Behavior-Based vs. System-Based Training and Displays for Automated Vertical Guidance

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ABSTRACT

Aircraft automation, particularly the automation surrounding vertical navigation has been cited as an area of training difficulty and a source of confusion during operation. A number of incidents and accidents have been attributed to a lack of crew understanding of what the automation is doing. This paper describes an experiment which tested a new display for automated vertical guidance. The study utilized a training package designed to teach the vertical guidance portion of the Flight Mode Annunciator (FMA), as seen in normal operations of the McDonnell Douglas MD-11. The results of the study showed that this type of training can be successfully delivered via a computer based training device. Additionally, the results began to show a trend in favor of the new display, although without reaching statistical significance. This study is part of a larger project to improve the recognition and understanding of the "objectives and behaviors" of automated systems through a formal methodology. The formal methodology, referred to as the operational procedures methodology, integrates the design of the system with the design of the training and display information requirements for that system (Sherry, 1995).

INTRODUCTION

Aircraft automation, for the purposes of this paper, will be defined as the autopilot and autothrottle subsystems, and the Flight Management System. The autopilot controls the heading and pitch of the aircraft, and the autothrottle, as the name implies, controls the different power settings required for the different automated tasks in flight. The Flight Management System (FMS) contains information used to calculate the most optimal trajectory of the aircraft. Early autopilot systems could only handle one or two functions, but with the addition of the FMS, the new "autoflight systems" have gained considerable complexity. This complexity requires pilot knowledge of the different "modes", or configurations of the system.

"Mode management" difficulties in aircraft automation have been well documented as incidents and accidents, errors observed in operation, and difficulty in training (FAA HFT Report, 1996). One common complaint is that pilots are not trained on how to use and understand the Flight Mode Annunciator (FMA), the primary automation display. The current FMA requires the pilot to integrate and interpret the displayed information, but not all of the knowledge required for this level of understanding is provided in training.

Changes in the new Air Traffic Control environment will place greater stress on knowledge of automated vertical guidance. Even today, there are FMS arrivals that cannot be flown without Flight Management System guidance.

Sherry, et al. (1996) propose a new method for the annunciation and training of knowledge-based avionics. This study is an evaluation of this methodology. We used a part task trainer to evaluate pilot performance in learning the Vertical Guidance portion of the McDonnell Douglas MD-11 autoflight system.

We propose a "Behavior-Based" FMA to help improve pilot recognition and understanding of the automation. "Behavior-Based" refers to annunciation of the overall situation of the aircraft. This allows the pilot to focus more on the objectives and behaviors of the aircraft. In contrast, the current "System-Based" FMA presents the individual autopilot and autothrottle modes, which requires the pilot to integrate the information presented to decipher the objectives and behaviors of the aircraft.

The Current "System-Based" FMA

The Vertical Guidance information on the current Flight Mode Annunciator of the MD-11 consists of a speed target, a speed mode, an altitude mode and an altitude target (see Figure 1.).

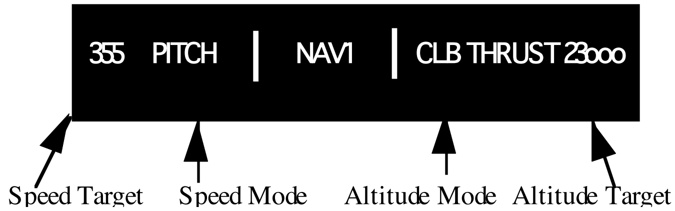

Figure 1. The Current "System-Based" FMA

The speed target is the speed that the aircraft is trying to achieve. The speed mode refers to how the autopilot or autothrottle will control the speed of the aircraft to achieve the speed target. There are two methods for an aircraft to maintain speed. In the first mode, the autopilot varies the pitch of the aircraft to achieve the speed target. This is commonly referred to as "speed on pitch." In the second mode, the autothrottle varies thrust to maintain the speed target. This is commonly referred to as "speed on thrust."

The altitude mode describes how the altitude target will be achieved. Corresponding to the speed mode, the altitude mode reflects whether the autopilot is tracking an altitude, such as maintaining a constant altitude or path, or the autothrottle is tracking a constant thrust setting. Only certain combinations of speed and altitude modes can appear together. To illustrate using the climb example given above, the altitude mode CLB THRUST will only appear with the PITCH speed mode. THRUST and CLB THRUST will never be seen as a combination, because the autopilot and autothrottle operate together. If speed is controlled by thrust, then the autopilot must control the altitude of the airplane with pitch, and vice-versa

The "Behavior-Based" FMA

We propose a change from the current "System-Based FMA to a "Behavior-Based" FMA that integrates the speed and altitude control modes, we describe these combinations as "behaviors" of the aircraft (see Figure 2.).

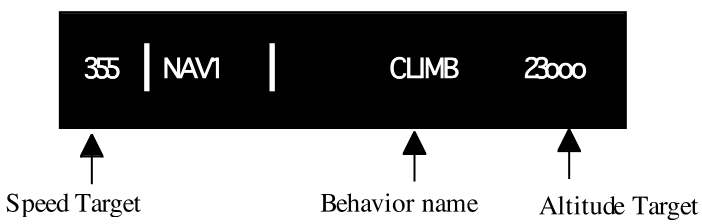

Figure 2. The "Behavior-Based" FMA

<u>Guidelines for the "Behavior-Based" FMA</u>

We used four guidelines in designing the "Behavior-Based" FMA, called task relevance, exclusivity, system-display design agreement, and display discrimination.

<u>Task Relevance</u>

Task relevance refers to using behavior names which are operationally meaningful to the pilot. ATC does not ask a pilot to "PITCH and CLB THRUST to Flight Level 230", and pilots do not talk to each other this way. This can be seen in by comparing Figures 1 and 2. The FMA should be used by the pilot to confirm that the objectives of the autoflight system match the objectives of the pilot. Additionally, from previous research (Hutchins, 1996), we know that not all pilots agree with the speed on pitch, or speed on thrust view of flying the airplane. This requirement to learn, and think about the system a certain way seems to be a source of difficulty. The "Behavior-Based" FMA avoids this problem by using an integrated description. Using the behavior names also makes the task of predicting the next autoflight transition easier by focusing more on the objective of the system, and less on the method used by the autopilot and autothrottle for achieving the current targets.

<u>Exclusivity</u>

Exclusivity refers to using a unique name for each operationally meaningful automation behavior. An example of this can be seen in the difference between the LATE DESCENT and PATH DESCENT OVERSPEED behaviors.

Aircraft with Flight Management Systems calculate a descent path which is the most efficient way to descend the aircraft. This is referred to as the optimum descent path. The LATE DESCENT behavior was developed to cope with the situation that arises when the aircraft is forced to fly beyond the optimum descent path. The view of the pilots on the design team for this situation was that the airplane will continue to have excessive energy until it has returned to the optimum descent path. The goal of the automation is to return to the optimum descent path as quickly as possible once the airplane is allowed to descend. This objective is achieved by an increase in aircraft target speed, and a change in how the speed of the aircraft is maintained.

In contrast, the PATH DESCENT OVERSPEED behavior was designed to handle situations in which the initial calculation of the optimum descent path resulted in a path that was too steep. The optimum descent path naturally shallows out in the later stages of the descent, so the objective of this behavior is to hold the speed of the airplane constant, and wait for the optimum descent path to “catch up” with the airplane. This behavior is achieved with a speed target that is generally slower than the LATE DESCENT speed target.

The difference between these behaviors for the pilot, is the result of the different objectives for which the behaviors were designed. The higher speed target in LATE DESCENT may take some pilots by surprise if they are not aware of the objectives of the automation. Additionally, because LATE DESCENT reflects the aircraft position beyond the path, the pilot should be aware that the possibility of not making a waypoint altitude restriction has increased. Another difference is that PATH DESCENT OVERSPEED is an automatic speed protection behavior, and, unlike LATE DESCENT, is not pilot initiated. The situations and behaviors are different, but the displays for the current “System-Based” FMA seen in the left column of Figure 3 are almost identical. The “Behavior-Based" FMA, seen in the right column of Figure 3, provides a unique and meaningful label for these two different situations.

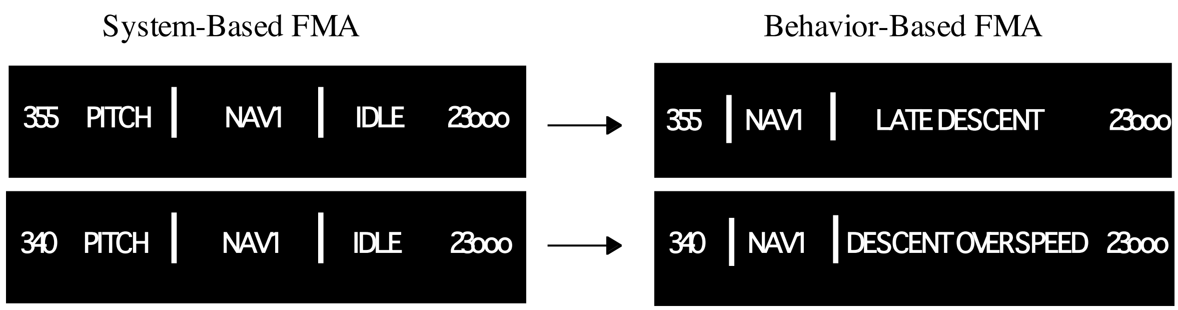

Figure 3. Comparison of “System-Based” FMA and “Behavior-Based” FMA for LATE DESCENT and PATH DESCENT OVERSPEED

System-Display Design Agreement

System-Display design agreement refers to using the system model as the source and structure of the information to be displayed. An example of this can be seen in the FMA display for an automated Flight Management System (FMS) Descent (depicted in Figure 4). In the current MD-11, the word PROF is used to denote that the behaviors and targets are calculated by the FMS. This is represented on the FMA by the use of magenta colored characters. When behaviors and targets are not chosen by the FMS, they are represented on the FMA in white. Despite the color convention to determine the automation use, the current MD-11 FMA also uses PROF as a label to describe an optimum path descent. This format disagrees with the system-display design agreement guideline.

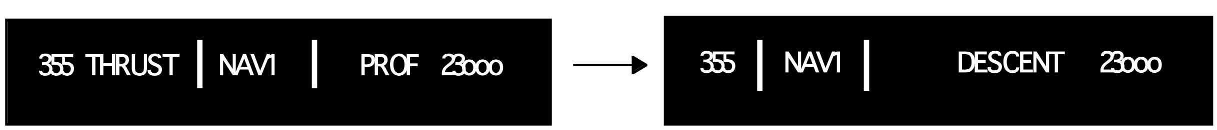

Figure 4. Comparison of “System-Based” FMA and “Behavior-Based” FMA for PATH DESCENT

Lack of system-display design agreement results in exceptions to the rules needed to understand and operate the system. Each exception requires the pilot to learn at least one more rule on how to interpret the display. It does not take many of these extra rules to make systems with this much complexity difficult to learn.

The behavior based FMA took advantage of the meaningful names that the designers gave to the different behaviors and replaced the speed - altitude control mode combinations with these names. These are shown in the right-hand column of Figure 5.

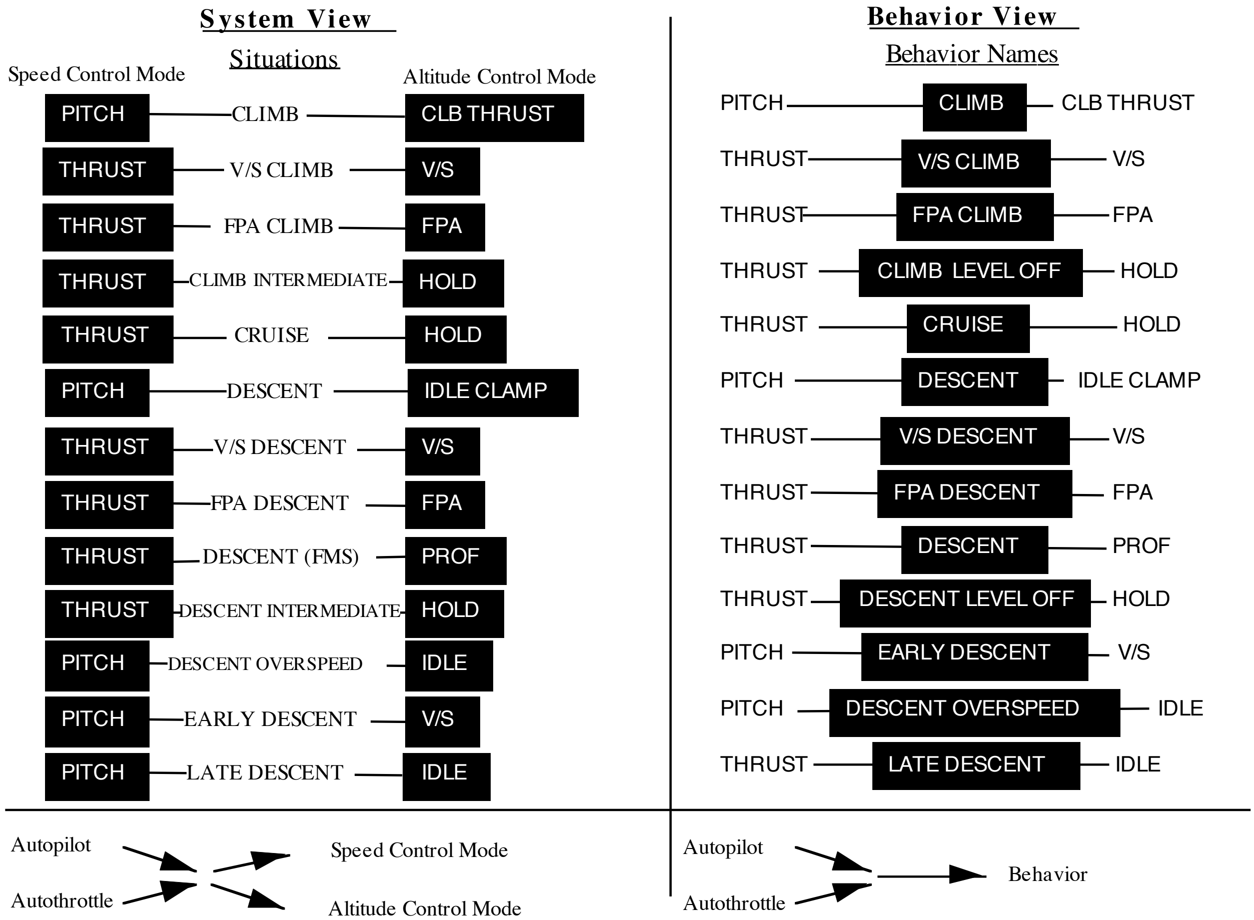

Figure 5. “System-Based” versus “Behavior-Based” Flight Mode Annunciations

Display Discrimination

The display discrimination guideline refers to optimizing the differences between the different behavior annunciations. More information can be derived at a glance from the “Behavior-Based” FMA than from the “System-Based” FMA. This can be seen when comparing the graphical differences in the displays. Because all capitol letters are used in the current FMA, which removes one dimension of differentiation, and color is used for other purposes, word length becomes a major characteristic of differentiation between modes. The “System-Based” FMA uses descriptions which tend to be about 5 characters in length. In contrast, the “Behavior-Based” labels are shorter for frequently used behaviors, and use longer descriptions for behaviors that are not the norm. This convention agrees with Zipf’s law for using command languages for human-computer interaction. (Ellis and Hitchcock, 1986) Notice that CLIMB, CRUISE and DESCENT in the “Behavior-Based” FMA are thought of as the most frequently used methods of flying the airplane, and that the other behaviors use names which are longer than these, hopefully providing better discrimination.

A possible concern about this experiment could be a question as to why we think we can eliminate the speed or altitude control modes. The altitude control mode displays information that is similar, if less descriptive than the behavior name, so the question then becomes, “what right do we have to delete the speed control mode?”

The response to this concern is threefold. First, the speed mode does not give accurate information all the time. In fact the speed mode is an approximation of the most used form of speed control. An example of this is LEVEL CHANGE which uses a complicated set of algorithms to make a smooth transition from level flight to a climb or descent. Therefore, although the FMA is annunciating speed on pitch, the airplane is not always using pitch to control the speed. Second, the speed control mode is only in question in descent, where energy management, in the form of the use of drag devices becomes an issue. If one views the behaviors listed in Figure 5, there are only two high energy conditions, LATE DESCENT, and DESCENT PATH OVERSPEED. These are the only times that drag devices should be needed, and the aircraft will respond in an expected manner for these behaviors. The last argument is that the combination of speed and altitude control modes have resulted in a set of displays that, without training on the design of the system, are not recognized by a large number of pilots currently using the system. The "Behavior-Based" FMA asks pilots to remember how speed is controlled for the different behaviors, if it is necessary, but we believe the benefits of simplification outweight the risk of possibly increaing memory load for one or two behaviors. In fact, a behavior based display should use names which are descriptive enough that a pilot should agree with the system design, and therefore shouldn't be required to memorize all the different behaviors.

METHODS

The experiment consisted of comparing the "System-Based" FMA and the "Behavior-Based" FMA presented in the 2 columns of Figure 5. The platform used to evaluate the displays was a computer based training package designed to train and test recognition of the Flight Mode Annunciations seen in normal operations of the MD-11. The training package was designed to run on a standard internet browser using a laptop computer, which allowed it to be viewed over the internet. The computers were run locally, and were specially configured to collect data from each participant. The training material defined each item of information on the FMA, but only taught the Vertical Guidance portions of the FMA in detail.

The organization of the material in the training package consisted of five training modules, and a test module. The test questions were identical except for the FMA display. The training material was almost identical, with the only exception being items that were unique to each display. The reduction in the number of display items in the "Behavior-Based" FMA resulted in slightly less training material (about 5% less) for that condition. The information covered in each training module included the lower-level automated modes, referred to as the basic modes, and the fully automated (Flight Management System) modes, referred to as the PROF modes. The mode space covered in the 5 training modules can be seen in the behaviors and displays shown in Figure 5.

The final section was composed of an evaluation section with 20 test questions. These questions were developed so as not to favor the "Behavior-Based" FMA. There were 4 categories of questions. The first category presented one FMA configuration and asked the participant to select the appropriate description. The second category presented an FMA and asked about the future behavior of the aircraft. The third category presented a situation and asked the participant to select the correct FMA from among a set of FMAs. The last category presented the participant with a situation and asked which FMA would be correct for the future behavior.

Thirty-four current DC-10 pilots and instructors with no previous commercial glass cockpit experience volunteered to participate in this study. Each pilot was presented with one of the two FMA displays. The participants were randomly assigned to each display condition.

RESULTS

Examining the results in Table 1, it can be seen that the results showed a trend favoring the "Behavior-Based" FMA, but this trend did not reach significance. The first column in the table shows the scores for the questions at the end of each training module. Notice that there is essentially no difference between the 2 groups for this measure. In the second column is the measure of performance between the 2 groups for the test questions. Here we see the test starting to favor the "Behavior-Based" FMA, but it has not reached significance. The last 2 columns show the overall performance of the 2 conditions for score and time. Again, we see that the numbers are starting to show a trend favoring the "Behavior-Based" FMA, but we cannot say that it is definitively better for learning the Vertical Guidance System.

Condition / Performance	Average Quiz Score (19 total)	Average Test Score (20 total)	Overall Average (Score 39 total)	Average Completion Time
System-Based FMA	15.5 (2.961)	15.4 (3.0)	30.9 (5.6)	1 hour 23 min.
Behavior-Based FMA	15.8 (2.298)	16.7 (1.7)	32.5 (3.6)	1 hour 13 min.
T-Values	t(32)=.001, p=n.s.	t(32)=-1.47, p=.15	t(32)=1.73, p=.1	t(32)=-1.3, p=.2

Table 1. Descriptive Statistics

DISCUSSION

One possible reason for these results may be attributed to the type of training used. This study evaluated the performance of the "System-Based" and "Behavior-Based" FMAs in learning declarative knowledge. Since the training had to be developed from scratch for both groups, the same model used for the new display was used for the training. It is possible that the use of the "Behavior-Based" model for training is more powerful than the effect of the different displays. It appears that once a student recognizes the different behaviors that are possible in the automation, the transformation to different displays does not make as much overall difference. The individual questions may provide more information than the overall comparisons. Analysis of the individual questions may highlight areas in which one of the displays is weak compared to the other.

FUTURE WORK

The next step in this project will be to evaluate the "Behavior-Based" FMA in a full-mission MD-11 simulator. We have built a version of the "Behavior-Based" FMA that runs on actual flight hardware. The simulator study will use MD-11 pilots who have at least 1 year experience on the airplane. The participants will be given one of the 2 training packages that were developed in the current study. The objective of the simulator study will be to evaluate pilots ability to understand the behavior of the vertical guidance system, in the form of 3 questions. "What is the airplane doing now?", "Why is it doing that?", and "What will the airplane do next?"

Additionally, there are two other areas that should be explored. First, a reaction time measure may show improved performance in the amount of time needed for recognition and understanding with the "Behavior-Based" FMA. Second, a goal in training the system should be "better retention over long periods of time". This suggests a longitudinal type evaluation. It would be interesting to take the volunteers in this study and evaluate them using the test questions without the training material, to test retention sometime in the future.

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