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Flight Deck Information Automation: A Human-in-the-Loop In-Trail Procedure Simulation Study

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Abstract

Information automation systems are generally intended to support pilot tasks and improve flightcrew awareness and decision making, but not to directly control the aircraft or its systems. As a result these systems do not include cases where automation decisions and actions directly affect the aircraft performance, flight path or systems. Next Generation Air Transportation System (NextGen) operational concepts and technologies will dramatically affect both the types and amount of information available on flight decks. Much of that information will be produced by flight deck information automation systems that collect, process, and present that information to the flightcrew. It is therefore important to understand the human factors characteristics of information automation systems and identify human factors issues specifically related to information automation. This paper presents an investigation of two information automation characteristics (functional complexity and automation visibility) using prototype oceanic In-Trail Procedures (ITP) display systems. The outcome will be used to develop and iterate recommendations for design and evaluation of information automation systems that will mitigate the identified human factors issues.

Introduction

The goal of many, if not a majority of flight deck systems introduced in recent decades has been to perform different types of information processing and display functions. These systems operate by integrating data from multiple sources and converting data to information displays that are intended to be more intuitive to understand (e.g., a synthetic vision display). Information automation is devoted to the management and presentation of relevant information to flightcrew members [1]. Information automation can be used to integrate, summarize, distribute, format, abstract, prioritize, categorize, calculate, process, and display information in a variety of ways to support flightcrew tasks. Examples of information automation include moving maps, synthetic vision, advisory, and information elements of caution and warning systems, data communication interfaces, electronic charts, and electronic flight bag (EFB) functions.

It is anticipated that Next Generation Air Transportation System (NextGen) operational concepts and technologies will dramatically affect both the types and amount of information available on flight decks [2]. Much of that information will be produced by flight deck information automation systems that collect, process, and present that information to the flightcrew. It is therefore important that information automation designers and evaluators understand potential human factors issues related to these systems. For example, do they cause excessive workload in the interaction required? Do they provide information that may not be completely accurate and must be interpreted carefully by the flightcrew? Also, understanding “characteristics” which are the distinguishing attributes or features of information automation will help to identify human factors issues and develop information automation design/evaluation recommendations.

This paper presents an investigation of two information automation characteristics (functional complexity and automation visibility) using prototype
oceanic In Trail Procedures (ITP) display systems. Details of the selected characteristics and an overview of ITP are described first, followed by description of the method and results of an empirical study. Then recommendations and research gaps are described. The outcome of the study will be used to develop and iterate recommendations for design and evaluation of information automation systems that will mitigate the identified human factors issues.

**Background**

The study was conducted within the framework of ITP which is a NextGen operational concept that encapsulates the challenges of information automation on the flight deck. Dudley et al. [3] lists nine characteristics specific to information automation. Two of these characteristics are the focus of this study because they were considered to be most relevant to the information automation system under consideration. The two characteristics are functional complexity and automation visibility. A brief overview of the information automation characteristics under consideration and the ITP concept are provided in the following subsections.

**Functional complexity**

Functional complexity refers to the number and diversity of information automation functions, the intricacy of the processing, the number and type of inputs and outputs, and the number and nature of inter-relationships and inter-dependencies [4],[5]. Functional complexity affects error management because it could be more difficult to detect whether an information automation system with high functional complexity is performing as intended, and whether the system is providing accurate outputs [6]. Additionally, flightcrew interaction with complex information automation could distract from primary flight deck responsibilities and cause loss of positional awareness and automation mode awareness [7].

**Automation visibility**

Information automation visibility refers to the ability of an automation system to provide adequate feedback about its current state, what information is being used, and how the information is being processed [8]. This characteristic may also be referred to as opacity [8]. In order for automation to be visible, the feedback must provide a view into the automation’s state and activities in a manner which can be properly interpreted by the operator and allows the operator to predict its behavior. This logic includes the sources the information automation is using for input and the algorithms and/or models for how the system is generating the outputs. A system with high automation visibility will allow its behavior to be predictable by fostering the development of an accurate mental model and provide ways for the flightcrew to verify its outputs. A system with poor automation visibility could create human factors issues such as a loss of situation awareness and increases in workload. However, the appropriate amount and timing of automation visibility information (e.g., “explanatory” information) should be carefully evaluated because too much additional information or supporting information presented at an inappropriate time (e.g., during time-critical tasks) could add workload and head down time [10].

**In-Trail Procedure (ITP)**

ITP is intended to allow pilots on oceanic routes to reduce the separation required to change flight levels in non-radar airspace. It requires the use of Automatic Dependent Surveillance (ADS-B) information to compute required distance and speed relative to various surrounding aircraft. An ITP flight level change requires the flightcrew to: (i) verify that a set of ITP initial criteria are met; (ii) request ITP flight level change clearance from Air Traffic Control (ATC); (iii) re-validate ITP criteria when a clearance is received from ATC; and (iv) execute the maneuver while maintaining specified ITP speed and vertical speed conditions. Prior research shows that pilots may occasionally forget important facts relevant to the ITP procedure. The anticipated benefits provided by ITP include enhanced efficiency, safety, and passenger comfort [11]. A complete overview of ITP including definitions of relevant ITP terminology is available [12].

The main goal of the current evaluation was to assess the information automation characteristics of three ITP display manipulations. Potential human factors issues related to ITP as an example information automation system are suggested by Murdoch et al., [11] which presents data showing
pilot errors associated with the different stages of ITP. He found that several participants made selection errors (requesting ITP instead of standard clearances and vice versa), and participants in his study also included incorrect information in clearances, selected inappropriate reference aircraft, and made syntax errors in formulating a clearance request.

**Method**

**Participants**

Twelve airline pilots from a cross section of regional and major airlines participated in the study (total flying hours: 2,000 - 14,000). The study was conducted in a low fidelity part task simulator facility. Both objective and subjective data were collected.

**Independent Variables**

The automation level of prototype ITP displays was the independent variable in the study with the following levels:

- Manual (high visibility, high complexity)
- Semi-Automated (high visibility, low complexity)
- Fully Automated (low visibility, low complexity)

The manual concept requires the pilot to assess and generate an ATC clearance (high complexity). The semi-automated concept provides step by step automated ITP procedural guidance until an ATC downlink clearance is generated (low complexity). The fully automated concept provides a single-step automated ATC clearance generation based on desired flight level (low complexity). All three systems have a graphical ITP traffic display to show the basic information needed to formulate an ITP clearance request. In addition, the manual and semi-automated ITP display concepts have a traffic status window which provides detailed information about selected traffic (high visibility) while the fully automated does not (low visibility).

**Dependent Variables**

The dependent measures for the study included both subjective and objective measures. The subjective measures comprised questionnaire ratings, participant comments and workload ratings. The subjective data was correlated with real-time objective data from scenario-specific datasheets.

The following are the dependent measures for the study are listed in Table 1.

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>Metric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Participant decision to request ITP</td>
<td>Requested Decision: Yes/No.</td>
</tr>
<tr>
<td>Time to generate ITP clearance</td>
<td>Time from end of task instruction to ITP clearance request.</td>
</tr>
<tr>
<td>Time to re-validate ATC ITP response</td>
<td>Time from ITP clearance approval to accept/reject decision.</td>
</tr>
<tr>
<td>ITP clearance accept/reject decision</td>
<td>Accept/Reject Decision: Yes/No.</td>
</tr>
<tr>
<td>Traffic Awareness</td>
<td>Identification of non-reference traffic (Non-ITP criteria traffic).</td>
</tr>
<tr>
<td>Percentage of ITP task time spent on ITP Help information (ITP Checklist)</td>
<td>Total head-tracker dwell time (per trial).</td>
</tr>
<tr>
<td>Subjective workload</td>
<td>Bedford workload scale.</td>
</tr>
<tr>
<td>Subjective ratings and comments on information automation aspects of ITP displays.</td>
<td>5-point response scale.</td>
</tr>
</tbody>
</table>

**Experiment Design**

A within-subject (repeated measures) design was used for this evaluation. All participants viewed five scenarios for all three ITP display types. An additional scenario was designed for training to familiarize participants with the simulation environment and the features of the ITP display types. One scenario was specifically designed to investigate decision aiding aspects of the displays based on the information automation characteristics.
An ITP distance requirement was not met in the scenario. The participant was expected to identify this discrepancy without requesting an ITP clearance (correct decision). All scenarios were based on a route between Tokyo and Los Angeles.

The order of conditions was counterbalanced using a Latin Square design to minimize the known disadvantages of a within-subject design such as carryover effects, fatigue and practice. The same scenario conditions were used for all participants.

**Task**

From 2009 to 2012, Honeywell partnered with United Airlines to develop and test an ITP application for a Class III Electronic Flight Bag (EFB) under a contract to the US Federal Aviation Administration (FAA) [13]. This previous research provided the basis for three new prototype concepts of ITP displays differing in the level of information automation assistance to the pilot for the ITP maneuver: Manual, Semi-Automated, and Fully Automated. These levels provided manipulation of the two information automation characteristics – Automation Visibility and Functional Complexity.

**Displays**

The ITP display is a vertical profile view that shows aircraft at flight levels above and below the ownship (Figure 1). No experimental task required information presented on a conventional plan view display of traffic.

![Figure 1. Basic Layout of ITP displays](image)

All three ITP display systems used in this evaluation guide the user through the process of formulating ITP clearance requests because formulating an accurate ITP clearance requires a broad range of inferences. The systems prompt users to specify parameters or perform tasks necessary for formulating valid requests based on the level of automation.

The two automated systems (semi and fully automated) were designed to prevent errors during the process of formulating an ITP clearance. The systems provide feedback when errors are made; the error messages are intended to be descriptive and to communicate the cause of errors.

The ITP display window presents information to formulate ITP clearance requests and shows aircraft within 3000 ft (above and below) of the ownship’s altitude. In addition to the Flight Identifier (ID), aircraft data tags show the ITP distance and groundspeed differential parameters; both are needed in determining whether an ITP clearance is appropriate.

Table 2 summarizes the differences between the ITP display types used for the study.
Table 2. Summary Description of ITP Display Types and Automated Aid provided

<table>
<thead>
<tr>
<th>Display Feature</th>
<th>Level of Information Automation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>manual</td>
</tr>
<tr>
<td>Graphical ITP traffic display and procedural guidance</td>
<td>✓</td>
</tr>
<tr>
<td>Highlighting of traffic with parameters in non-ITP</td>
<td>X</td>
</tr>
<tr>
<td>Criteria range.</td>
<td></td>
</tr>
<tr>
<td>Valid selected Flight Level</td>
<td>X</td>
</tr>
<tr>
<td>Valid and Invalid Reference Aircraft Differentiated</td>
<td>X</td>
</tr>
<tr>
<td>Automated Reference Aircraft Selection</td>
<td>X</td>
</tr>
<tr>
<td>Automated ITP Clearance Generation</td>
<td>X</td>
</tr>
<tr>
<td>ITP Automation Messages</td>
<td>X</td>
</tr>
<tr>
<td>Traffic Status Block Information</td>
<td>✓</td>
</tr>
</tbody>
</table>

✓ = Feature or function present
X= Feature or function absent

Each ITP display system provides ITP procedural guidance in a dedicated window for formulating an accurate ITP clearance through a number of steps. An “ITP Clearance” control (button) is used to initiate ITP procedural guidance.

**Scenarios**

A summary of the scenarios is presented in Table 3. Scenario duration varied by scenario but was typically 5 minutes. The same dependent measures were recorded for all participants in all scenarios under all the treatment conditions.

Figure 2 shows the general layout of the simulator setup for the ITP evaluation. The ITP display was presented in the center display console between the two pilots (participant and experimenter). The help information was provided on the PED outboard of the participant.
### Table 3. Scenario Matrix

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Leading climb</td>
<td>ITP climb with ownship leading the reference aircraft.</td>
</tr>
<tr>
<td>2</td>
<td>Following descent</td>
<td>ITP descent with ownship following reference aircraft.</td>
</tr>
<tr>
<td>3</td>
<td>Unable due to re-assess failure</td>
<td>Reference aircraft is converging on ownship and initially 20 NM behind. ATC delays granting ITP clearance - it is granted once reference aircraft is at 14 NM ITP distance and therefore in violation of the ITP initiation criteria. Participant is expected to re-assess validity of reference aircraft upon receipt of ITP clearance and reject clearance. The objective of the scenario was to evaluate whether participants would re-assess ITP initiation criteria after receipt of an ITP clearance.</td>
</tr>
<tr>
<td>4</td>
<td>Unable due to ITP Distance</td>
<td>Reference aircraft does not meet the ITP distance requirement (ITP Distance &gt; 15NM). ATC rejects ITP request if participant does not recognize ITP criterion is not met and requests a FL change. The objective of the scenario was to investigate if participants identified violation of ITP initiation criteria prior to formulation of the ITP request, or whether they understood the reason for clearance rejection in the case of an ITP request.</td>
</tr>
<tr>
<td>5</td>
<td>Unable due to re-assess failure</td>
<td>Reference aircraft is converging on ownship and initially 20 NM behind. ATC delays granting ITP clearance - it is granted once reference aircraft is at 14 NM ITP distance and therefore in violation of the ITP initiation criteria. Participant is expected to re-assess validity of reference aircraft upon receipt of ITP clearance and reject clearance. The objective of the scenario was to evaluate whether participants would re-assess ITP initiation criteria after receipt of an ITP clearance.</td>
</tr>
</tbody>
</table>

![Figure 2. ITP Display Set Up](image-url)
Procedure

Participants were briefed to “think out loud” about their intended actions/decisions. ITP help information in the form of an ITP Checklist was available on a personal electronic device (PED) located outboard at all times.

Prior to the start of each scenario, an experimenter who acted as a confederate participant read out the need for an urgent ITP climb or descent for the scenario due to bad weather or turbulence. For simplicity, the auto flight system was used to fly a common flight plan for all scenarios. Participants were required to assess ITP criteria and generate ITP requests in a timely and accurate manner. Although ITP is intended to use datalink communication, for this study, participants were instructed to read out clearances to ATC as they would communicate normally using voice over radio.

Two in-scenario tasks were used to measure the level of participant traffic awareness. To simulate pilot’s normal traffic awareness role on the flight deck, they were required to identify all moving traffic elements on the display at the end of each scenario. Participants were also required to identify all traffic elements which did not satisfy ITP criteria. At the end of each scenario, the participants provided a Bedford workload rating associated with the ITP element of the scenario. Expected participant tasks were to:

- Assess ITP criteria
- Generate timely and accurate ITP requests (clearances)
- Understand and respond to ITP clearances by ATC
- Identify moving traffic
- Identify non-reference traffic

During the scenario an experimenter (confederate pilot) assisted by the other experimenter (who served as a pseudo ATC controller) collected real-time data such as time to generate clearances, participant decision and participant comments using a scenario datasheet.

Results

Analyses of variance (ANOVA) were used to explore the effects of the independent variable (ITP display type) on the dependent variables. In cases where the F-test indicated a significant effect of an independent variable, the Least Significant Difference (LSD) post-hoc test was used to investigate which pairs of means differ. All statistical tests were evaluated at a 0.05 level of significance. Vertical bars in all graphs denote standard error.

Task Performance

Only those dependent measures resulting in significant effects or subjective data that show obvious differences will be discussed below. The following dependent measures showed no significant effects: (1) Time to re-validate ATC ITP response, and (2) Identification of moving traffic on ITP display.

Pilot Decision to Request ITP

One scenario was specifically designed to investigate decision aiding aspects of the displays based on the information automation characteristics. In this scenario, the reference aircraft in the scenario did not meet the ITP distance requirement (ITP Distance > 15NM). The participant was expected to identify this discrepancy without requesting an ITP clearance (correct decision). If the participant did not recognize that the ITP criterion was not met and requested a FL change, ATC rejected the ITP request.

Figure 3 shows the number of correct and incorrect decisions for each of the three displays. All participants correctly recognized that the ITP distance criterion was not satisfied for both the semi and full automation displays. However, for the manual display, four out of 12 participants made the incorrect decision of requesting an ITP clearance (correct decision). If the participant did not recognize that the ITP criterion was not met and requested a FL change, ATC rejected the ITP request.

As expected the complexity of the ITP task and lack of automation aid resulted in decision making errors for the manual displays. Conversely, the lack of automation visibility for the fully automated display did not affect participant decision making and we believe this was because automation visibility was
more than compensated by the automated display features.

![Figure 3. Pilot Decision-Making.](image)

**Time to generate ITP clearance**

A plot of the average time to generate an ITP clearance for the three displays is shown in Figure 4 (brackets with “*” shows conditions that were significantly different). There was a significant effect of display type ($F(2, 22) = 6.73 \ p<0.005$), such that the full automation display differed significantly from both the manual ($p<0.05$) and semi-automated displays ($p<0.05$), but there was no significant difference between the manual and semi-automated displays.

![Figure 4. Average Time to Generate ITP Clearance.](image)

**Workload**

An analysis of variance (ANOVA) was used to evaluate the hypothesis that the workload level during ITP flight level changes is significantly different when using ITP displays which varied in information automation characteristics. We found a significant difference between the workload ratings of the three display types for ITP flight level change maneuvers ($F(2, 22) = 3.85 \ p<0.05$) (see Figure 4 (brackets with “*” shows conditions that were significantly different)).

![Figure 4. Average Workload for ITP Display Types.](image)

**Information Automation Aid**

Participants were asked to rate the degree to which each ITP display type aided their performance of the ITP task. Ratings were provided on a five-point scale (Very High – None). The results are summarized in the form of a histogram in Figure 5.

10 out of 12 participants rated the information provided by the fully automated display as “very high.” 9 out of 12 participants felt the aid provided by the semi-automated display was “high.” All participants rated the information provided by the manual display as either “Low” or “Moderate.”

![Figure 5. Information Automation Aid.](image)
Pilot Understanding of Display Behavior

Participants also rated their understanding of the ITP display functional behavior (what the system was doing and why). Participants provided ratings on a five-point scale (Very High – None). The results are summarized in the form of a histogram in Figure 6.

Potential for Human Errors

Participants were asked to identify and list any aspect of the design of ITP displays that could make the flightcrew vulnerable to error after using all three display types. As shown in the histogram summarizing the results in Figure 7, all participants (12 of 12) felt the manual display had a potential for error. One half of the participants (6 of 12) felt the semi-automated version was not vulnerable to error. A slight majority (7 of 12) felt the fully automated display had aspects vulnerable to error.

Discussion

Pilots made more ITP request decision making errors when using the Manual ITP display compared to the other display types. This was expected because of the complexity of the ITP task and lack of automation aid in the Manual concept. Pilots made correct decisions when using the fully automated display suggesting that the low automation visibility did not have an effect. The time to generate an ITP clearance (task performance) for the Full automation display was significantly shorter than both the Manual and Semi-automated displays. The average workload rating for the fully automated ITP display was significantly lower than both the Manual and Semi-automated. Participant ratings indicate that the automated displays were better than the manual displays on several dimensions – they better aided their ITP task performance, they led to a better understanding of what the automation was doing, and they had lower potential for error.

Based on the results of the empirical study, we developed and iterated recommendations for the design and evaluation of information automation
systems. These initial recommendations will require more complete and thorough validation studies.

**Functional Complexity**

a) If information automation systems are functionally complex, help functions might be appropriate for non-time critical situations.

Many information automation systems such as decision and management aids may be strategic in nature. Consequently, one solution to managing and understanding the complexity of these systems is a help function. Help functions in strategic situations could serve not only as a real-time aid in understanding a system’s behavior or its outputs, but it could serve as an augmentation to training and knowledge maintenance as well.

b) The functional complexity of an information automation system should be assessed in terms of pilot ability to understand the system’s behavior even if there is little or no interaction required.

Advisory Circular (AC) 25.1302-1 [14] describes the need to consider the functional complexity of installed equipment when assessing whether pilots can safely perform all of their tasks. Introducing pilot responsibilities in conjunction with complex information automation, regardless of whether it is a system which requires substantial interaction, may affect pilot performance and require pilot understanding of system state and behavior consistent with 14 CFR25.1302 (c) (1).

c) Information automation functional and display complexity can compromise usability – in some cases it may be better to have a less capable system that reduces complexity and is easier to use.

Adding new functions to an existing display are often seen as a way to improve operational safety and efficiency. Each additional function can add to the complexity of a single system or device in terms of pilots’ understanding of its behavior and the ease of interacting with the device as defined in 14 CFR 25.1302 (b) and (c). This could negatively affect user workload and the overall usability of the system.

**Automation Visibility**

a) Information for verifying or checking system reasoning and output should be available and displayed in a manner that is easy to detect and easy to access.

14 CFR 25.1302(b) (3) states that “…information intended for the flightcrew’s use must enable flightcrew awareness … of the effects on the airplane or systems resulting from flightcrew actions.” Crew awareness includes understanding the limitations of information automation systems. The complexity of the task, the design of the interface, and the saliency of the information all play a role in whether pilots can detect inaccuracies. Even in cases of high automation visibility, where the automation reveals its reasoning to the pilot, it is often difficult to notice what is not there. Thus the interface should provide support to help pilots know what information to look for to assess information automation output. Explanations of system behavior and states, and quality of information outputs should be available upon demand.

b) Presentation of information to help pilots understand information automation state and outputs should be balanced against potential increases in pilot workload due to the time and attention needed to process this extra information.

The requirement for operationally relevant system behavior to be predictable and unambiguous (§ 25.1302 (c) (1)) will enable a qualified flightcrew to know what the system is doing and why. This means a flightcrew should have enough information about what the system will do under foreseeable circumstances as a result of their action or a changing situation that they can operate the system safely. This requirement distinguishes system behavior from the functional logic within the system design, much of which the flightcrew does not know or need to know. [AC 25.1302-1, 5-6.a. (2)]. In some cases, a small amount of automation visibility information, or automation visibility information that can be accessed on demand but not presented automatically, should be considered. If visibility information can be built into the information automation outputs themselves, less processing may be required to validate the outputs. Providing too much automation
visibility information, especially in busy phases of flight, could create workload issues.

Conclusions

Our work also provided insights in terms of useful future research to examine open questions about information automation. While not meant to be comprehensive, some of our initial thoughts are provided below.

Assess the tradeoffs between automation visibility and increased pilot workload and task times

It was clear from our empirical study that automation visibility comes with a potential cost in workload and task time. While our results showed modest evidence for improved performance with better automation visibility, there were more obvious results in terms of higher workload and task times for conditions where automation visibility was higher. Research is needed to better understand these tradeoffs and identify cases where the benefits of more visibility information outweigh the increases in workload and task times so that design and evaluation guidance can be developed related to how much additional automation visibility information is appropriate for different situations.

Assess the impact of aggregate information automation systems

Many of the issues identified in these analyses are likely to be most problematic at an aggregated level – when multiple information automation systems are considered. These issues include information overload, workload, distraction, overtrust, and so on. Research which addresses these aggregated effects is needed to fully understand some of the overall consequences of adding more and more information automation systems to the flight deck. Due to the fact that the effects of implementing multiple information automation systems may or may not be additive in nature, this research could help system evaluators understand potentially complex interactions.

Based on the results of the study, we identified human factors considerations which are consistent with existing FAA regulatory and guidance material for the design and evaluation of information automation systems. For example, with respect to information automation visibility, we suggest that information for verifying system logic and output should be available and displayed in a manner that is easy to use. However, this display of information to help pilots should be balanced against potential increases in pilot workload due to the time and attention needed to process this extra information.

References


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