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Analysis of the Human Performance Risks and Benefits of Adaptive Systems on the Flight Deck

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Abstract

Objective. Human performance risks and benefits of adaptive systems were identified through a systematic analysis and pilot evaluation of adaptive system component types and characteristics.
Background. As flight-deck automation is able to process ever more types of information in sophisticated ways to identify situations, it is becoming more realistic for adaptive systems to adapt behavior based on their own authority.
Method. A framework was developed to describe the types and characteristics of adaptive system components and was used to perform a risk/benefit analysis to identify potential issues. Subsequently, eight representative adaptive system storyboards were developed for an evaluation with pilots to augment the analysis results and to explore more detailed issues and potential risk mitigations.
Results. Analysis identified the principal drivers of adaptive "triggering conditions" risk as complexity and transparency. It also identified the drivers of adaptations risks/benefits as the task level and the level of control vs. information adaptation.
Conclusions. Pilots did not seem to distinguish between adaptive automation and normal automation if the rules were simple and obvious; however, their perception of risk increased when the level of complexity and opacity of triggering conditions reached a point where its behavior was perceived as non-deterministic.

Keywords: adaptive automation, Human-automation interaction, flight-deck design, risk and benefit analysis

Introduction

Risk in aviation has typically been related to air traffic accidents that result in significant loss of property or loss of life (Netjasov & Janic, 2008). The level of risk is generally determined from a combination of the probability of occurrence and the consequences (Sheridan, 2008). In the development of new technology, designers try to identify risks that stem from design and component failure, and factor in the risk of human error (Orasanu, Fischer, & Davison, 2002. The objective of this work is to anticipate the risks and benefits of adaptive systems as they are introduced onto aircraft flight decks, and thus is concerned primarily with the design factors of the technology and human factors of the adaptive joint pilot-automation systems that determine the level of predicted risk and benefit.

Adaptive systems are the automation component of joint human-machine systems that can change their behavior to meet changing user needs, often without explicit human instructions (Scerbo, 2001). Adaptive systems do this by tracking and sensing information about users, their current tasks, the state of the systems they interact with, and their environment. Adaptive systems are growing in importance as the next generation (NextGen) air traffic management systems (ATM) are being realized. NextGen will use satellite-based navigation and interconnected database systems to guide and track air traffic more precisely than was previously feasible (FAA, 2015. NextGen will increase capacity using reduced aircraft spacing and faster-paced ground operations, delegating more responsibility to the pilots for spacing from other aircraft, and requiring more precise navigation on defined routes, altitudes, and times of arrival at specified waypoints. NextGen implementation will require new, more complex automation (Landry, 2009) and may result in substantial changes in pilot and controller roles and responsibilities. Furthermore, the division of roles and responsibilities between humans and automated systems may not be static, but may change depending on the current context. Automated systems may have to adapt to the situation and change their behavior, under specific conditions (based on predetermined decision criteria and functions designed into the automation), in order to best support the pilot needs in the current situation.

Flight-deck automated systems are able to adapt their behavior based on flight-situational priorities and context because they have increased sophistication and processing capability that enable them to integrate aircraft data, sensor data, stored databases, communicated information, and real-time flight crew inputs. For instance, an adaptive flight-deck automation system might intervene (e.g., when preprogrammed parameter limits are exceeded indicating that the pilot needs additional assistance) or perform preselected "overhead" tasks (such as information, communication or display management) to address the pilot's needs in the current and predicted situation. This can reduce pilot workload and allow pilots to focus more on primary flight tasks and less on accessing and retrieving information, configuring their displays, categorizing and prioritizing communications, and so on. Of course, realization of these benefits depends on detailed design features of the adaptive systems. Real-time adaptations also have significant potential disadvantages due to complexity that leads to incomplete flight crew comprehension and awareness of automation programming. If the outputs are less predictable to pilots, there may be more opportunity for unexpected automation behavior that surprises the flight crew, compromised pilot situation awareness, and cases where the automated system adaptation is inappropriate to the situation and provides outputs that are annoying, or worse, disruptive to flight crew performance.

While extensive literature exists on the development of adaptive systems concepts (Sheridan and Verplank, 1978; Rouse, 1988; Endsley and Kaber, 1999; Parasuraman, Sheridan, & Wickens, 2000; Rothrock et al. 2002; Feigh, Dorneich, & Hayes, 2012; Kaber, 2013), relatively sparse data exist on human-performance risks and benefits with adaptive systems in real operational settings Hilburn, Molloy, Wong, & Parasuraman, 1993; Dorneich, Ververs, Mathan, Whitlow & Hayes,2012), where safety and human performance depend on dynamic interaction of tasks, operators, and the environment.

In order to address these issues, an adaptive system framework is presented that identifies and characterizes its components, the various design options (types) for each component, and the characteristics on which to evaluate the risks and benefits for each type. A risk/benefit analysis was performed to identify potential issues. Subsequently, an evaluation with pilots was conducted to provide the pilot perspective when exploring issues and potential risk mitigations. The value of this work is in identifying risks and benefits that should be considered when evaluating adaptive flight-deck automation that will enable safe and efficient flight in a NextGen environment.

Adaptive Systems Framework

Three key areas were identified within a generic closed-loop adaptive system (see Figure 1) as the most relevant for the analysis of risks and benefits:

- *Triggers*. Knowledge of context (the state of the world, human, mission, and system) used as a trigger to initiate changes in the adaptations manager.
- *Decision processing*. Algorithmic process to determine when and what adaptive automation to invoke.
- *Adaptations*. Temporary changes in automation behaviors and/or human-machine interface, designed to mitigate situations identified by triggers.

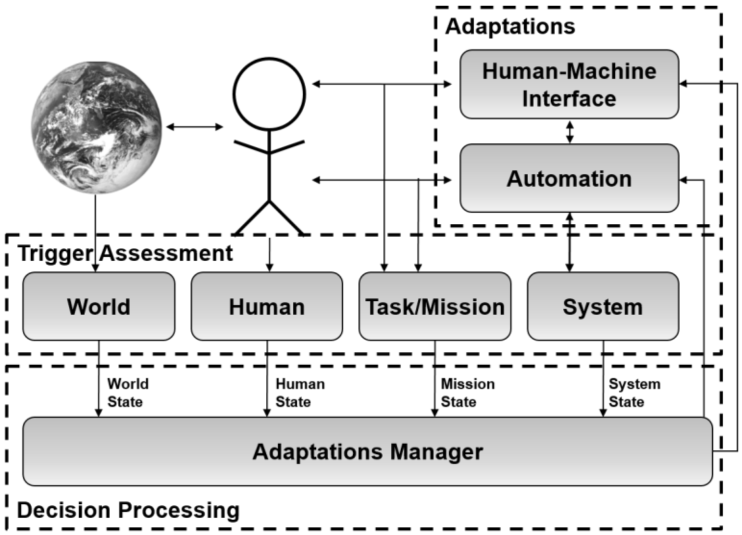

Figure 1. A generic adaptive system block diagram.

This paper focuses on triggers and adaptations, the system elements most observable to operators, and thus most applicable to human-factors risks and benefits. The analysis of triggers and adaptations is the subject of the next section. An analysis of the decision-processing risks was also conducted but only a summary of findings is presented as follows. Complex statistical processes (linear discriminant models, neural nets) that suffer from a lack of transparency were deemed highest risk. The second group of processes (behavioral models, decision matrices, and Bayesian inference) were also seen as complex but were ranked to have lower overall risk given that they are based in human-understandable terms and thus are more intuitive and transparent. Decisions based on production rules were deemed the least risky, as they are repeatable, fast, and not necessarily complex. However, they suffer from a lack of robustness and sensitivity to change. For more detail, see Dorneich, Rogers, Whitlow & De Mers (2012).

Types and Characteristics

Types of triggers and adaptations are defined as specific options within each area's design space. For instance, trigger types include task status, operator-state measurements, and environmental events. Likewise, examples of types of adaptations include task offloading, task prioritization, and interruptions management.

Additionally, triggers and adaptations can be described by a unique set of *characteristics*, defined as properties or attributes that describe an automation system's operation, and can be used to identify potential human-factors issues.

Triggers. There are many sources of information upon which an adaptive system can develop a sense of the current situation, including information which can be sensed, observed, or modeled. While there are many possible categorizations (Byrne and Parasuraman, 1996; Rouse, 1988; Sheridan and Parasuraman, 2006), five broad categories were identified (Feigh et al., 2012) as shown in Figure 2.

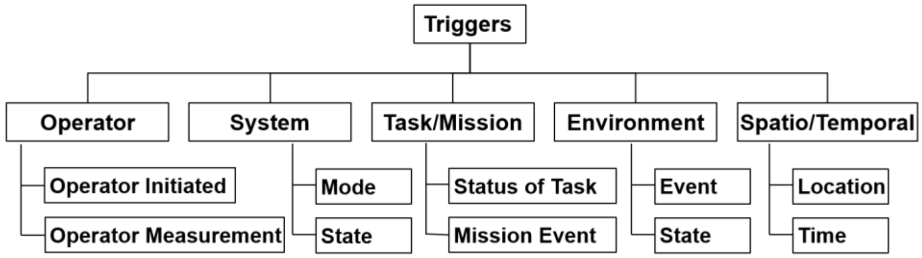

Figure 2. Taxonomy of triggers, based on Feigh, Dorneich, & Hayes (2012).

Operator triggers can be operator initiated or derived through measurements of the operator. When pilot action triggers adaptation, these systems are typically referred to as adaptable systems (Opperman, 1994), and this is included here for completeness. Measures of operator cognitive or physical states can be estimated via sensor data, inferred via models, or derived via interaction with the system (Scerbo, 2001). Estimates of the *system* include its modes of interaction, and current and anticipated future states. Estimates of the *task/mission* depend on a dynamic representation of tasks performed by the joint human-automation system (Krogsaeter & Thomas, 1994) to enable task-status tracking and the detection of mission events. Estimates of the *environment* are a representation of the events and states of the world outside of the immediate system and operator. Estimates of *spatio-temporal* criteria include time and location. Table 1 describes each trigger type, based on the taxonomy in Figure 2, and includes a representative example.

Table 1. Trigger Types.

Trigger Type	Category	Trigger Type Definition	Example
Operator-Initiated	Operator	Pilot action required to trigger adaptation. Typically referred to as *adaptable systems*, included here for completeness.	Pilots changing autopilot descent mode (Sarter & Woods, 1995)
Operator Measurement	Operator	Direct real-time measurement of operator physical or neurophysiological state or indirect measurement via secondary measures such as task performance.	Electroencephalogram-based assessment of workload (Dorneich et al, 2007).
System Modes	System	Grouping of several system configurations that corresponds to a set of unique system behaviors.	Cell phone in “airplane mode” to prevent signal transmission.
System States	System	Current configuration of automation, aircraft, or systems.	Aircraft may be at a fuel level that requires a diversion decision (“bingo fuel”)
Mission Event	Task/Mission	Mission events based on a mission plan	Trigger based on transition between phases of flight
Task Status	Task/Mission	Current task state (e.g. initialization, progress, or completion), usually based on a task model.	Trigger changes based on a model of action planned, and completed tasks (Miller & Funk, 1997)
Environmental Events	Environment	External conditions, such as weather, traffic, terrain, or some combination.	Sensor-based detection of proximity to terrain
Environmental State	Environment	An environmental state external to the aircraft that is detected either automatically or through communications from other crew member, other aircraft, or ground personnel.	External communications of runway closure; Detection of ambient light levels to determine screen brightness (Feigh et al., 2012)
Location	Spatio-temporal	Absolute or relative location of the automation	GPS location of aircraft; Five miles from top-of-descent.

Time	Spatio-temporal	Temporal criterion	Trigger based on time in flight.

The set of characteristics was developed (see Table 2) based on a variety of background material, including EASA AMC 25.1302 (2011), human-error categories (Stanton et al., 2010; Embrey, 1986; Pocock, Wright, & Harrison, 1999; IATA, 2007), and known automation human-factors issues (Rogers, 2011).

Table 2. Characteristics of triggers.

Trigger Characteristic	Risk/Benefit Characteristic Definition
Complexity	Inference complexity; number of pieces of data needed to calculate trigger
Transparency	The ability of the system to communicate why and when it will trigger a change.
Projectability	Reliability of the system to predict a future state (in a useful time frame)
Resolution	The ability of the system to resolve multiple levels of triggers that are useful
Sensor/Data reliability	Likelihood that the trigger data are reliably available and noise-free
State assessment reliability	Reliability of inferring a state from raw data
Pilot interaction requirements	Amount of interaction required of pilot to explicitly support trigger
Acceptance/Trust	Confidence of the pilots in the trigger

Adaptations. Possible adaptations can be broken down into four broad categories (Feigh et al., 2012), illustrated in Figure 3:

- *Modification of Function Allocation*. A system can dynamically change *who* (human or machine) performs each function.
- *Modification of Interaction*. A system can dynamically change *how* it presents information to users.
- *Modification of Content*. A system can dynamically change *what* information it presents to the user.
- *Modification of Task Scheduling*. A system can dynamically change when tasks are performed, including which tasks are performed first.

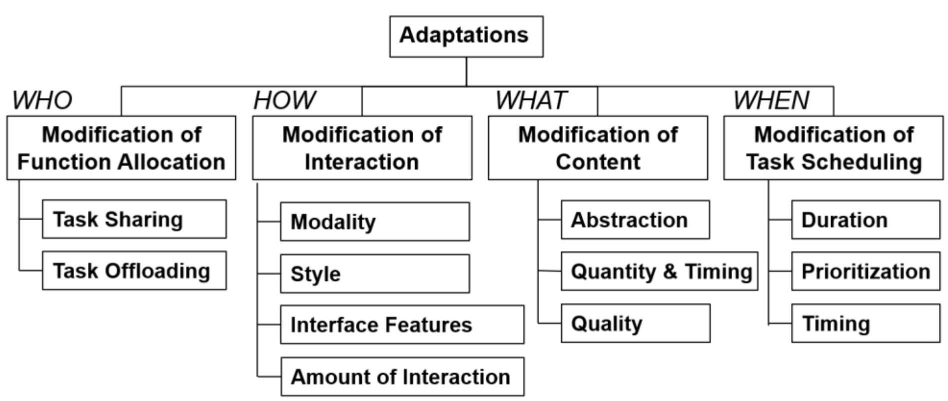

Figure 3. Taxonomy of Adaptations, based on Feigh, Dorneich, & Hayes (2012).

Based on the taxonomy in Figure 3, descriptions and examples are provided in Table 3 for several types of adaptations.

Table 3. Adaptations Types.

Adaptations Types	Category	Description	Examples
Task Sharing	Function Allocation	Automation and human share execution of the task	Sharing of lateral and vertical navigation control between pilot and automation (Inagaki, 2003)
Task Offloading	Function Allocation	Automation alternatively takes over task from human, and returns task to manual	Traffic Collision Avoidance System (TCAS III) will take over the function of flying an airplane when a collision with another aircraft is imminent (Botargues, 2008).
Modality	Interaction	Presentation modality is adapted	Change message from text to speech
Interaction style	Interaction	Changes to the timing, politeness, and/or method of interaction	Tutoring systems that change the etiquette of feedback to mitigate user frustration.
Interface features	Interaction	Changes to the location and/or saliency of presented information	Highlighting information on a display; content-dependent menus.
Amount of interaction	Interaction	Changes to the how often, how much, and when the human interacts with the system	Tutoring systems that recede into the background as the student expertise grows (Dorneich & Jones, 2001).
Abstraction	Content	Information can be aggregated or abstracted to focus on salient aspects and reduce the processing time for the human to interpret the presented information	Changing from detailed system display to higher-level summary (e.g. star display). Ecological Interface Design strives to choose the correct abstraction for key functional relationships (Burns & Hajdukiewicz, 2004)
Information Quantity & Timing	Content	How much information to present, when to present it	De-cluttering to remove information during extreme attitudes (Newman & Haworth, 2004); Display reconfiguration during emergency.
Quality	Content	Changes in the quality of the information content	Reducing video stream frame rate to meet task deadline (Mohan, Smith, & Li, 1999).
Duration	Task Scheduling	The amount of time allocated (may affect quality of response)	Change time allocation to minimize slack time and optimize resources (Tulga & Sheridan, 1980)
Prioritization	Task Scheduling	Task ordering, task switching	Alerting systems
Timing	Task Scheduling	When to direct attention away from or keep attention on the current task	Scheduling communications to highlight important messages or defer less important messages (Dorneich et al, 2012)

A set of 26 characteristics was developed that define the attributes used to judge the risks of the adaptation types (see Table 4). The characteristics were developed based on the same sources used to develop Table 2.

Table 4. Adaptations risk characteristics.

Characteristic	Adaptation Characteristic Definition
Authority change	Magnitude of change in traditional pilot authority
Complexity	How complicated is the adaptation from the pilot's perspective
Transparency	How detectable (by the human) and understandable is the adaptation
Predictability	Humans can reliably predict adaptation output based on situation
Accuracy	The degree of which a measurement, calculation, or specification conforms to correct value
Pilot interaction requirements	Magnitude of additional pilot interaction requirements to make adaptation work as intended
Acceptability	Are pilots likely to use the system if given a choice
Robustness	Accuracy of results in the face of inaccuracies/noise in the inputs
Disruptiveness	Degree to which adaptation disrupts current task
Ease of override & reversal	How difficult would it be to undo impact of adaptation once triggered
Trust/complacency	Likelihood that adaptation will lead pilots to over-trust it and cease to scrutinize its performance
Knowledge & skill requirements	Level of knowledge/skill required to make adaptation useful
Communication & coordination requirements	Level of additional human-human communication and coordination required to make adaptation useful
Distraction potential	Degree to which adaptation distracts from other task responsibilities
Understandability	Does pilot understand what the outputs of the adaptation are and their implications
Integration impact	Integration impact of additional capabilities required to support adaptation (certification risk increases with scope of system impact)
Novelty	Degree of difference from current systems (more difference has higher inherent certification risk)
Interference	Probability of changing the way pilots interact with existing systems (and interference with task flow, scanning behavior, etc.)
Misleading information potential	Likelihood that adaptation could generate misleading information that could induce pilot error and/or confusion
Failure modes	Potential for negative impact to pilot performance when system fails or adaptation fails or stops inappropriately
Situation awareness	Negative impact on situation awareness
Workload impact	Amount of extra pilot workload that adaptation induces
Usability impact	How easy is the system to use
Trainability impact	How easy is it for pilots to learn how to use adaptive system effectively
Pilot Performance	How well does adaptation support human task performance
Error detectability	How easy is it to detect erroneous system behavior

Six of the characteristics were used to judge the benefits for adaptation: situation awareness, workload, usability, trainability, pilot performance, and error detectability. These were chosen from the larger set of 26 characteristics because they reflect the human-performance constructs by which human-factors benefits on the flight deck are typically described.

Analysis

Method

Objectives. The objective was to assess potential human performance risks and benefits relevant to adaptive system design.

Protocol. Both triggers and adaptation types were evaluated. The two system-based trigger types were combined (System States & Modes), and the two spatio-temporal trigger types

(Time & Location) were combined, resulting in eight triggers being evaluated. The adaptation type Information Quality was not included in the analysis, resulting in 11 adaptations types being evaluated. Two-dimensional scoring matrices were defined with types (rows) and characteristics (columns) for trigger risk (8x8 matrix), adaptations risk (11x26 matrix), and adaptations benefit (11x6 matrix).

For this study, risk was defined as factors that may lead to unsafe outcomes or failure of the automation to operate as intended. For both the analysis and the pilot evaluation, the term risk was left largely undefined beyond this basic definition so as not to constrain feedback from participants. Both groups of participants were asked to assess predicted system risks of new technology that has not been implemented fully, so historical trend data may not match with expected or predicted risks (Rose, 2008). Likewise, benefits were focused on operational, safety, or crew performance improvements due to the technology.

A team of three analysts rated each combination of characteristics and types (i.e., matrix cell) on a scale of 1 (low) to 5 (high). Low risk would not impact safety/aircraft operation/crew workload, and high risk might cause a crash. Low benefit would be lack of any improvements where high benefit would greatly improve safety/aircraft operation/crew workload. For instance, a matrix cell might ask the analyst to rate the risk associated with the potential disruptiveness (characteristic) of a task offloading (type) adaptation. The analyst team raters each had over 10 years of experience in adaptive systems. Each analyst individually provided ratings with rationale. The final ratings were based on a series of reconciliation meetings where the three analysts presented their rationale each in turn, discussed and resolved discrepant ratings, and determined one rating per cell. The team established a secondary process if they could not come to a consensus agreement (i.e. asking an outside expert to "break the impasse"). However, in all cases, analysts were able to reach consensus.

Assumptions and Limitations.

The characteristics developed to assess risks of adaptations were derived from a systematic review of the literature and existing guidance material; However, the current set of characteristics could contain redundancies. This would result in some risks being "double-counted," thereby giving more weight to the riskier characteristics and increasing the average risk. For instance, if the characteristics of transparency and trust/overreliance capture the same risks, then perhaps the ability of the pilots to understand a system's inner workings (transparency) was directly responsible for the pilots' level of reliance (trust/overreliance).

Another limitation is inherent in any process that requires consensus in a team, including limited time, ideas not thoroughly discussed by team, dominant personalities, non-contributing members, ineffective communication, conflict between team members, and inability to focus on the task (Catlett & Harper, 1992). The process was designed to mitigate some of these issues. Team members were asked to rate items individually first, thus their opinions were more likely to be heard. The process was designed to limit discussion to the most important items, and those discussions were focused by giving team members numbers to react to.

This analysis was based on a risk assessment method where the values assigned to the risks and benefits relied solely on expert judgment. The data collected was subjective, and should be considered as a preliminary, top-down first pass at quantifying the risks and benefits.

Results

For each of the three matrices, the types were ordered by the analysts' ratings, with qualitative groupings into higher, intermediate, and lower categories. It should be noted that these groupings are somewhat arbitrary, and primarily serve to distinguish rating levels relative to each other. The three scoring matrices are presented in the Appendix. The characteristics that were the strongest drivers of ratings are discussed below.

Triggers. Risk scores for each type of adaptive system trigger were averaged across characteristics to create an overall risk score (see Figure 4). The full ratings matrix can be found in Figure 11 in the Appendix.

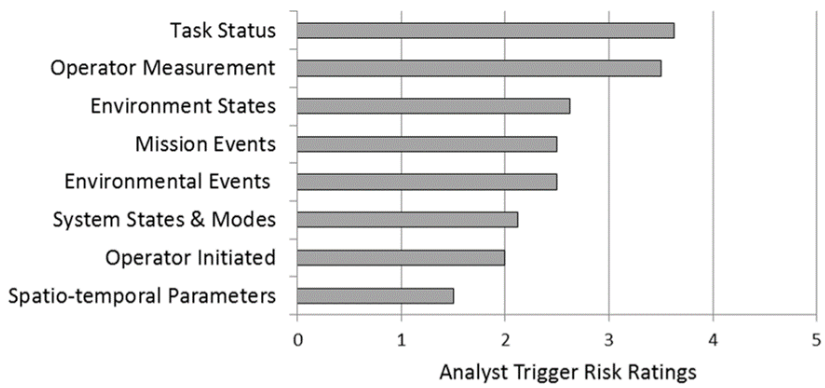

Figure 4. Risk ratings for each trigger type.

The higher-rated risk triggers included task tracking and direct measurement of operator state, driven by issues related to complexity, transparency, and state assessment reliability. Intermediate-rated risk triggers included conditions external to the humans or the automation itself: communications, mission parameters, and environmental events. The lower-rated risk triggers included the automation system states and modes, operator initiation, and spatio-temporal parameters.

Task Status. Risk is driven by complexity and state assessment reliability. Pilot understanding can be compromised by lack of observability of the raw task-tracking data as well as the high inferencing requirement. Absence of sufficient task data could compromise assessment reliability, as could unconventional pilot behavior.

Operator Measurement. Risk is driven by transparency, complexity, resolution, and state assessment reliability. The state of the art of direct operator measurement only provides limited resolution (e.g., 2-3 levels of workload), and even then, the accuracy from moment to moment is modest, thus leading to the higher risk for reliability.

Environmental State. Risk is driven by sensor/data reliability. The reliability and availability of communicated data could vary widely across types and situations. Likewise, different sensors could be negatively impacted by noise. This trigger could be compromised by data communication failure or human error.

Mission Events. Risk is driven by complexity, resolution, and reliability. While phase-of-flight is easily projected, other mission states could be much more difficult and may require model tracking fused with external event awareness. If this trigger relies on complex, fused data, the system should project it judiciously to avoid false positives given that the projection inherits the uncertainty of task tracking and external event identification

Environmental Events. Risk is driven by resolution. Environmental data resolution can be negatively impacted by the availability of high-dimensional data and the rate of external communications. For example, when flying into a thunderstorm, communicated or sensed data may not "keep up" with the forward progress of the aircraft so the system could "miss" opportunities due to poor temporal resolution.

System States and Modes. Risk is driven by transparency. While generally a lower risk trigger, aircraft states or modes may not be as observable to pilots as other triggers. This is particularly true of automation modes, as mode awareness is a well-known challenge for the design of modern flight decks (Sarter, Woods, & Billings, 1997).

Operator-initiated. Risk was driven by resolution and pilot interaction requirements. Humans are not able to reliably assess hazardous states of their own cognition, such as distraction and information overload, making it more difficult for pilots to trigger automation adaptations in a timely manner. Additionally, this trigger effectively adds another task for pilots, requiring the operator to remember to consider opportunities to initiate automation. This requires prospective memory which is compromised under high workload.

Spatio-Temporal Parameters (e.g., time, locations). This was rated as the lowest risk trigger due to its relative simplicity (which enables human understanding), reliability, and precision.

Adaptations. The risks were averaged across 26 characteristics, as presented in Figure 5. The full ratings matrix can be found in Figure 12 in the Appendix.

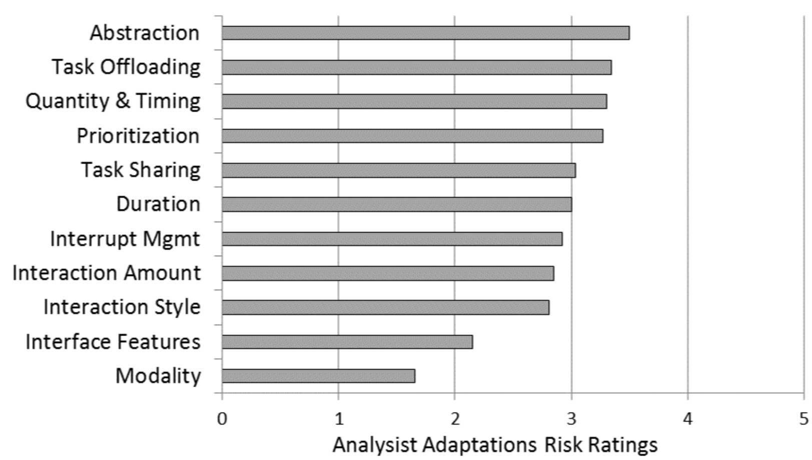

Figure 5. Risk ratings for each adaptation type.

The group with the higher-risk ratings involved changes at the task level: changing the level of abstraction of information designed to support a task, offloading the entire task, changing the quantity and timing of task support, and task scheduling. Intermediate risk adaptation types involved changes within a task: sharing of a task with automation, interrupting one task with another (or blocking another task from interrupting the current one), and changing the amount or style of interaction during task execution. Only changing the allocation of time (duration) for a task does not fit this pattern. The final lower-rated risk adaptations types, included more incremental changes involving the changes to the pilot interface, changes to information content, and changes to the modality of information.

The benefits were averaged across six characteristics, as presented in Figure 6. The full ratings matrix can be found in Figure 13 in the Appendix.

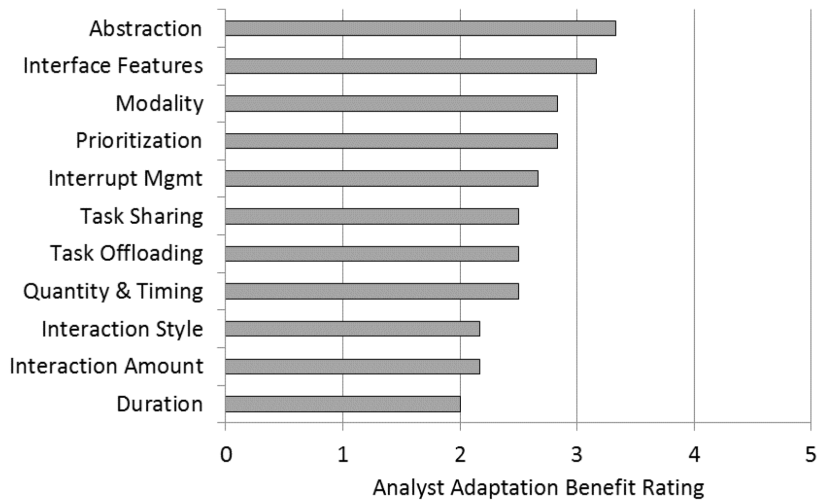

Figure 6. Benefit ratings of adaptation types.

Adaptations to the user interfaces such as abstracting information, or changing the location/salience of the information, were judged to provide the highest benefit. Adaptations such as changing the amount of interaction required or changing the time allocated for task performance were judged to provide the lowest benefit. Interestingly, adaptations that on the surface appear to be a larger departure from current automation roles, such as managing interruptions, and offloading or sharing tasks dynamically between automation and the pilots, were judged to be of intermediate benefit. The characteristics that were the strongest drivers of risks and benefits of the adaptations are discussed below for each adaptation type.

Abstraction. This is the adaptation with the highest overall risk score, driven by error detectability most of all, but also knowledge and skill requirements, trainability, and misleading information potential. Information can be aggregated to present only the most salient information to decrease the processing time it takes to interpret the information. For example, converting detailed system information to an at-a-glance display that only conveys to the pilots if the system is within normal operating parameters. On the other hand, it might be difficult for pilots to understand how the system arrived at the abstraction and make it difficult to detect errors.

Additionally, as something that happens only in certain situations, pilots would have to be trained on how to do the task two ways, although the abstraction would have to be intuitive to be effective. The adaptation may be disruptive, taking pilots out of their normal information-gathering flow, which may affect pilot acceptance. No longer working with raw data, pilots may lose situation awareness of information needed for other tasks. However, high-level-of-abstraction risks might be mitigated for highly determined tasks where pilots do not need significant insight or detailed data.

This adaptation also has the highest overall benefit score, driven by situation awareness and workload. It should enable more efficient acquisition and maintenance of the operational “big picture.” The need for abstraction to be adaptive rather than a permanent design feature acknowledges the fact that there will still be situations when pilots need to review and analyze more detailed information in order to manage the situation correctly.

Task Offloading. Two risks rated highly were novelty and authority change. This would represent a large change flight-deck task allocation from the current convention of strict and fixed separation between automation and pilot. Despite the prevalence of automated flight modes, pilots are still accustomed to being the final authority of task execution. Both Boeing and Airbus automation design philosophies give ultimate control of the aircraft to the pilots; however, Airbus’ design philosophy allows the automation to override the pilot (Balog, 2011). For instance, the autopilot/flight director in the Airbus A380 has a traffic and collision Avoidance (TCAS) mode that allows the autopilot to automatically control the flight path to conduct a TCAS maneuver (Airbus, 2016). In contrast, Boeing’s design philosophy uses automation to aid the pilot in operation of the airplane, setting soft limits to control rather than Airbus’ hard limits (Abbot, 2001). Competent, experienced pilots trust themselves to manage their own task load, so they will be skeptical of automation deciding when to take control. The feasibility of override or reversal decreases over time from the onset of the adaptation. For example, if automation only partially completes a task, it may be challenging to transition control back to the pilot. Likewise, for some tasks it may be a challenge to undo actions completed as a result of the task offloading.

Benefits are driven by workload and situation awareness. Interaction and coordination workload are reduced with task offloading. However, situation awareness benefits less for task offloading than for task sharing because it could be harder for pilots to monitor progress on entire tasks allocated to the automation, in comparison to the task-sharing case where they are still involved at the subtask level.

Quantity & Timing. This adaptation was rated highly compared to others, driven by transparency, error detectability, communication and coordination requirements, integration, and disruptiveness. Many pilots prefer having more information and having it immediately. If changes are subtle, they may be difficult to detect. The timing aspect of this adaptation may have secondary effects on the communications and coordination requirements related to other tasks, in addition to the distraction potential.

The benefits were rated to be more modest compared to other adaptations. Having the right information at the right time may benefit situation awareness, usability, and pilot performance.

Prioritization. Risk ratings were driven most by novelty and interference, as well as authority, trust/complacency, disruptiveness, and pilot interaction requirements. It may be difficult for pilots to properly align their trust in such a system. Under high workload, they might not be skeptical enough of an automated prioritization of tasks, treating the adaptation direction as a de facto procedure. Likewise, it may be difficult to identify failure modes. Such a system would be very dependent on a robust task model, requiring knowledge of tasks across multiple systems. By its very nature, this adaptation is likely to be disruptive and require additional pilot interaction to switch tasks when required.

Benefits are driven by workload and pilot performance. Less effort spent on managing tasks reduces workload directly. This should also significantly improve pilot performance on other more directly mission-relevant aviate and navigate tasks because pilots will have more time and effort to dedicate to these tasks.

Task Sharing. Risk is driven by accuracy, pilot interaction requirements, sensitivity, and robustness. In addition to appropriately decomposing a task into shareable sub-tasks, the system must also communicate task-state information regularly and accurately, and complete the sub-tasks appropriately. This adaptation will add interaction requirements because pilots will now be additionally monitoring the execution of the automation task responsibilities. The system reasoning will be impacted by the reliability of the task-state assessment, which could result in a high robustness risk.

Benefits are driven by workload and pilot performance. Task sharing clearly has a workload benefit because automation is performing some subtasks that pilots normally perform. However, pilots will still need to monitor the automation performance of the shared tasks, so workload benefits will not be as high as if they were able to offload those tasks completely (Pritchett, Kim, & Feigh, 2014). This adaptation would also benefit pilot performance because task performance should be easier.

Duration. Risk is driven by pilot performance, acceptability, trust, and novelty. If the time allocation has been modified to accommodate other tasks in the workflow, the pilot would be faced with the choice of not completing the task in time, or perhaps reducing the quality of the result in order to make the deadline. This tradeoff may be appropriate, but may be a difficult one for pilots to accept. Although there is some precedent for this type of adaptation (Required-Time-of-Arrival or Top-of-Descent as a deadline), the allocation of more or less time for tasks may be seen as novel. The more precise the timing requirements, the more an error would be compounded.

Benefits are driven by workload and pilot performance. If pilots are given a time budget for a task, this would provide a smoother task flow and fewer missed or near-missed deadlines overall, thus achieving a better balance of workload across the entire flight. This should improve overall pilot performance as well.

Interruptions Management (Timing). Risk is driven by authority, predictability, interference, and integration. By directing attention, this adaptation has increased authority over pilot's task priorities, and intentionally interferes with current task flow. Such a system would need to be highly integrated across systems in order to coordinate interruptions from multiple systems.

Benefits are driven by situation awareness, pilot performance, and error detection. The benefits are judged to be high because it brings information to the pilot's attention that he or she may have otherwise missed. Such a system may also reduce unnecessary task switching due to interruptions.

Amount of Interaction. Risk is driven by complexity and transparency. Given a substantial change from a fixed interaction frequency, this adaptation could be perceived as more complex. There would likely be a non-intuitive mapping between the change in parameters and the frequency of change.

No characteristics for this adaptation showed a high potential benefit relative to other adaptations. If more interaction is deemed appropriate in order to encourage pilots to consider more details of a situation or to ensure full pilot understanding of a situation, then situation awareness should be increased and errors might be better detected.

Interaction Style. Risk is driven by acceptability and novelty. Varying the timing, politeness, and method of interaction could be disconcerting to pilots and negatively impact the acceptability of this adaptation. While manipulating the timing of interactions could have situation awareness and performance benefits, it could be disrupting for pilots accustomed to a certain style of interactions.

The main benefit of tailoring the interaction style to the individual or situation is usability. Adapting how terse or verbose the interaction is, and what type of communication protocol is used, should make the interaction more natural, convenient, and usable.

Interface Features. This adaptation was ranked as lower risk, driven by trust/complacency. Pilots may become complacent because most of these adaptations do not foster pilot skepticism. Most pilots are familiar with display changes, so they will be more likely to accept changes without scrutinizing the automation reasoning behind them. Humans have a tendency to economize effort in sampling information (Hertwig, Baron, Weber, & Erev, 2006); the most convenient information source would be preferentially sampled over less convenient information sources.

Benefits are driven by usability, error detection, and situation awareness. Pilots will need less effort to search for information and would be assisted in distinguishing the most important information, improving usability. Assuring that the right information is being attended to should help pilots detect errors and improve their overall situation awareness.

Modality. This adaptation was ranked lower risk. A change in modality is very salient and could distract pilots from ongoing tasks.

Benefits are driven by situation awareness. Modality changes should make it more likely that information will be attended to when presented on a channel that has more bandwidth, given other perceptual demands of the situation. This change in salience will also effectively direct pilots' attention to high-priority information.

Evaluation by Pilots

Method

Objective. The objective of the evaluation was to collect pilot feedback to augment the risks and benefits ratings from a pilot perspective.

Participants. Seven male and one female pilot participated in the study; seven are currently captains and one is a lead test pilot. All were rated as Air Transport Pilots, four were instructors, and current aircraft type ratings ranged across general aviation, business, and commercial. The participants averaged 56 years of age (range 43-67), 8,475 (4,100-20,000) total flying hours, and 2,800 (100-7,000) hours in glass cockpits.

Protocol. Participants were briefed on general types of triggers, with one or two examples for each, followed by scales in which participants rated the potential risk (1= very low risk, 5= very high risk) of each of the eight trigger types rated by the analysts . Participants were given the same risk definitions as the analysts. They provided one overall risk rating (rather than rate characteristics individually), and asked to provide a rationale for their risk rating. Participates were reminded to base their ratings on the general type of trigger, not the specific examples provided.

To assess the adaptation risks and benefits, eight "paper" storyboards were developed to represent notional adaptive automation concepts across the range of the key adaptation types, and with different combinations of risks and benefits (see Table 5).

Table 5. Adaptive systems concepts chosen for storyboard development.

Adaptation	Category	Risk	Benefit	Flight-deck Concept
Task Sharing	Function allocation	Medium	Medium	Clearance negotiation and entry
Task Offloading	Function allocation	High	Medium	Clearance negotiation and entry
Interface Features	Interaction	Low	High	Context-based highlighting
Modality	Interaction	Low	Medium	Text to speech for annunciations
Abstraction	Content	High	High	Weather integration and abstraction
Quantity & Timing	Content	Low	High	Phase-of-Flight based de-cluttering display
Prioritization	Task management	High	Medium	Communication scheduler
Interruption Mgmt	Task management	Medium	Medium	Alert escalation

Participants were presented the storyboards as a short narrative description of the circumstances under which the adaptation might occur, the adaptation itself, and accompanied by pictures where possible. As an (abbreviated) example, two storyboards for the Modification of Function Allocation are provided as follows. In the first example, participants were briefed/updated on the move to data-link as the primary means of communication in Next Generation (NextGen) Air Traffic Control (ATC). Crew will receive a new clearance from ATC via the Controller Pilot Data-Link Communication (CPDLC). Digital communication will allow clearances to be electronically sent rather than by voice. Data-link will increase the frequency and complexity of cockpit text-based communications. The analysis of clearances requires pilots to assess several parameters that influence clearance feasibility. A task-sharing application would offload some (but not all) of the pilot tasks to automation. Increased automation assistance would only be offered in situations where pilot workload was high and time criticality of the incoming CPDLC message was high. The exact level of assistance offered would be determined by these triggers. As an example of the task-sharing adaptation, when a pilot has the greatest need (i.e. high pilot workload, very little time to complete) the system could evaluate the clearance and display the relevant information for deciding whether to accept the clearance (see Figure 7 left). Once the Evaluate button is pressed, the system could make a recommendation of the appropriate response (see Figure 7 middle). The pilot could then accept or reject the recommendation. In the second example, continuing this scenario, a Task Offloading adaptation would go beyond the Task-Sharing adaptation to offload all of the pilot tasks to automation. The system takes a higher level of control: automation carries out all the tasks associated with evaluating a CPDLC request, implements the requested changes to the flight plan (Figure 7 right), and notifies the pilot that an action has been taken.

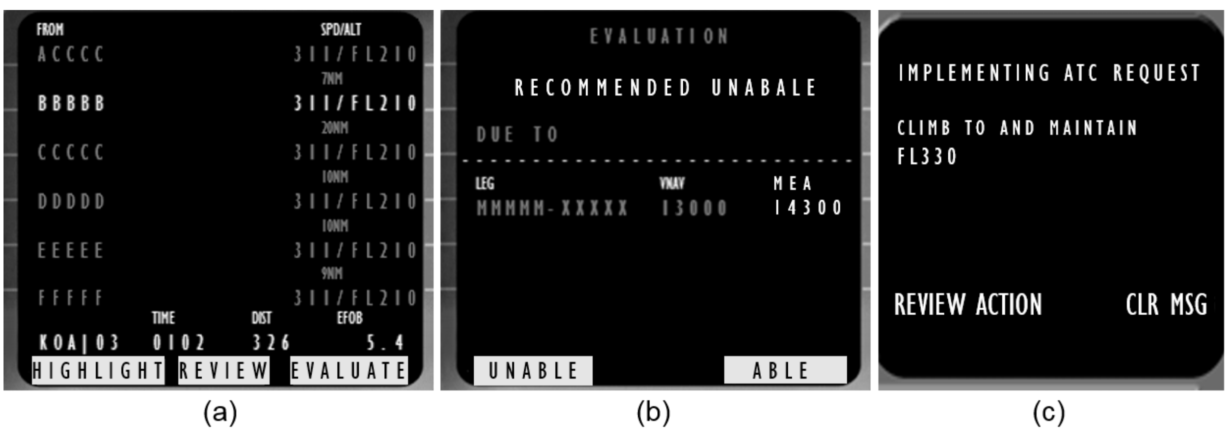

Figure 7. Clearance evaluation task sharing ((a) and (b)) and task offloading (c).

In addition to this storyboard and illustrations, participants were also given descriptions of other examples to broaden their exposure to the concepts within an adaptation category. In describing the "task offloading" example, participants were briefed on other concepts. For instance, the automation could take over the flight maneuver in a situation where a Traffic Collision Avoidance System Resolution Advisory (TCAS RA) is issued, the pilot has not complied within 5 seconds, and the automation confirms that the TCAS RA maneuver would not jeopardize the flight (assumes a very accurate surveillance system, such as ADS-B). This has the potential to reduce the number of cases where a delay in responding to the TCAS RA causes a near miss or potential mid-air collision.

The goal was to provide, for each adaptation type, concrete examples based on one detailed example plus several brief descriptions of other examples, rather than just provide a definition. Participants were asked to base their ratings on the general type of adaptation, and not on the specific examples provided. Participants rated risk and benefits on a scale of 1 to 5. Pilots provided one overall risk and one overall benefit rating for each adaptation type. Rationale was collected to understand what drove their ratings.

Results

Trigger Risks. Figure 8 compares risk ratings between pilots and analysts. The two ratings were significantly and strongly correlated (r(6)=.73, p = .037). Generally, all risk ratings comparisons were within 0.5, except for spatio-temporal triggers, where analysts rated it the least risky overall (1.8), driven mainly by transparency. Spatio-temporal information will become more important as NextGen implementation matures. Pilots commented that the triggers they rated lower risk were those already in use today. Pilots felt that the higher-risk triggers of Operator Measurement and Task Status Both were difficult to accomplish, complex, and subject to individual variability. Both approaches may not have the levels of accuracy pilots said they needed to accept the system.

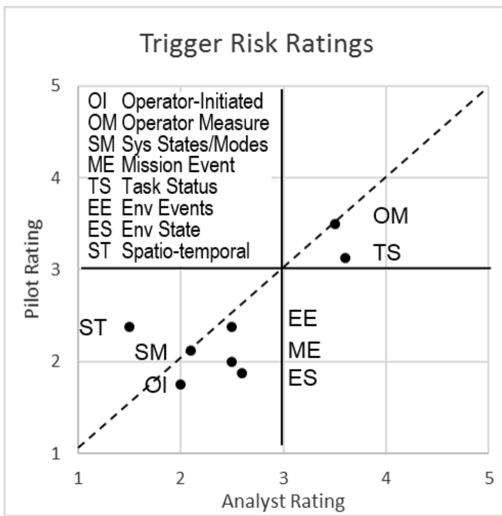

Figure 8. Trigger risk ratings for analysts and pilots.

Adaptation Risks. Figure 9 compares risk ratings between pilots and analysts. There was a non-significant correlation of r(6) = .16 (p = n.s.) between the two ratings. Overall, pilots rated the risks lower than analysts, except for Task Offloading and Modality.

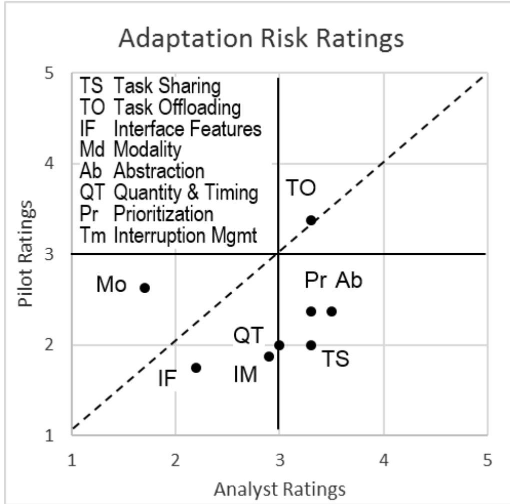

Figure 9. Adaptations risk ratings for analysts and pilots.

Task offloading was rated by pilots and analysts as the riskiest adaptation type. Pilots commented that the principal driver of their higher-risk rating was that the adaptation takes pilots out of the decision-making loop. Pilots were concerned if missing, but needed, information is shifted to another modality.

Pilot risk ratings were lower than pilots in the remaining six pairs of ratings. One explanation is because the analysts rated 26 characteristics for each adaptation type, some characteristics may be redundant, giving more weight to the riskier characteristics and driving up the average risk (a limitation discussed later). The lower-risk group where pilots and analysts agree (e.g. interface features), participants felt that these adaptations did not take control out of the hands of pilots. Pilots commented that some of the ideas presented to them were just extensions of simple adaptive systems in use today, with perhaps more automation intelligence, sophistication, and complexity. Pilots felt that the implementation details of most of these concepts that will ultimately determine the risks and benefit levels.

Adaptation Benefits. Figure 10 compares benefit ratings between pilots and analysts. There was a non-significant correlation of $r(6) = .34$ (p = n.s.) between the two ratings. Pilots rated benefits higher than analysts, just as analysts rated more overall risks than pilots. In general, pilots were very positive about the storyboards they reviewed as part of the evaluation. Pilots generally liked the adaptive nature of the system, although there was skepticism about the benefit of adaptive systems over good full-time, well-designed automation concepts.

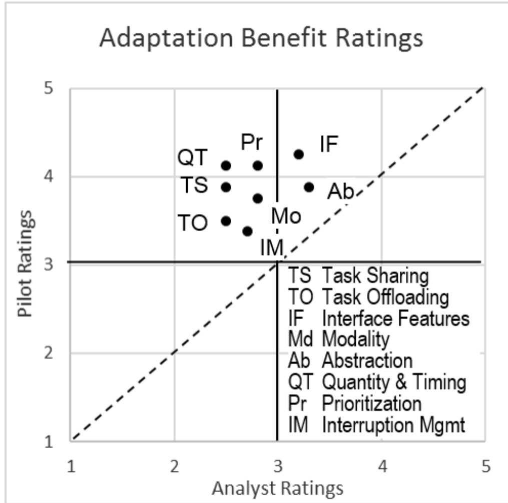

Figure 10. Adaptations benefit ratings for analysts and pilots.

Discussion

There may be a higher risk for adaptive systems, as compared to full-time automated systems, simply because they turn adaptations on and off based on aspects of the situation. Both pilots and analysts felt that operator-initiated adaptations, more were lower risk, given that the operator is still in control of when adaptations turn on and off. Pilots and analysts agreed that task tracking and operator measurement were the highest rated risk triggers. Both triggers are novel, and would require a high level of reliability given that they are not easily transparent to the pilots. Understanding why and predicting when the automation triggers change requires knowledge of the conditions governing the transition (Javaux, 2002). Both analysts and pilots identified inherent risks when the level of complexity and transparency reaches a point where the adaptive system's behavior is perceived as non-deterministic (stochastic) by pilots. One pilot speculated that once the number of triggering conditions approached five or more, pilots would lose the ability to understand what the system is doing, and what it will do next, which the pilot equated to the loss of pilot awareness of the automation. The pilots in the study wanted the triggers to be understandable and simple; however, if the system "got it right", they were less concerned with transparency and complexity. Further research will be needed to quantify the level of complexity and transparency that drives the perception of non-determinism, and the level of reliability that may mitigate the risk.

Analysis identified the principal drivers of adaptations risks/benefits as the level of control vs. information adaptation. Pilots rated adaptations that changed information displays as lower risk than adaptations that potentially affected the direct control of the aircraft. Pilots felt that adaptive systems should always request permission to take control of the aircraft, reflected in the higher-risk ratings with task offloading adaptations where the pilot is taken out of the decision-making loop, which can lead to surprises. While information support was useful, pilots preferred designs where the human makes the final decision. Pilots clearly saw the potential benefits of increasingly active automation that could anticipate pilot needs and automatically trigger changes in automated support. Those benefits, however, will only be realized when carefully weighed against the costs.

There were several lessons learned that inform future efforts in this area. First, participants reinforced the lesson that adaptive systems are not new to the flight deck, nor are pilots' perceptions of the unpredictability of automated systems. Therefore, operational data could be collected on potential risks related to both adaptive systems and those that appear to the user to exhibit non-deterministic behavior. Second, it became obvious that pilots in our study thought about flight-deck automation somewhat differently than did the analysts in our study. Many of the nuances that the analysts focused on were unimportant to the pilots – they very elegantly simplify problems with adaptive systems to factors such as whether the behavior of the system is understandable or not, and whether it "gets it right." Finally, pilots were concerned that the complexity of these types of systems may make the system less predictable, and therefore less acceptable in control applications. Although acceptability may relate to many other characteristics such as complexity and transparency, it is fundamentally related to whether adaptations are perceived to provide value to the pilots without resulting in an annoying behavior or impediment to pilots' ability to perform their tasks. This could be the biggest challenge for all but the simplest, most basic adaptive systems – will the adaptation reliably and consistently make changes that pilots need or want?

This work represents pilots' and analysts' assessments of the risks and benefits of increasingly complex and capable adaptive systems under development to meet the demands of NextGen. As such, the results presented in this paper must be considered preliminary, given the subjective nature of the data and the small number of both analysts used in the analysis and pilots in the evaluation. Furthermore, using a component framework to assess potential adaptive system risks and benefits from a pilot perspective was useful, but not sufficient, to identify all potential risks and benefits. The set of 26 characteristics may have contained overlap, leading some risks to potentially be over-weighted because two characteristics may be redundant. An independent set of characteristics would provide a better basis for any assessment tool to evaluate risks and benefits of adaptive systems. To address this limitation, work is being conducted to develop a systematic assessment of the characteristics that would reveal any redundancies or mismatches between them. Similarly, equally weighting characteristics could add risk, and not considering inter-dependencies among the characteristics may be a weakness of the current analysis. Similarly, just classifying triggers as a certain type only partially tells the story of the potential risk; the number of triggers, the combination of triggers of different types, and the observability of the triggering events are all very important in identifying risks.

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Appendix

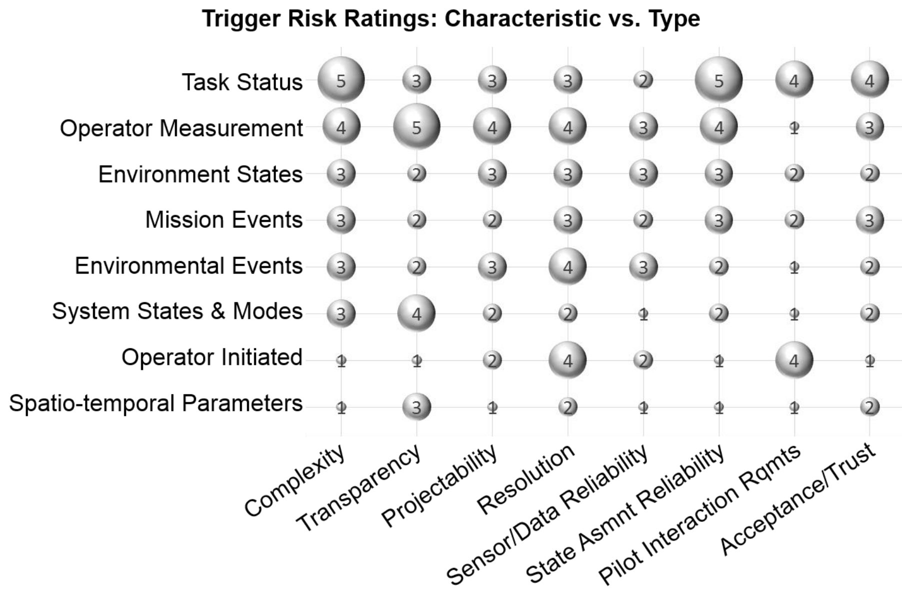

Figure 11. Trigger risk ratings for each combination of adaptation type and characteristic.

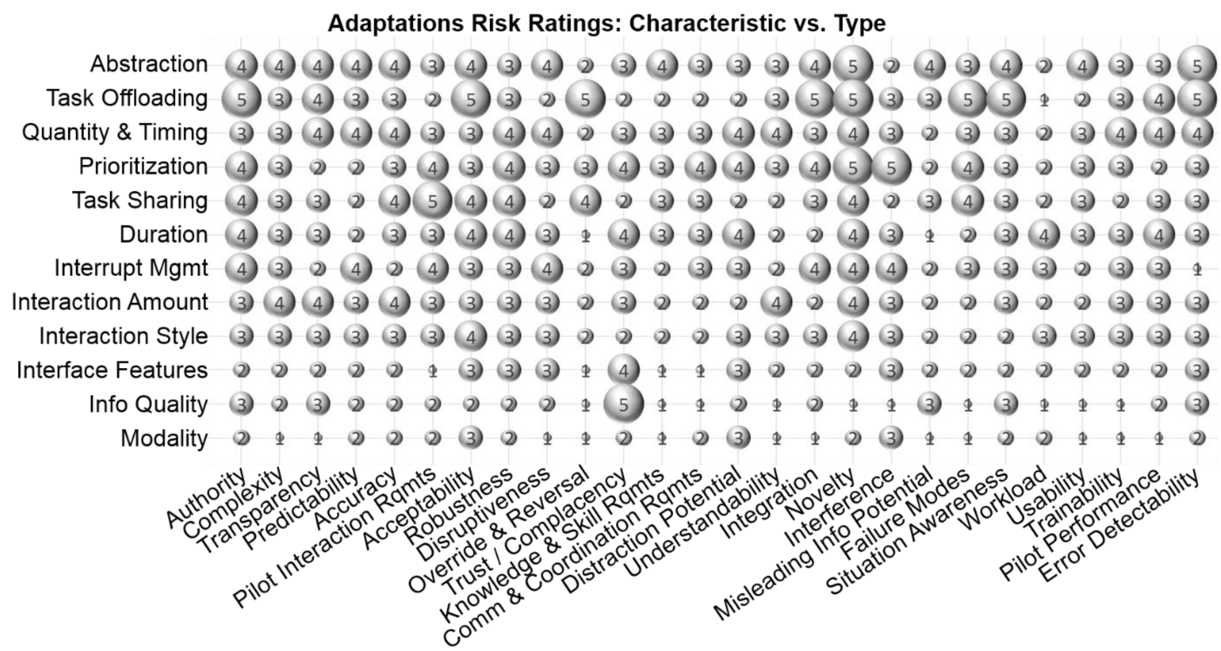

Figure 12. Adaptation risk ratings for each combination of adaptation type and characteristic.

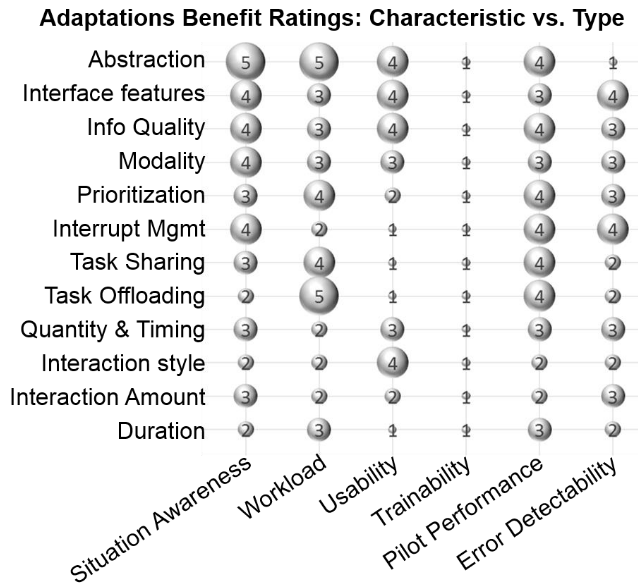

Figure 13. Adaptation benefit ratings for each combination of adaptation type and characteristic.