as indicated by their tasks grouping of aviate-navigate-communicate.

INTRODUCTION

Documented instances exist where some type of early notification to the flight crew of a system parameter deviation could have prevented or lessened the consequences of an aircraft's system failure [1], [2]. This early notification may improve decision making by allowing the flight crew to be more informed, thus increasing the safety of the flight [3]-[5]. Current research has shown that predicting system failures bring potential benefits for increased safety of flight [6]-[9].

Research has indicated a strong pilot preference for predictive information [6]. Other results garnered from this study have demonstrated that pilots do use the predictive information to affect the alert and its consequences [8]. For instance, with predictive information (in the form of knowing that a parameter was moving abnormally or of knowing the time to an alert), pilots retrieved checklists, descended, diverted, and declared an emergency earlier [8]. These results also indicated that the longer the time pilots had until a parameter reached an alert range, the earlier they performed various tasks [8].

The same research, though, also indicated that pilot perceived workload increased slightly with the predictive information [9]. In addition, pilot perceived situation awareness decreased with predictive information but increased with increasing <u>initial time intervals until a parameter alert range was reached</u> (ITIs). This, in addition to pilots performing certain tasks earlier with increasing ITI, reemphasized that the changes in pilot behavior should also be analyzed.

The possible changes in pilot behavior as defined by the order (absolute and relative) pilots would perform certain tasks and how this order affected their stress levels had not yet been fully analyzed. Currently, flight crews have defined procedures and tasks they must follow when a parameter reaches an alert range but no such procedures exist regarding a parameter *moving towards* an alert range. Therefore, it was of interest to determine if and how predictive information might affect pilot behavior. Thus, this paper presents the results from an investigation of the behavior of pilots exposed to various levels of predictive information.

Objectives

This experiment was conducted to determine the effects predictive information would have on pilot behavior in an operational setting during non-normal system events. Pilot behavior was defined as the tasks pilots did and when they did these tasks. The tasks were: when the pilot noticed the failure, accessed the appropriate checklist, took action to affect the alert, turned the plane off-track, diverted, declared an emergency, called dispatch, talked to the flight attendant, and obtained weather information at the diversion airfield.

Experimental Variables

Of the four experimental variables, two were directly manipulated: the predictive information available and the ITI. The predictive information available, a between-subject variable, was one of three types: (1) none (baseline), (2) whether a parameter was increasing or decreasing abnormally (direction), or (3) the time remaining to a parameter alert range (countdown). The second variable was the ITI, a within-subject variable, and it had four levels: (1) 1 minute, (2) 5 minutes, (3) 15 minutes, and (4) ETA+45 minutes (Estimated Time to Arrival). Baseline predictive information and ETA+45 minutes ITI, which place the alert beyond the end of the flight, were control conditions. The third experimental variable was the four independent faults each subject encountered, and was partially controlled in that the parameter would degrade in a regulated manner. The last experimental variable, task, was calculated based on when subjects performed certain tasks, such as diverting.

Predictive Information Available. In the baseline condition, no predictive information was available. Thus, when a parameter reached an alert range, the subjects saw the typical alert message (e.g., CABIN ALT) with the accompanying aural alert (table 1). In the other two conditions, direction and countdown, a text message on the alerting system screen notified subjects that a parameter was moving towards an alert range once a failure occurred. For the direction condition, subjects were told that a parameter was increasing or decreasing abnormally (table 1). For the countdown condition, subjects were told when a parameter would reach an alert range for the given aircraft state (table 1). The onset of an alert was updated in increments of whole minutes if the time remaining was greater than 1 minute. If the time to an alert was less than 60 sec, the message updated for every 15-sec change in the onset of an alert.

Table 1 - Examples of Predictive Information

Condition	Predictive Information	Alert Information
Baseline	none	"CABIN ALT"
Direction	"CABIN ALT INC"	"CABIN ALT"
Countdown	"CABIN ALT 7MIN"	"CABIN ALT"

In all cases, the predictive information presented to subjects was always correct and accurate. The predictive information had an alert category of advisory. Furthermore, parameters increased or decreased at a constant rate dependent on the state of the aircraft. Lastly, in the direction and countdown conditions, the related standard alert information message replaced the predictive information message when the parameter reached an alert range.

ITIs. Each subject saw four ITIs (the time interval to an alert once a failure began): (1) 1 minute, (2) 5 minutes, (3) 15 minutes, and (4) ETA+45 minutes. The configuration of the aircraft affected the actual time to an alert; for example, throttling back the affected engine during the scenario with the EGT (Exhaust Gas Temperature) increase delayed the onset of an alert.

Faults. All four data runs, or scenarios, and the training run included a fault in which a parameter would eventually reach an alert range if the subject took no action. The faults were (1) cabin altitude increase, (2) forward cargo overheat, (3) EGT increase, and (4) oil quantity decrease. The training run had an avionics overheat. All failures were designed to behave as realistically as possible [10]-[13] and are described below.

For the scenario with the cabin altitude increase, the cabin altitude increased to the airplane altitude. The outflow valve, if checked, was fully closed once the failure started. Although the increase could not be controlled through the environmental system, the cabin altitude warning would not be reached if the subject descended below 10,000 ft mean sea level and if he had at least 4½ minutes until the alert range was to be reached—the time needed to descend from the initial altitude of 37,000 ft to 10,000 ft.

In another data run, the forward cargo hold, initially set-up for carrying animals, had a temperature increase. If the subject changed to the cargo mode, the temperature increase would slow due to the lower temperature setting. Also, if he discharged the forward cargo fire bottle before the alert range was reached, the forward cargo temperature would never reach the alert range. If the subject discharged the forward cargo fire bottle after the fire warning, as the forward cargo fire checklist instructs him to do, the temperature would drop below the alert range.

During the scenario with the EGT increase, the EGT rose steadily and if it reached the alert range, the subject would have to follow the engine failure/shutdown procedure. The subject could slow the increase if he throttled back the engine with the increasing EGT or stopped if he shut down the affected engine. If the subject restarted the engine, the EGT would again increase until it reached the alert range.

Finally, one scenario resulted in an oil quantity decrease due to loss of oil. The decreasing oil quantity drove the oil pressure down and the oil pressure triggered the alert once it reached an alert range. The only way to decrease the rate of oil loss was to shut down the affected engine.

For the avionics overheat training run, changing the avionics mode to override from its initial position of normal decreased the rate of temperature increase. Furthermore, by disconnecting bus 3, the temperature would stay below the warning limit. Thus, the load on bus 3 was the primary cause of the overheat.

Tasks. Several tasks the subjects could take that would affect the onset of an alert and the gravity of the failure were of interest. These tasks were when they (1) accessed appropriate checklists, “checklist,” (2) took actions to affect the time to an alert, “action,” (3) diverted, “divert,” (4) descended, “descend,” (5) obtained weather information at the diversion airfields, “weather,” (6) turned off-path, “turn,” (7) declared an emergency, “emergency,” (8) talked to the head flight attendant, “flight att,” and (9) called dispatch, “dispatch.” The time when (10) the warning occurred, “warning,” and (11) the failure started compared to when a warning occurred or would have occurred, “init alert,” were also recorded.

All failures had checklists associated with them. Thus, if a parameter reached an alert, the subject should follow the checklist. A subject could access the checklists before the parameter reached an alert range if he so desired.

The specific actions considered as trying to affect the onset of an alert depended on the scenario. These actions were checking the outflow valve position for the cabin altitude increase failure, changing the forward cargo compartment mode from animal to cargo or discharging a forward cargo compartment fire bottle for the forward cargo fire scenario, and throttling back or shutting down the affected engine for the EGT increase and oil quantity decrease scenarios.

Since the flight was under ETOPS (Extended Twin-engine OPerationS) rules, subjects had to divert for the oil quantity decrease and EGT increase failures when they shut down an engine. The ETOPS rules do not specify a diversion is necessary with cabin pressure loss, but for fuel efficiency reasons and passenger comfort, the logical choice would be to divert. If a subject had a forward cargo fire warning, he would be required to divert under ETOPS rules. If a subject discharged the fire bottle before the fire warning, thus preventing the temperature from increasing into the alert range, he did not technically have to divert, but prudence recommended diverting anyhow because of the strong possibility of fire.

Three of the faults required subjects to descend: (1) the cabin altitude increase, and after engine shutdown for both (2) the EGT increase and (3) the oil quantity decrease. Also, checking weather at the diversion airport, turning off path, declaring an emergency, telling the flight attendant the status of the flight, and calling dispatch to let the company know the current situation was not explicitly required but was considered good airmanship.

EXPERIMENT DESIGN

Subjects

Twelve glass-cockpit airline pilots familiar with ETOPS rules participated as subjects. Seven were currently first officers, the remaining five were captains. The average age was 48 years old and the average commercial airline flight experience was 16 years.

Test Design

This experiment was run in the Advanced Civil Transport Simulator at the NASA Langley Research Center. This simulator had flight performance characteristics similar to a Boeing 757. The flight deck resembled a Boeing 747-400 or MD-11. The subject acted as captain, pilot-not-flying. A confederate first officer (F/O) was pilot flying and he was well versed in the operation of the simulator. A confederate air traffic controller (ATC) and company dispatch operator provided the necessary coordination with the ground.

The flight was from Dulles airport to Charles de Gaulle airport with a 60-minute ETOPS rule; i.e., the plane was never more than 60 minutes from an alternate airfield. The 60-minute rule was used in order to have several PETs (Point of Equal Time); i.e., the point where the plane was 60 minutes from any suitable alternate airport. The scenarios were set up such that each segment of flight started before a PET; thus, this experiment only included the cruise phase of flight. If the configuration of the aircraft did not change during the fault, the affected parameter would reach an alert range a few minutes before the aircraft intersected the PET except in the ETA+45 minute condition.

Any materials and information the subject needed were provided to him. Plotting charts, landing plates, a dispatch weather briefing, and a flight plan were available in paper form. Checklists were electronic and mimicked the Boeing model of the quick reference handbook [14]. Voice communication was used for ATC and dispatch. Both ATC and dispatch were able to supply current weather information at any of the diversion airfields. Basically, the weather at all diversion airfields was acceptable for landing—drizzle with a ceiling around 1,000 ft and visibility approximately 1½ miles with winds at no more than 10 knots. ATC also reasonably expedited (within 15 sec) any requests subjects had regarding course changes. The confederate F/O was able to answer operational questions from the subject; i.e., he supplied all the operational information normally found in the aircraft manual. Lastly, subjects made any passenger announcements or held conferences with the head flight attendant, or purser, to the experimenter sitting in the back of the simulator.

As mentioned earlier, the faults, the ITIs, and tasks were within-subject variables while the predictive information was between subjects. Since subjects could only see each failure once, each subject had four data runs in addition to a training run. Thus, all subjects saw each of the four faults once and each of the four initial times to an alert once with only one of the three types of predictive information.

Dependent Measures

The dependent measure was when subjects performed the various tasks listed above.

Procedure

When a subject first arrived, he received an overview on this experiment. After this introduction, the confederate F/O gave a detailed description of the simulator and its operation, and the flight plan to the subject before the training run started. The training run included the avionics overheat fault 15 minutes into the flight. The ITI was 5 minutes given the initial aircraft configuration. No data were recorded during training.

A short break was taken after the training run and before data run 1. An hour lunch break followed the first data run. After lunch, the subject completed data runs 2 through 4. Each data run took approximately 30 minutes. At the end of each data run, the subject was asked about the failure, his actions, and his workload. The presentation order of predictive information and initial time to an alert were counterbalanced while scenario order was only partially balanced due to the number of subjects.

Data Analysis

All times were normalized in order to extricate the fact that different ITIs occurred during the flight. If the times were not normalized, the data clustered around four discrete categories dependent on the initial time to a parameter alert range. The normalized time ratio was

$$\text{normalized time ratio} = \frac{\text{time at which X occurred}}{\text{actual time to alert}}.$$

Times were taken from failure start. The actual time to alert was when the alert truly occurred or would have occurred had the subject not done something to prevent it such as shut down an engine. Subjects were not penalized in the data analysis if they did not perform a particular task.

A multidimensional scaling using SPSS®, Statistical Product and Service Solutions, was done calculating an Euclidean distance from the normalized time ratio data [15]. SPSS® was also used to do a hierarchical cluster analysis again using the normalized time ratio data.

RESULTS

Order of Tasks

The order subjects accomplished the tasks are similar except for some transpositions (figs. 1 and 2). With predictive information (fig. 1), subjects performed the vast majority of tasks earlier with the direction predictive information than in the baseline condition, and even earlier with the countdown predictive information. Subjects also did tasks earlier the greater the ITI (fig. 2). In fact, for the 15-minute ITI, subjects accomplished everything before the alert.

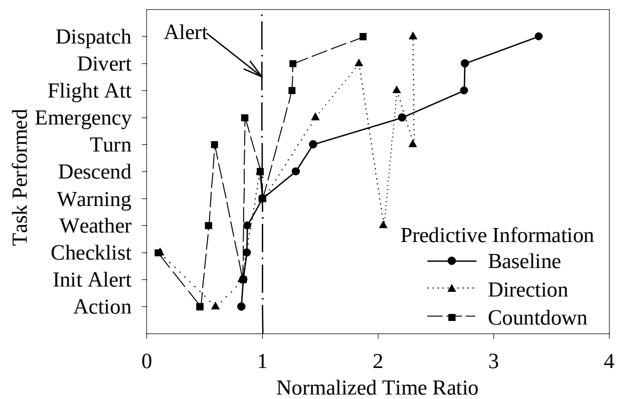

Figure 1 – Time Tasks Performed by Predictive Information

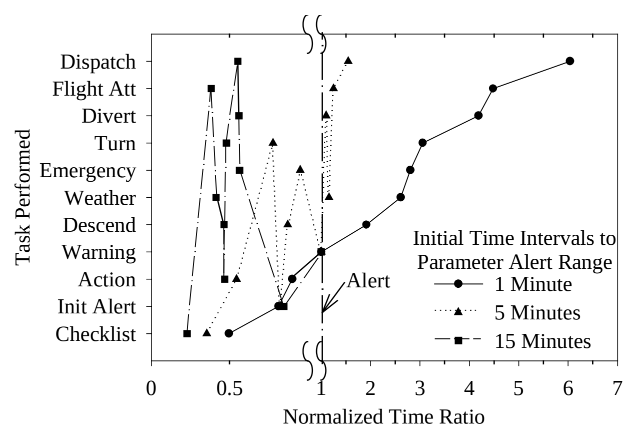

Figure 2 – Time Tasks Performed by ITIs

Multidimensional Scaling

The multidimensional scaling for the normalized time ratio data by predictive information and 1-, 5-, and 15-minutes ITIs had one dimension but the one dimension differed depending on the particular condition (figs. 3 and 4). Not enough data were present for the ETA+45 minute condition. The dimension changed with increasing predictive information and increasing ITI. For the baseline and 1-minute ITI, the dimension was locus-of-control. The locus-of-control was defined by how much control the subject was able to exert over the task. At the other end of the spectrum, countdown predictive information and 15-minutes ITI, the dimension entailed aviate-navigate-communicate. For the direction and 5-minute conditions, the dimension was muddled because it was transitioning from locus-of-control to aviate-navigate-communicate.

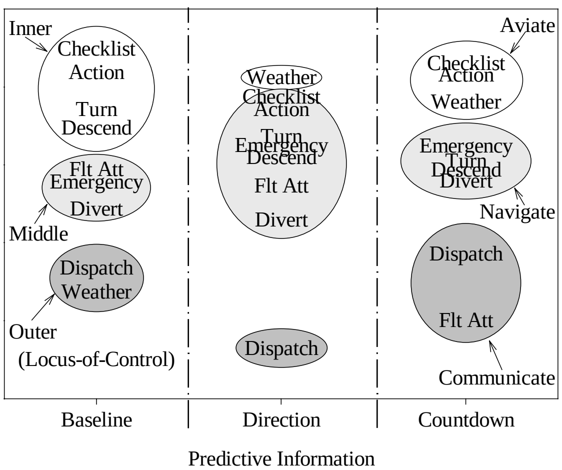

Figure 3 – Clustering by Predictive Information

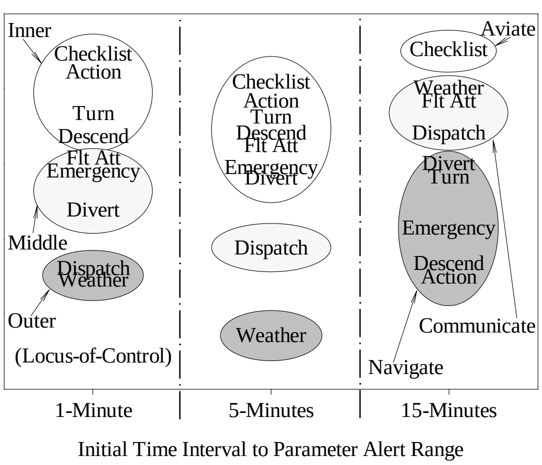

Figure 4 – Clustering by ITIs

Cluster Analysis

A cluster analysis for the normalized time ratio data was done for each predictive information condition and for each ITI except for ETA+45 minutes since not enough data were present for that condition. Figures 3 and 4 show the cluster analysis. The clustering for baseline predictive information and 1-minute ITI are the same. The clusters were interpreted to be inner-loop locus-of-control to outer-loop locus-of-control. For the countdown predictive information and for the 15-minute ITI, the groups are aviate, navigate, and communicate. As mentioned with the multidimensional scaling above, the clusters for the direction and 5-minute conditions were muddled since the dimension is changing from locus-of-control to aviate-navigate-communicate.

DISCUSSION

To explore the effects predictive information would have on pilot behavior, a simulator experiment tested three types of predictive information and four ITIs. The three types of predictive information were (1) baseline, (2) direction, and (3) countdown, and the four ITIs were (1) 1 minute, (2) 5 minutes, (3) 15 minutes, and (4) ETA+45 minutes.

As the amount of predictive information increased (baseline to direction to countdown) or the ITI increased, subjects accomplished most of their tasks before the actual alert occurred. Note that the time to task and checklist access in the baseline condition may have been artificially low because subjects were primed for a failure. Thus, they may have been more diligent scanning the instruments looking for deviations.

Subjects organized the time they did their tasks by locus-of-control for the baseline predictive information and 1-minute ITI, and by aviate-navigate-communicate for the countdown and 15-minute conditions. For the other two conditions (direction and 5-minutes), the dimension was in transition from locus-of-control to aviate-navigate-communicate. For the 15-minute ITI, the ordering of the groups was aviate, communicate, navigate. As compared to the countdown condition, the 15-minute condition gave subjects enough time to broadcast their intentions before having to carry them out; thus, communicate and navigate switched places. Notice that the baseline, and 1- and 5-minute conditions have the same ordering although the exact values are different. The similarity of the baseline and 1-minute ITI suggests that the 1-minute ITI is not enough of a forewarning to be of benefit. Furthermore, the similarities of the 5-minute ITI plus its transitional groupings to the baseline condition suggests that a 5 minute forewarning gives the subject just enough time to affect the failure and the onset of an alert. This is further substantiated by the vast majority of tasks being completed before the alert for the 5- and 15-minutes ITI.

These results suggest that with the foreknowledge of a possible problem and with enough of a forewarning ($\geq$5 minutes), subjects were able to plan their tasks thinking more of the overall mission, aviate-navigate-communicate. This movement also corresponded to previous data analysis which found that situation awareness increased with increasing ITI and that subjects with predictive information focused more on the mission (aviate-navigate-communicate) rather than the spatial aspect (locus-of-control) of the aircraft, which is appropriate since subjects as pilots-not-flying should have been more concerned about the overall mission [9].

CONCLUSIONS

Overall, predictive information and the longer prediction times moved subjects to performing tasks before the alert actually occurred and had them move to a more mission oriented center indicated by their tasks becoming more strategic and grouping by aviate-navigate-communicate.

Other aspects, though, must be investigated before the full usefulness of predictive information can be understood. Further research into the optimal prediction time, acceptable false alarm rate, and accuracy of the predictive information must be done. Also, it would be of benefit to ascertain how useful the information would be when pilots are not primed for a failure. On the more operational side, the ability to estimate the time to an alert with the false alarm rate and accuracy required by the pilots needs to be investigated before procedures are developed using predictive information.

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