Lunar Landing: Dynamic Operator Interaction with Multi-Modal Automation Systems

By

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B.S., Mechanical Engineering
The University of Portland, 2008

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Abstract

The ability of operators to "gracefully transition" (maintaining control and awareness of the system without excessive workload or decrements in flight performance) between levels of automation (LOA) in several case studies and in a simulated lunar landing was investigated in anticipation of future lunar missions.

Endsley's situation awareness model (extended to apply to supervisory control systems) and the Sheridan/Verplank and Proud/Hart LOA scales were used to analyze six maritime, aviation, and aerospace case studies and formulate design guidelines for enhancing mode transitions. These motivated an experiment in which thirteen subjects with flight simulator experience flew 24 approach trajectories (half including a landing point redesignation) that transitioned from a fully automatic flight control mode to either: pitch rate-control/attitude hold (RC/AH) with automatic rate-of-descent (ROD), roll-pitch-yaw (RPY) RC/AH with automatic ROD, or RPY RC/AH with incremental ROD. Subjective and objective workloads were measured using a Modified Bedford Scale and secondary task response time, respectively. A tertiary task - verbal callouts of altitude, fuel, and location, provided a measure of pilot situation awareness. Flight performance was evaluated using the pitch axis tracking error.

Friedman pairwise tests demonstrated that secondary task response time significantly increased following the mode transition. Subjects' workload ratings, when ranked, showed unanimous agreement that workload was lowest prior to the transition, and highest during. The accuracy of the situation awareness verbal callouts decreased significantly after the transition. The immediate effect of redesignation was statistically concordant across subjects. Pitch axis tracking mean square error following a mode transition was greater in trials with redesignations ($p = 0.0005$), and increased consistently with control mode difficulty (p = 0.025) in runs with no redesignation, but not in runs with redesignations.

Using callouts to assess the dynamics of situation awareness is a novel technique. Dramatic changes in subjective and objective workload and situation awareness occur after mode transitions, depending on control mode difficulty, that have an apparently reciprocal relationship. The case studies and experimental results suggested a dozen guidelines for design of supervisory control systems intended to promote transition gracefulness.

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Denique: gloria Patri, et Filio, et Spiritui Sancto. Sicut erat in principio, et nunc, et semper, et in saecula in saeculorum.

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Chapter 1

Introduction to Graceful Transitions

1.1 Graceful Transitions

Multi-modal automation systems, by their nature, require operators to transition between modes to accomplish mission goals. Nonetheless, as detailed in Sections 2.1-2.2, existing theories of supervisory control, taxonomies of Levels of Automation (LOA), and design heuristics (e.g. Fitt's List) largely focus on choosing a single appropriate level of automation for the particular application, ignoring the fact that automated systems need to be designed to facilitate graceful transitions between operating modes. Some aspects of mode transitions have been captured using concepts such as "mode awareness", "clumsy automation" and "automation surprise." For the purposes of this thesis, we defined the ability of a supervisory control system to gracefully transition between modes as:

> The ability of a complex system to change between levels of automation/levels of supervisory control (including automation modes) with the operator maintaining control and awareness of the system without excessive workload or sacrificing system performance.

1.2 Real-World Applications

In cases of commercial aviation, multi-modal automation systems are used in everyday procedures, with numerous goal-specific modes that operators must constantly navigate between. Difficulties associated with mode transitions have been noted by several authors

[1, 2, 3, 4]. Understanding how to implement such systems without excessive workload or sacrificing system performance is vital to improving safety and efficiency.

The following sections detail several case studies and highlight the dramatic effects that multi-modal automation systems can have on operator workload and situational awareness, as well as overall system performance. These case studies are used to develop a set of design principles for multi-modal system automation design with respect to the dynamic relationship between modes. These case studies also help to form the basis for the experiment detailed in previous sections.

Chapter 2

Case Studies Background

2.1 Understanding Automation

Recent increases in the computational power of computers have outstripped the understanding of how best to implement their abilities, leading to a lopsided relationship in computer-integrated systems; increasingly complex systems are supplied with an immense set of capabilities with less understanding of the effects on operator performance [5, 6]. As a result, many automation derived failures have been introduced into such systems that were otherwise absent (see Section 6.2). A consideration of optimal automation implementation with respect to the operator was initially taken by Fitts et al. [7], who compiled a comprehensive list of recommendations regarding task allocation between man and machine (see Table 2.1). Revisions to this approach have been made, adding new design guidelines and modifying past assumptions regarding comparison between the human and computer [5, 8]. Additionally, some terminology has been defined.

- Clumsy Automation - Automation that places additional and unevenly distributed workload, communication, and coordination demands on pilots without adequate support [1]; automation that lightens workload when it is already low, and raises it when it is high [1]; automation that creates periods of work "under" load or understimulation and periods of work overloads or bottle necks.

- Brittle Automation - Automation that possess only limited functionality and little or no capability to learn; the set of situations the automation addresses is too small, and doesn't have the capability to respond to the entire range of normal operation activities [9].

- Literal Automation - describes the character of a conventionally automated system, strictly to follow the instructions given by the human operator no matter whether

Table 2.1: Fitts' List: Machines vs. Human

	Human Strengths		Machine Strengths
1	Ability to detect small of visual or acoustic energy.	1	Ability to respond quickly to signals, and to apply great force smoothly and precisely.
2	Ability to perceive pattern of light or sound	2	Ability to perform repetitive, routine tasks.
3	Ability to improvise and use flexible procedures.	3	Ability to store information briefly and then to erase it completely.
4	Ability to store very large amounts of information for long periods and to recall relevant facts at the appropriate time.	4	Ability to reason deductively, include computational ability.
5	Ability to reason deductively.	5	Ability to handle highly complex operations, i.e. to do many different things at once.
6	Ability to exercise judgement.		

they are correct or might wrong [10].

- Opaque Automation - Automation that fails to provide sufficient feedback concerning its activities [3, 11].
- Automation Surprise - The result of a breakdown in the interaction between human operators and automated systems, where it is difficult for the human to track the activities being completed by the automation and as a result is surprised by the behavior of the automation. Leads to questions like, what is it doing now, why did it do that, or what is it going to do next [7, 9].
- Automation Mode - An automated process that is capable of carrying out long sequences of tasks autonomously in the absence of additional commands from the human supervisors [7], not withstanding parameter changes by the operator.
- Automation Level - A point within a continuum that specifies the full or partial replacement of a function by automation that was previously carried out by the human operator. This implies that automation is not all or none, but can vary across a continuum of levels, from the lowest level of fully manual performance to the highest level of full automation [12].
- Supervisory Control Level - A point within a continuum that species the authority, responsibility, and allocation of functions within a task between the automation and

the human operator [13].

2.2 Levels of Automation

Sheridan and Verplank initially proposed Levels of Automation (LOA) as a way of describing automation in undersea telerobotics, and this approach has become standard in automation design and analysis [14]. Parasuraman, Sheridan, and Wickens later reevaluated this approach and summarized Sheridan's original levels, as shown in Table 2.2 [12]. Other LOA taxonomies have been produced, most notably those of Endsley and Wickens [15, 16, 17].

Table 2.2: Parasuraman, Sheridan, & Wickens' LOA [12]

Level	Description
10	The computer decides everything, acts autonomously
9	informs the humans only if it, the computer, decides to
8	informs the human only if asked
7	executes automatically, then necessarily informs the human, and
6	allows the human restricted time to veto before automatic execution, or
5	executes the suggestion if the human approves, or
4	suggests one alternative
3	narrows the selection down to a few, or
2	The computer offers a complete set of decision/action alternatives, or
1	The computer offers no assistance: the human must take all decisions and actions.

Parasuraman, Sheridan, and Wickens proposed a new LOA taxonomy which added a second dimension in light of the four stage model of human information processing (simplified from more extensive models [18]). This taxonomy describes human information processing as an iterative serial sequence of information acquisition, information analysis, decision selection, and action implementation and suggests levels of automation within each stage [12]. This second dimension in the classification of automation is similar to the OODA model (an acronym for observe, orient, decide, and act), an analysis method used in modeling fighter pilot information processing techniques [19, 20]. Endsley and Kaber used a similar approach while investigating the dynamic relationship between different levels of automation [15]. Later, Proud and Hart [21] used the OODA model specifically for describing this second dimension by developing a 2D LOA taxonomy that had 8 LOAs for each phase. These levels were used in the analysis of the case studies and are described in Appendix A, Table A.1.

2.3 Situational Awareness

A model proposed by Endsley of situational awareness is shown in Figure 2.1 [22]. This model shows the critical role that situational awareness plays in the decision making process and provides a general description of the more specific case of operator awareness and response during a mode transition. Such specificity has been suggested previously [3, 23]. The model maps the following effects as they relate to situational awareness:

- Individual's information-processing mechanisms
- Innate abilities
- Experience
- Training
- Goals and objectives
- Preconceptions

Additionally, factors not external to the user are included:

- System capability
- Interface design
- Stress and workload
- Complexity
- Automation

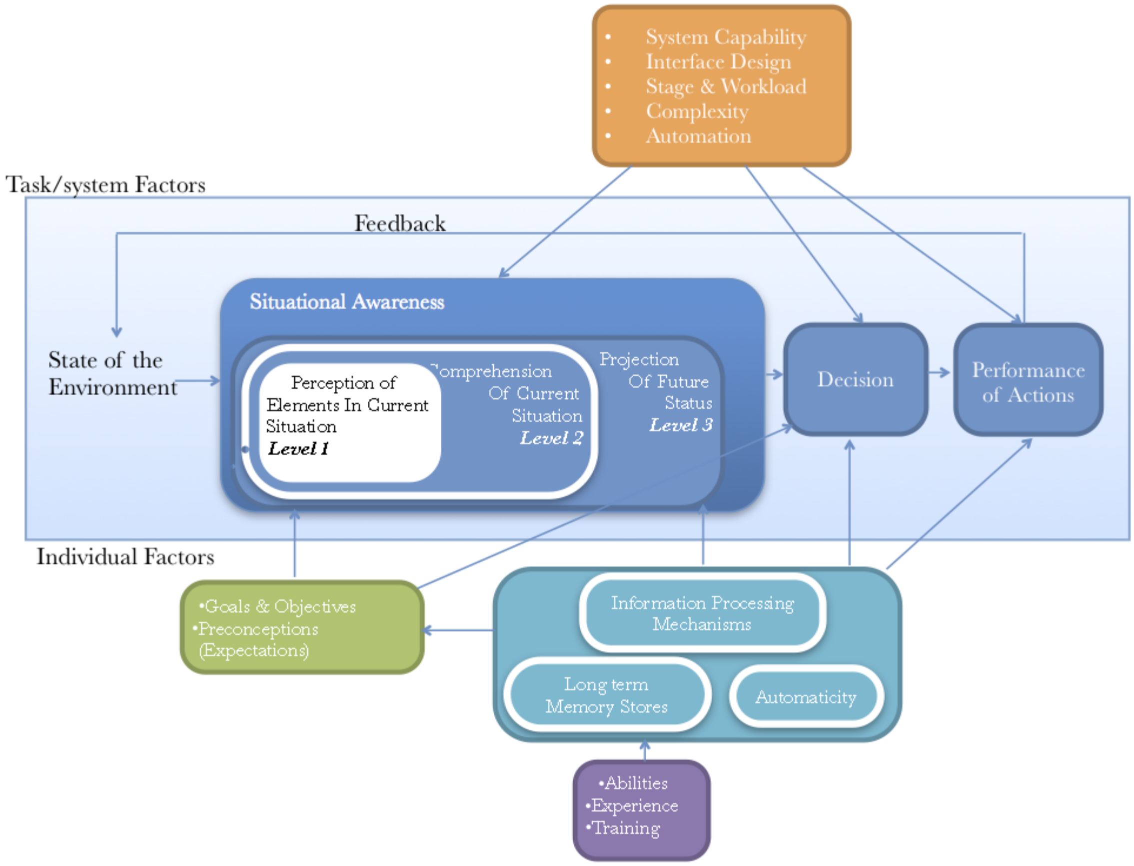

Figure 2.1: A model of situational awareness in dynamic decision making [22]

This model does not suggest that inadequate situational awareness leads to poor performance; downstream cognitive processes such as decision making can positively influence outcomes [24]. The underlying mechanisms of this model are further elucidated by Endsley in a mechanistic model, shown in Figure 2.2, which distinguishes the following blocks of a four stage model of information processing: perception, interpretation-comprehension-projection, decision making, and action guidance. Human preattentive processing, attention resources, and memory are included as well. As detailed in Chapter 3, the Endsley model shown in Figure 2.1 was further extended to describe situational awareness and information processing in order to provide a conceptual framework for analysis of some case studies of mode transition accidents and incidents. Hence additional details of the Endsley model are reviewed below.

Short Term Sensory Store
This element refers to the use of stimuli characteristics, such as spatial proximity, color, shape, and movement to preattentively (prior to using attention resources) filter and highlight information [25, 26]. This block serves to reduce a sensory scene into a manageable set of stimuli, varying in salience. The recognition of certain stimuli in this block help form the basis of Level 1 situational awareness [27].

Attention Resources
Attention resources feed each block within working memory and serves as governor for how much information may be processed at once. Attention resources not only determine the quantity of information that can be processed, but the quality by which it is processed as well [27]. Long-term memory, cue salience, and frequency of occurrence all play a factor in the allocation of attention resources [28].

Perception
Perception further categorizes and filters information following preattentive processing. However, in contrast to the short term sensory store, attentive resources are used here in applying learned expectancies based on long term memory [29, 30, 31, 32, 33, 34, 35]. Advance knowledge of information characteristics and expectations, such as might be developed by repeated experience in an environment and top-down attention processing, facilitate this process, which produces the elements of Level 1 situational awareness [27].

Interpretation-Comprehension-Projection
This block forms Level 2 and 3 situational awareness and is otherwise referred to as working memory, in which new information is combined with pre-existing information to form a "composite picture" of a situation [27]. Projections to future states are also made here, which form Level 3 situational awareness; however, this function is highly taxing on working memory capacity [36].

Decision Making
The decision making block refers to processing following data synthesis and may contain any number of heuristics or probabilistic algorithms for determining a course of action [37]. One such model of decision making is of Bayesian statistics and Causal Induction Theory [38]; however, such specificity is not required in this model, as this block only specifies the general translation from data to action decision.

Action Guidance
Action guidance refers to the execution of a chosen action, anywhere from complex athletic and coordinated movement to the pressing of a button. Depending on long-term memory stores, this block can experience a certain amount of automaticity, referring to a preprogrammed execution of the action requiring fewer attentional resources than a more conscious action [27].

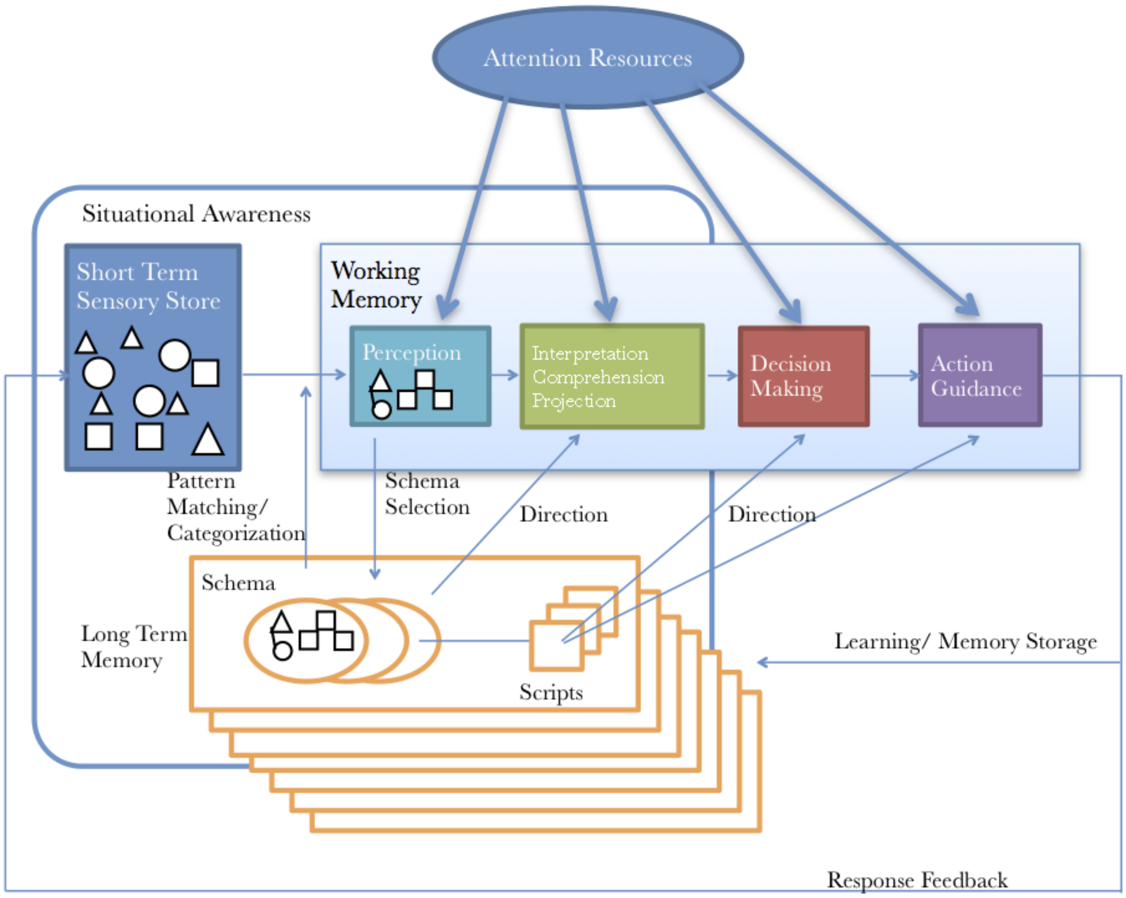

Figure 2.2: A mechanisms model of Situational Awareness [22]

Long Term Memory

For the purposes of this model, long-term memory encompasses the concept of *mental models*, which are defined as "mechanisms whereby humans are able to generate descriptions of system purpose and form, explanations of system functioning and observed system states, and predictions of future states" [39]. Such mental models are related to the *schema* represented in the model, which provide a framework for perception and associations in complex networks of incoming information [40, 41]. Additionally, specialized *scripts* are associated with these schema, which provide preprogrammed sequences of actions [42].

Chapter 3

Case Studies Methods

3.1 Framework for Analysis

The model in Figure 2.1 is particularly applicable for the purposes of understanding the ability of a system to transition gracefully, as situation awareness (and mode awareness, a subset of situational awareness) are a key element in graceful transitions; however, the model is vague with respect to the human-computer decision making processes. As such, an updated model is proposed in Figure 3.1, which was used as a basis for identifying factors in graceful transitions in the case studies.

This updated model specifies 3 levels of mode awareness, similar to the concept of system awareness, as a subset of situational awareness [3, 23]: the awareness of a the available modes and the current mode of operation (Level 1), the current mode output as well as the logic behind that output (Level 2), and any future modes that will be experience and how those will behave in context of the system and environmental states (Level 3). Automation is also characterized by (1) the complexity of its architecture [10], (2) its capabilities/limits of operation [9], (3) the characteristic of the particular mode of operation being considered [7], (4) the interface design between the operator and the automation, (5) the opacity of automation, both concerning the mode as well as the overall architecture [3, 11], and (6) the disparity between the two modes of operation being considered in an analysis.

These proposed model updates flow from both insights gained from the case studies as well as updates to Endsley's mechanistic model, shown in Figure 3.2. This particular model was used in identifying transition mechanisms and places the four-stage information processing model alongside a four stage automation model, similar to that proposed in recent LOA work [12, 15, 21]. In this model, LOA are an emergent property of information flow between the human and the automation within phases and between information processing blocks,

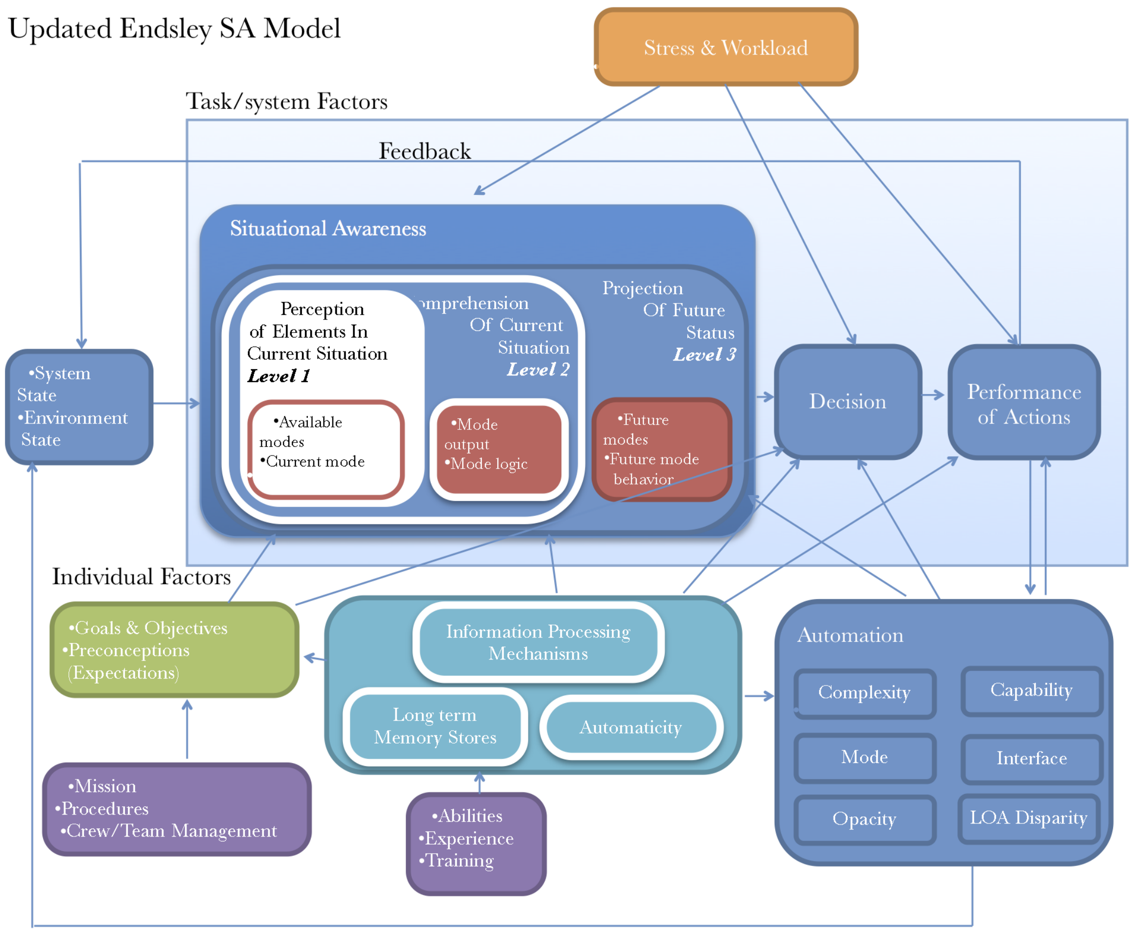

Figure 3.1: Updated model of dynamic decision making [27]

which is governed by the mode setting and represented as information flow valves. Parallel processing of multiple tasks is not explicitly modeled here; such task interactions should be considered in the future, as research concerning integrated and separable dimensions in display design suggests interesting interactions [18].

Mode Setting

The mode setting block determines which mode the system operates in and sets each of these parameters with respect to each phase of the active information processing. The mode setting process was included within the situational awareness block, as the mode setting is "machine long-term memory," and is analogous to machine situational awareness. Mode confusion has usually attributed to the human [43, 44], but the conservative human-systems designer might argue the converse: the machine was situationally unaware of the human.

Monitoring the mode setting affects additional attention resources from the operator: (1) attention resources are allocated to monitoring and setting the current mode setting and (2) the mode setting determines the allocation of attention to the four phases of human information processing. Though a mode may be cognitively undemanding, it might still draw a large amount of attention from the human based on a lack of trust in the automation at the time. Additionally, the mode setting affects the mental model of the operator in the way schema are developed and applied to the current situation; these schema recursively affect the chosen mode. This explains the well-known phenomena of operators developing whole new methods of controlling a system based on the implementation of automation.

Sensors

With any modern-day system, sensors are major and/or necessary component of data collection. The way in which these sensors are active (filtering, direction, sensitivity, fidelity, etc.) is directed by the mode setting and corresponds to the active mode of the entire system.

Active Mode

The active mode describes the flow through of information as determined by the mode setting. Given different LOA, information will flow between the human and the computer differently. For example, in a high LOA the synthesis of information from the two decision blocks (human and computer) being fed to the action blocks (human and computer) would primarily come from the computer.

The human processing phases will never be completely isolated from each other as the human processing model is continuous by nature. However, automation is able to ignore particular results, integrations, and actions from previous phases and is not continuously serial. Thus, parallel human processing can exist in a completely supervisory sense: the human can shadow the automation even at the highest levels of automation.

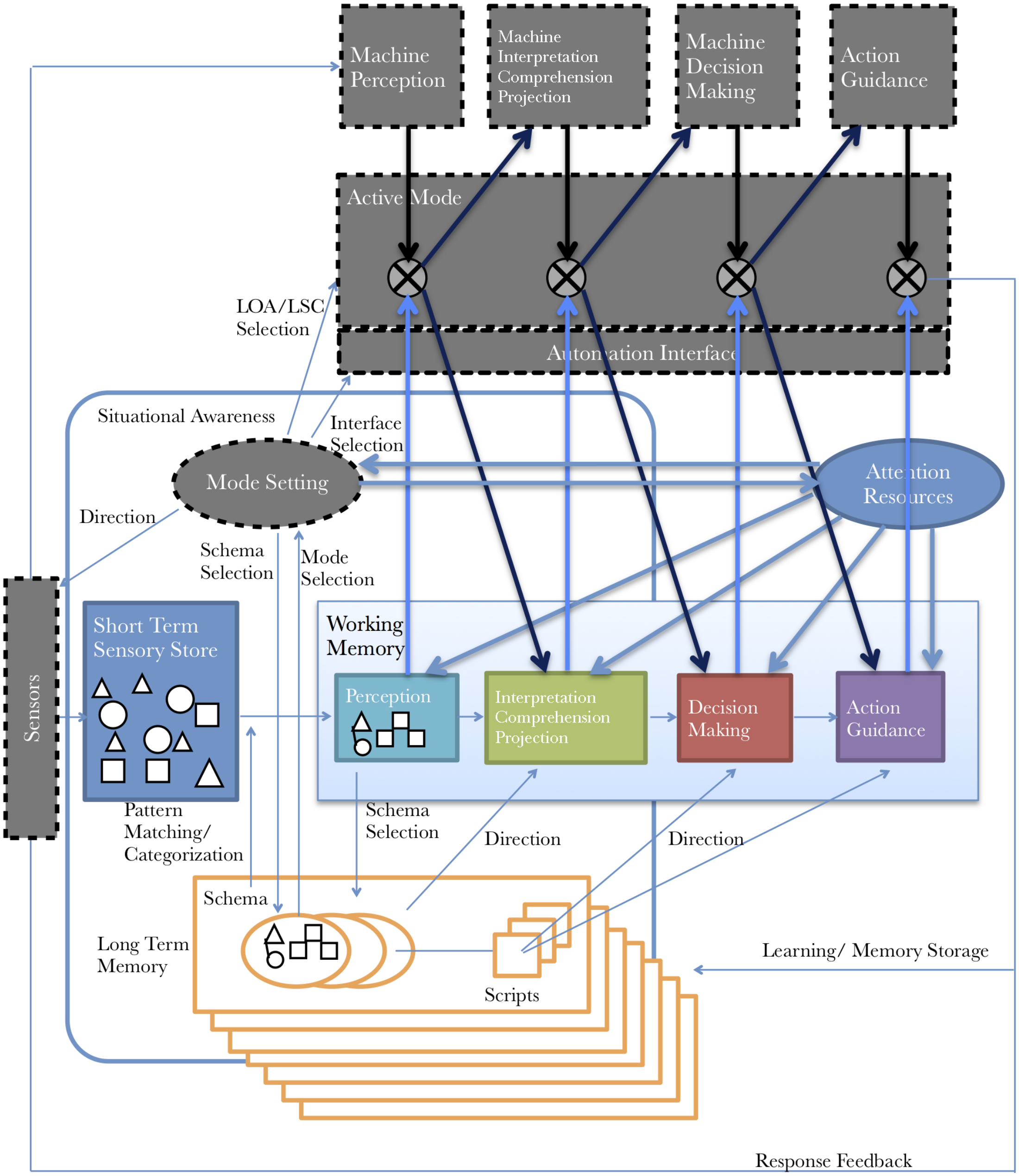

Figure 3.2: Updated model of situational awareness and information processing

Automation Interface
The automation interface is particularly important, as it determines how the active mode interacts with the human. The ideal interface should show no information lost between the active mode and human. The interface is determined by the mode setting of the currently active mode. In some cases the interface will not change with the mode setting (static displays, single screen displays, etc.); however, in highly complex systems, nested interface displays are very common.

Interface filtering is separate from that which is intended for display by the current active mode. An example of interface filtering occurred in the Apollo 13, where the critical piece of information was displayed to the astronauts at the time preceding the accident; however, due to the poor interface design that particular piece of information was missed. The active mode *intended* to provide this information to the user, but the design of the interface effectively blocked this information due to clutter. Such effects should not be confused with the filtering caused by high-workload: the interface refers to the passing of information to the operator, whereas workload affects the operator's reception of that information.

3.2 Overview of Analysis

Six case studies (shown in Table 3.1) from marine operations, aviation, and aerospace were selected and analyzed, each containing at least one instance of a mode transition. For each instance, the levels of automation of the mode prior to the transition and following the transition were defined. These levels of automation formed the basis for characterizing the "LOA Disparity" factor shown in Figure 3.1. This characterization was done first using Sheridan and Verplank's LOA taxonomy, and then using Proud and Hart's LOA taxonomy.

Table 3.1: Case studies in graceful transitions

Number	Application	Description
1	Maritime	The *Crown Princess* heeling incident
2	Maritime	The grounding of the *Royal Majesty*
3	Aviation	Crash of Aeroflot-Nord Flight 821
4	Aviation	TNT Airways Limited Cargo Flight 325N impact on runway
5	Aerospace	Space Shuttle STS-3 PIO at landing
6	Aerospace	Apollo 11 lunar landing

Following the particular characterization of "LOA Disparity", each transition was considered in the framework of the extended versions of Endsley's situational awareness models (shown in Figure 3.1 and 3.2). First, the triggering factors were identified based on Figure 3.1. Second, the same model was used to identify factors related to the ungracefulness of the transition were identified. This identification was based on earlier proposed definition of a "graceful transition". For example, in transitions with excessive workloads, stress and workload were identified as a factor in the ungracefulness, with other related elements as defined by the context of the transition. In cases of graceful transitions, no factors were identified. Third, mechanisms within the extended situational awareness model (see Figure 3.2) were identified. Finally, following this classification of each transition, specific design lessons were identified each transition. Each of these models was continually developed with each successive case study; if transition was not adequately characterized with the existing factors model, a new factor was added or an existing factor was expanded to encompass it. Because these models developed throughout the review of all six case studies, these models were retroactively applied to earlier-reviewed case studies for complete consideration within the full context of the completed models.

Separate summary lists of all active factors (triggering and gracefulness) and mechanisms in the case studies were made. The total occurrences of each factor trigger factor was divided by the number of transition instances to generate the occurrence percentage shown in Figure 4.1. The total occurrences of each factor in ungracefulness was divided by the number of total ungraceful transitions to determine the occurrence rates shown in Figure 4.2. The occurrences of certain mechanisms were also divided by the totla number of ungraceful transitions to generate the occurrence percentage shown in Figure 4.3. Using occurrence totals and the specific design lessons from each transition, a set of generalized Design Principles were created (see 4.1). The factors and mechanisms identified as active in each transition were then mapped to the general design principles based on the specific those lessons learned encompassed by that principle.

3.3 Overview of Case Studes

The following sections provide brief descriptions and summaries of the six case studies. There are a number of cases of mode transitions in application that could have been used. These case studies represent a broad set of applications for multi-modal automation and generally provided detailed reports adequate for the analysis of the mode transitions' effects.

3.3.1 Maritime Cases

The Crown Princess

The following case study refers to the Heeling Accident of the *Crown Princess* in the Atlantic Ocean off of Port Canaveral, FL on July 18th, 2006 [45]. The cruise ship *Crown Princess* heeled at a maximum angle of about 24 degrees due to a number of factors, chiefly being misguided input from the 2nd officer into control system that was too slow to respond. These control inputs followed the disengagement of the ship's autopilot, which was operating in a regime unsuited for its operational environment. No casualties were sustained in this accident.

The following instances of mode transitions were identified and analyzed within this case study:

1. Transition from manual steering to heading mode in the trackpilot by the captain.
2. Change in status of the 2nd officer from monitoring to supervising.
3. Transition back to manual steering from heading mode by the 2nd officer

(For a detailed analysis of this case study, see Appendix B.)

The Royal Majesty

As described in the NTSB reports [46], on June 10th, 1995, the Panamanian passenger ship *Royal Majesty* grounded on Rose and Crown Shoal about 10 miles east of Nantucket Island, Massachusetts, and about 17 miles from where the watch officers thought the vessel was. The vessel, with 1,509 persons on board, was en route from St. George's, Bermuda, to Boston, Massachusetts.

The major cause of the accident was the result of a loss of GPS data input into the NACOS of the ship, resulting in a transition to Dead-Reckoning. The bridge crew's failure to observe this mode change, which had been caused by a disconnected cable, ultimately resulted in the NACOS steering the ship off course due to a lack of current, wind, and sea data.

The following instances of transition were identified within this case study:

1. The navigator set the navigation and command system (NACOS) 25 on the navigation (NAV) mode
2. The transition of the position data from GPS to Dead Reckoning (DR) mode
3. The second officer switched from autopilot to manual when the *Royal Majesty* unexpectedly veered to port

(For a detailed review of the *Royal Majesty* Case Study, refer to Appendix C.)

3.3.2 Aviation Cases

Aeroflot-Nord Flight 821

On September 14th, 2008, Aeroflot-Nord Flight 821, a Boeing 737-500 crashed outside of the Perm Airport in Russia. Prior to the approach to the runway, the system experienced a large number of mode transitions, much of which was exacerbated by a asymmetric thrust split in the engines. On approach to Perm airport, the pilots attempted to execute a missed approach, during which the airliner lost radio contact and impacted the ground. There were no survivors [47, 48].

The accident report suggests that neither of the pilots had the skill or experience required to fly such a craft, which inevitably dominates any discussion of grace in mode transitions [47, 48]. Additionally, the pilot in command (PIC) was reported as being inebriated, greatly reducing his ability to cope with changes in the system. While it should be understood that no high-performance system such as a passenger airliner be required to operate gracefully with an impaired operator, the condition of this operator gives a unique look at the consequences of an "off-nominal" operator case and can provide insight into how to make a system more robust in terms of grace in mode transitions.

The following cases of transition were identified in this accident base on the report by the Russian Interstate Aviation Committee (MAK):

1. Prior to the approach, the autothrottle was disengaged. The transition was preprogrammed.
2. In entering the approach, a switch to "Altitude Hold" (ALT HOLD) was made. Prior to the transition, the aircraft had been operating in "Level Change " (LVL CHANGE) mode. Soon following a switch was made to "Lateral Navigation" (LNAV), with the report describing it as most likely mistaken input by one of the pilots. As such, a transition was made from "Lateral Navigation" to Control Wheel Steering in both roll (CWS ROLL) and pitch (CWS PITCH) immediately after.
3. During the approach a transition was made to full manual control by the disengagement of the autopilot.

(For a detailed analysis of this case study, see Appendix D.)

TNT Airways Limited Cargo Flight 325N

On June 15th, 2006, a cargo flight (Boeing 737-300) run by TNT Airways Limited attempted a CAT III[1]approach at the East Midlands airport. On approach the commander disengaged the aircraft autopilot by mistake. In attempting to reengage the autopilot the pilot failed to accurately judge his proximity to the ground and did not execute the TO/GA (Take-off/Go-around) procedure quickly enough to keep the airplane landing gear from hitting the ground. The autopilot was never successfully re-engaged. In the impact the nose gear was broken off. After regaining altitude, the crew made an emergency landing at Birmingham Airport (BHX) [43, 44].

[1]Category III A is a precision instrument approach and landing with (1) a decision height lower than 100 feet above touchdown zone elevation, or no decision height (alert height) and (2) and a runway visual range not less than 200 meters (656 ft).

The following transitions were identified in the case study:

1. The accidental transition to manual when the pilot attempted to respond to ATC.
2. The attempted transition by the commander to re-engage both autopilots immediately following the first transition case.
3. The last minute re-engagement of the autopilot in approach mode.
4. The final transition into TOGA mode just before ground impact.

(For a detailed review of this case study refer to Appendix E.)

3.3.3 Aerospace Cases

STS-3 Case Study

Throughout the initial missions of the space shuttle, a major portion of operations was devoted to final validation of the shuttle's systems. In particular, the autoland system capabilities and its interaction with the pilot was of particular concern to designers and operational managers. In STS-3, a scheduled transition to CSS mode (manual mode) resulted in a pilot-induced-oscillation (PIO) which, while it didn't cause a mission failure, led to a reevaluation of the ability of pilots to re-engage themselves in the control loop task at such a late stage. This was the only shuttle landing at White Sands, and the moving dust at the time of the land was thought to been related to the PIO [49]

The only transition being studied in this particular case study is that procedural transition which took place between autoland to manual.

(For a detailed look at this case study refer to Appendix F.)

Apollo 11

The first lunar landing was made in a "manual" control mode by Neil Armstrong; however, this was not considered the nominal landing [50]. Two mode transitions were examined in the first moon landing:

1. The manual control checkout which preceded the final transition into manual control (RCAH with Incremental Rate-of-Descent).
2. The transition to manual control, which was maintained until touchdown.

(For detailed look at the first moon landing see Appendix G.)

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Chapter 4

Lessons from the Mode Transition Case Studies

4.1 Design Principles

This chapter presents an analysis of the commonality of various factors in triggering mode transitions, and making them ungraceful. Based on this, a list of design principles is formulated that incorporate lessons learned from the case studies, shown in 4.1. Further discussion of the details behind these principles may be found in the Appendices. These design principles should be considered as guidelines context may require exceptions.

Table 4.1: Design principles indexed by case study

No.	Description	Case
1	Don't transition to a higher level of automation if the reverse operation will be required in the near future: the disparity of LOA has a more detrimental effect on performance when moving from high to low.	B.2, B.4, C.2, C.4
2	Design systems so that transitions ideally occur with low variance in system states.	B.2, B.3, B.4, C.2, C.4, D.3, F.1, G.1
3	A system should either improve the chances of correct action or safeguard against the wrong input. Reduce the number of input options available immediately after a mode transition, especially when high stress and workload are predicted.	B.4, C.4, D.4, F.1
4	Automation should be transparent (not opaque) *to the operator*, especially when switching between modes; however, caution should be taken to not overwhelm the operator with the inner-workings of the automation.	B.2, B.4, C.4, C.4
5	Make mode transitions extremely clear in activation and descriptions, especially when triggered internally or when state errors are slow moving.	C.3 D.7, E.4
6	Design modes to complete high level system goals and not low level state goals to reduce amount of "mode-hopping" (successively switching modes within a short period of time) which takes place. Combine similar modes and reduce the number of modes available.	D.6, D.7
7	Reduce the number of control loops which must be taken over in a transition. This principle must be balance with Principle 6.	D.4, D.6, E.3, F.1, G.2
8	Provide undo functions when safety margins permit, and explicitly inform the user when a transition cannot be undone.	D.5, D.6, D.7, E.2, E.3
9	Use authority to proceed when workload and time-pressures permit.	C.3, D.6, E.2
10	Use mode preview displays and trend displays when possible to augment operator situational awareness before and during a transition.	D.3, E.2, E.4, E.5 F.1, G.2
11	Design modes to reflect the way a human would approach the task, not how a machine might. This is related to Principle 4.	D.4, E.3
12	Reduce any extraneous stimuli generated by the system during mode transitions.	D.5, D.7, E.4, F.1, G.1, G.2

4.2 Triggers in Mode Transitions

A bar chart detailing the occurrence rate of certain factors in triggering mode transitions (both graceful or ungraceful) is shown in Figure 4.1. These occurrence rates show that the system states were the most pervasive of all the factors, with the performance of actions and operator automaticity as the second most frequent.

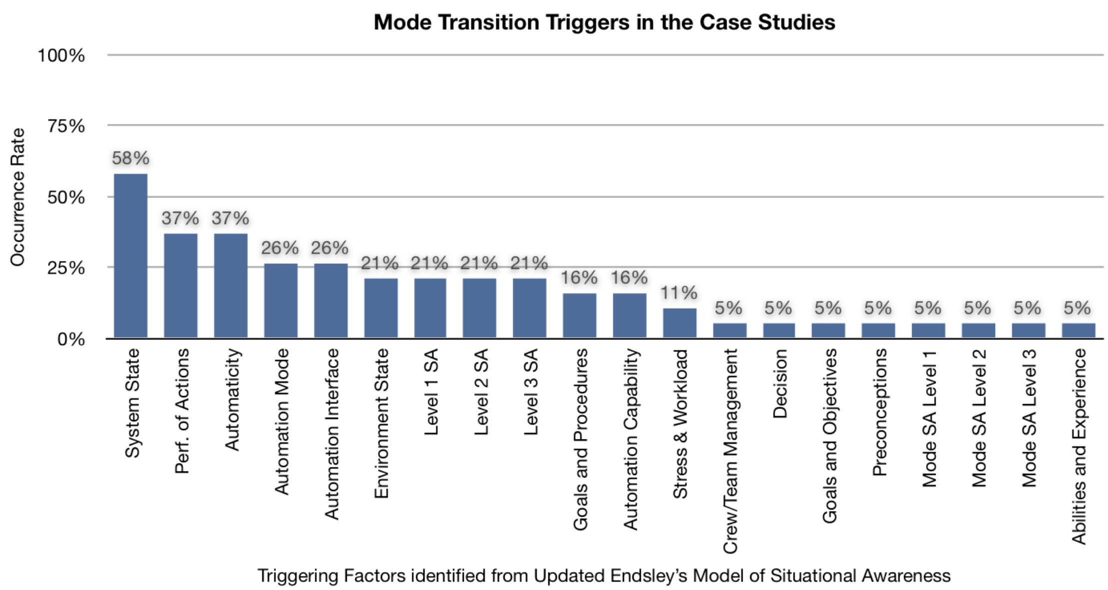

Figure 4.1: Occurrence rates of mode transition triggers from the updated Endsley model of situational awareness as identified in the case studies

4.3 Factors in Ungraceful Transitions

A bar chart detailing the contribution certain factors in causing a mode transitions to be ungraceful, as identified within the case studies, is shown in Figure 4.2. Most notably, high stress and workload were often present in making transitions ungraceful, as were the environmental state and the system states. Operator situational awareness, a related factor, was a frequent contributor as well. Table 4.2 maps these various factors to the Design Principles which address them.

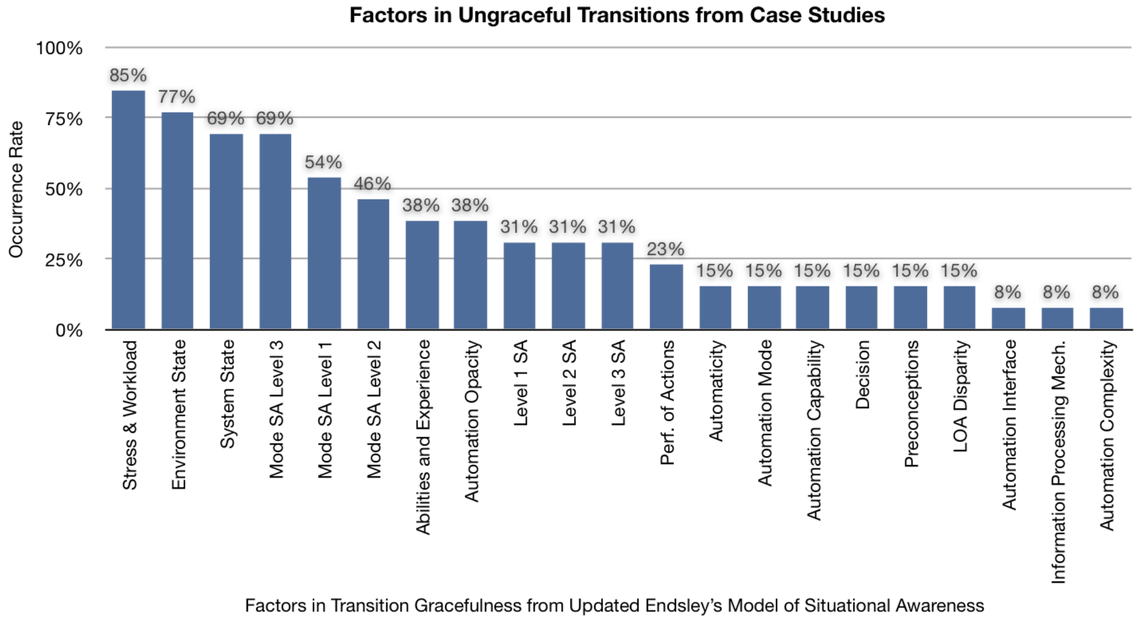

Figure 4.2: Occurrence rates of factors in ungraceful mode transitions from case studies

4.4 Mechanisms in Ungraceful Transitions

A bar chart detailing the occurrence rate of particular mechanisms resulting in ungraceful mode transitions is shown in Figure 4.3. The two most frequent mechanisms seen are attention resources and operator schema, suggesting that mode transitions generate a significant draw on such resources and often lead operators to develop faulty understandings of a situation. Additionally, the operator's inability to interpret, comprehend, and project information (linked to both attentional resources and schema) contributes to ungraceful transitions, based on case study review. Table 4.3 maps these mechanisms to the various Design Principles which address them.

Table 4.2: Factors from the updated Endsley model of situational awareness affected by design principles

Factor	Design Principle											
	1	2	3	4	5	6	7	8	9	10	11	12
System State		x					x			x		x
Environment State		x										x
General SA		x		x	x	x	x	x	x	x	x	x
Mode SA				x	x	x		x	x	x	x	
Interface					x	x		x	x	x	x	x
LOA Disparity	x				x							
Stress & Workload			x		x					x	x	
Opacity				x		x			x	x	x	
Capability						x		x				
Complexity						x					x	
Automaticity			x					x	x			
Info Processing Mechanisms					x					x	x	x
Action Guidance	x						x		x			

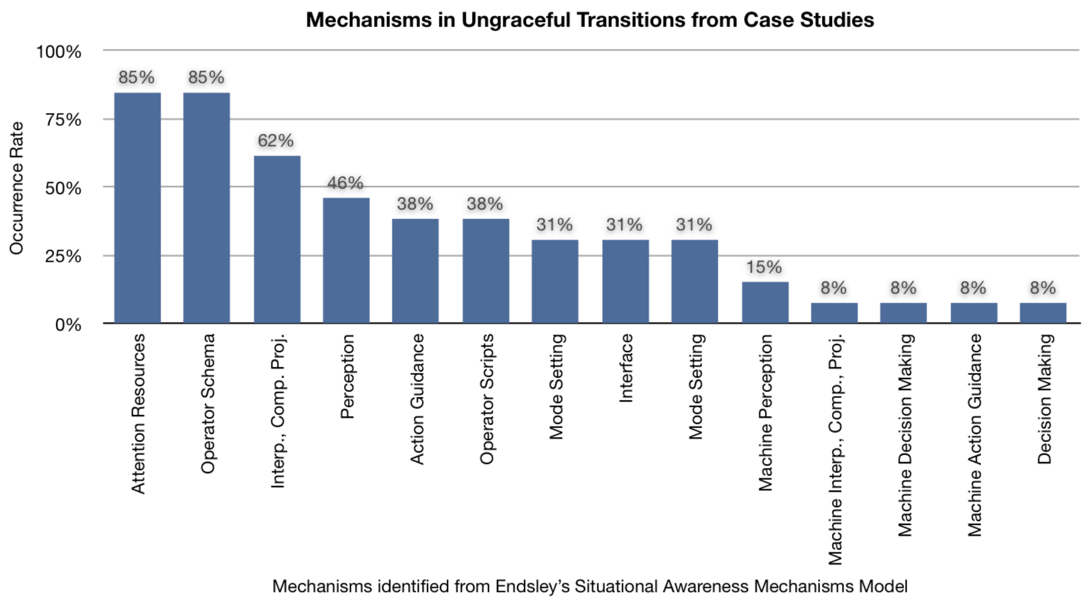

Figure 4.3: Occurrence rates of mechanisms from the updated Endsley mechanisms model of situational awareness as identified in the ungraceful mode transitions from case studies

Table 4.3: Mechanisms from Endsley's model of situational awareness affected by Design Principles

Factor	**Design Principle**											
	1	2	3	4	5	6	7	8	9	10	11	12
Mode Setting	x			x	x	x	x	x	x	x	x	
Action Guidance	x				x			x	x			
Schema			x	x		x	x		x	x	x	
Scripts			x									
Decision Making			x						x	x	x	x
Interface				x	x		x	x	x	x	x	
Perception					x						x	x
Attention Resources						x						x
Interp., Comp., & Proj.		x				x			x	x	x	x

4.5 Discussion

These case studies are only a small sample of ungraceful transitions in multi-modal automation systems. In particular, automation surprise and mode confusion are observed in these case studies quite often. This was recognized and is reflected in the adaptation of Endsley's models of situational awareness. However, the non-occurence of these phenomena should not be taken as identical to a graceful transition: ungraceful transitions as defined in this thesis can arise in cases where neither of these are present. Automation surprise and mode confusion can describe extreme cases of ungraceful transitions, but it are not identical; for example, the *Crown Princess* was a very ungraceful transition, and there was severe automation surprise, but this was caused by the system transitioning ungracefully.

Considering the large number of automation surprises seen in the case studies, it is not surprising that system states and operator automaticity were the most frequently occurring trigger factors (see Figures 3.1 and 4.1). First, the system states were what gave the operator a sense of automation surprise. Second, the automaticity of the operator suggests unconscious mode triggers, making it easier for operators to be surprised by the system states.

The significance of automation surprise as a symptom of ungraceful transitions is also shown by the large role that stress and workload played in the case studies. Environmental states and system states were also frequent factors in the ungraceful transition and were most likely related to the frequency of the workload and stress factor. The effect of workload and stress can clearly be seen in the role that attention resources and operator schema played as well. Attention resources were a viewed as a mechanism in 85% of the ungraceful transitions identified as ungraceful in the case studies, and this was often because of an insufficient supply of resources during the transition (Figure 4.3. Additionally, the operator schema were often incomplete (or wrong) regarding the system state and/or mode setting. While such conditions describe conditions disposed toward automation surprise, they also show that attention resources and operator schema are also important indications of a graceful transition: ample spare attention and a highly resolved operator schema are present in a graceful transition.

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Chapter 5

Historical Background on Lunar Landing Task

> "We choose to go to the moon. We choose to go to the moon in this decade and do the other things, not because they are easy, but because they are hard, because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept, one we are unwilling to postpone, and one which we intend to win, and the others, too."

-John F. Kennedy, 1962, *Rice University*

There is arguably no other phrase uttered by a politician that resonates with any aerospace engineer more than these words spoken by President John F. Kennedy in 1962 at Rice University [51]. These words challenged a generation of engineers to do something no one had ever done before. In going to the moon, humanity reached into the stars, grasping a vast new set of scientific questions and engineering challenges, least among which was the design of a controllable spacecraft.

The following chapters address this design challenge by investigating how operators dynamically interact with a multi-modal automation system purposed for lunar landing. Specifically, they describe an experiment which investigated the effects of control mode difficulty and landing point redesignation on pilot workload, situational awareness, and performance.

5.1 Lunar Landing Then

The initial concept in Apollo was one of direct descent and ascent: straight from the Earth, to the moon, and back [52]. Believing this to be an infeasible strategy, John Houbolt at

Langley Research Center championed the Lunar Orbit Rendezvous (LOR) strategy for landing on the moon, in which a small craft would detach from the main craft and proceed to the surface [53, 54]; however, in proposing such a strategy it became necessary to understand how a lunar lander would be piloted, if at all.

Beginning with the Mercury program, this was a central issue facing NASA engineers, a story which was documented by Tom Wolfe in the book, *The Right Stuff*, and dramatized by Philip Kaufman's movie of the same title. The question still remains one of importance and its influence in the design of Apollo has been one of interest in the development of technology[52]. Computers provided a rigidity to the mission which, while affording more certainty to NASA engineers, acted as handcuffs in an unforeseen situation. Additionally, what the computer should tell the pilot and the pilot's ability to respond became a question concern in a human-computer system.

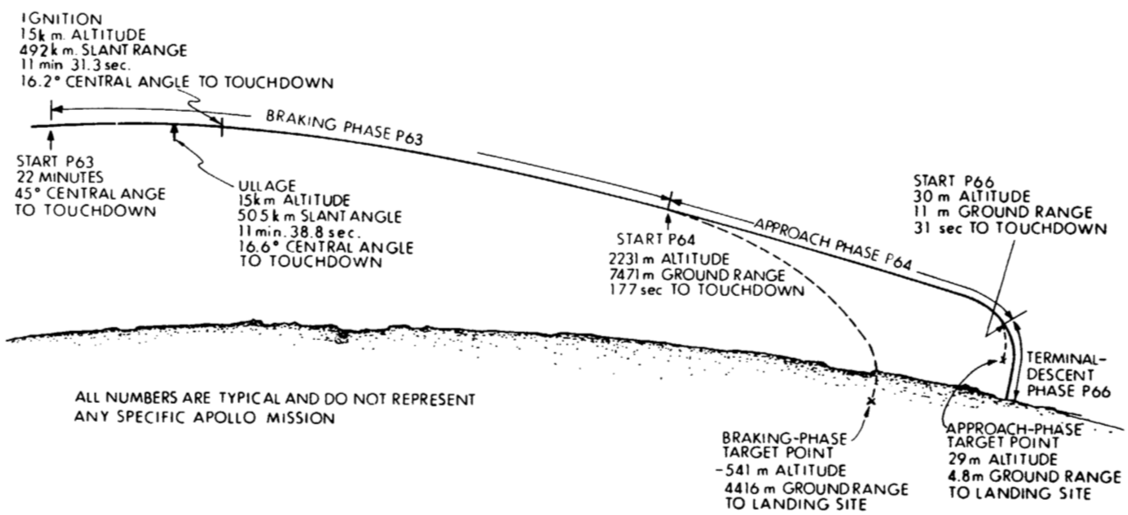


Figure 5.1: Apollo landing phases [55]

As engineers further refined the LOR concept and explored the question of human control, the concept of a phased lunar landing approach was developed. Such an approach, while not strictly fuel optimal, focused on increasing the reliability, redundancy, and flight safety of the landing [56, 57, 58]. It drew from NASA's aviation heritage by splitting a landing into a Braking Phase, Final Approach Phase, and Terminal Descent Phase (shown in Figure 5.1). In a nominal landing the computer flew the spacecraft through each phase, while the astronauts constantly monitored systems and provided authority to proceed to the computer; still, the astronauts would need to completely assume the flying task from the computer in the final stages of the landing. The flying task was extremely difficult, with

Neil Armstrong remarking [59]:

> "I think I was probably over-controlling a little bit...I was surprised that I had as much trouble as I did in determining translational velocities. I don't think I did a very good job of flying the vehicle smoothly in that time period [Landing Phase]. I felt that I was a little bit erratic."

Apollo 11 was by no means an exception: every touchdown on the moon's surface was done in manual control. Given the relatively poor resolution in the mapping of the moon up until that time, small landing hazards, such as rocks and craters could have (and almost did) proved fatal to the lunar module (LM). It was the job of the astronaut pilot, and the engineers had allocated more than a minute's worth of fuel, to deal with these contingencies as they arose by re-designating to a new landing site and, finally, to assume control of the vehicle and guide it to the surface [52].

Due to the complex nature of spacecraft thruster control systems, both available manual modes, P66 and P67, used computer-mediated inputs from the human to control the spacecraft. P66, the manual mode in which every single lunar landing occurred, provided Rate Control Attitude Hold (RCAH), in which inceptor deflections commanded the attitude rate of the spacecraft, which was otherwise held constant by the computer when there were no inceptor inputs. At the same time, the pilot was afforded incremental Rate of Descent (ROD) control, which gave him a degree of control over the vertical speed of the LM (ROD was controlled by increments of 1 feet per second using a toggle switch). P67, also known as Manual Guidance mode [60], was only meant as a backup to P66, affording the pilot with RCAH attitude control along with full continuous control over the main thruster. P67 was never used in flight, since it was found to be difficult to control [61].

These control modes were thoroughly investigated using the LLRV (Lunar Landing Research Vehicle) built by NASA [62, 63]. Minimal, if any, consideration was given to pilot performance in transitions between the fully automatic P65 program and any subsequent manual control mode that the astronaut might switch to. Fortunately, this didn't prove to be fatal to any of the missions due to the extreme amounts of training afforded to the pilots with the LLRV and LLTVs [59, 64, 65, 66, 67, 68]; however, the effect of the transition was hinted at in the first two missions [59, 64] when they described their "over-controlling" of the system. In future lunar landing, the effect of such transitions needs to be understood in order to ensure success.

5.2 A Phased Approach

Apollo separated lunar landing into three phases: Braking, Approach, and Terminal Descent, shown in Figure 5.1. Each phase was controlled by a different program within the

Lunar Guidance Computer (LGC) and helped fulfill the requirements of the mission architecture [56]. The crew, consisting of the commander (CDR) and the Lunar Module Pilot (LMP), was highly involved throughout the landing: the commander monitored and controlled the descent using visual cues, various hand controllers, and switches, while the LM pilot monitored the computer display, verbally relayed pertinent data (altitude, altitude rate, fuel, etc.) to the commander, and entered data into the computer [55]. Other additional tasks handled by the astronauts included data callouts to ground control (data requests lessened during the Terminal Descent Phase) as well as the operation of secondary systems (e.g. the communications antenna) which placed an extremely high workload burden on the pilots (see transcripts of Apollo 11 landing [50]).

5.2.1 The Braking Phase

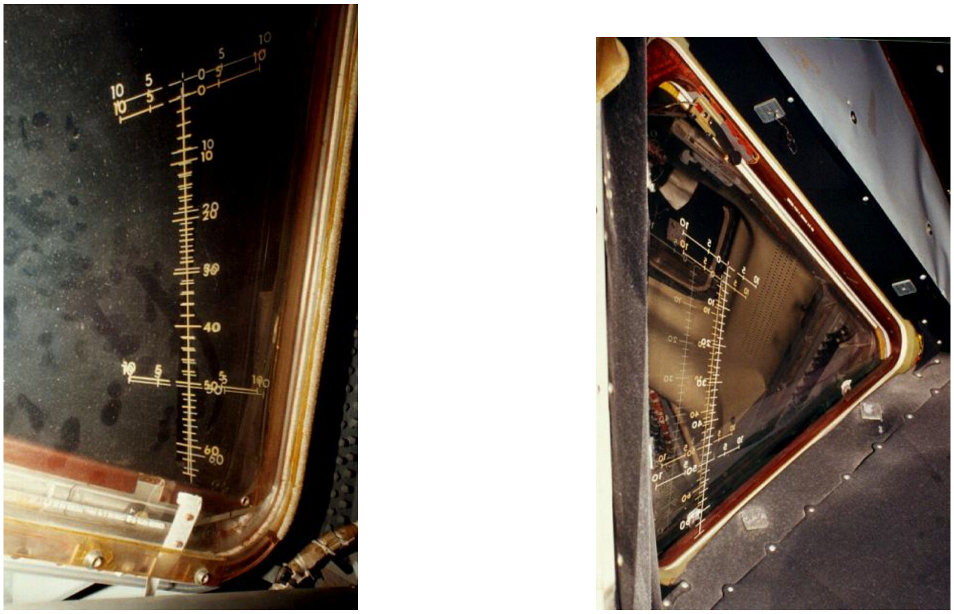
The Braking Phase followed Descent Orbit Insertion (DOI) and was initialized on command of the astronauts by the selection of P63 (Program 63 in the LGC) and occurred at an altitude approximately 50,000 ft above the moon's surface and 260 nm up range of the landing site. The DPS (Descent Propulsion System) engine operated at full throttle for nearly the entire duration of the braking phase as it was primarily designed for efficient propellant usage while reducing velocity for the approach phase [56, 58]. Orientation about the thrust-axis (yaw) was at the discretion of the pilots and during Apollo 11 the craft was oriented windows down for landmark tracking; however, in later landings this orientation was not kept in order to conserve fuel. Once the guidance-calculated TGO (Time-to-go) clock reached 60 seconds the computer automatically switched to P64 to begin the approach phase [56, 58]. Throughout this phase astronauts monitored the progress of the GN&C system. Transition to the Approach Phase was confirmed by the astronauts when the computer automatically switched to P64 [69].

5.2.2 The Approach Phase

The Approach Phase began when the "High Gate" guidance condition was reached (velocity at $\sim$730 fps, flight path angle at -14° [57]). This phase provided visual confirmation of the landing site by the astronauts and highlights the architectural choices concerning the human [56, 58]: continual visibility of the lunar surface was available during this phase until approximately 5 seconds before entering terminal descent [55]. Additionally, the human was allowed the opportunity to incrementally change the landing target using the landing point redesignation system, which consisted of a set of etchings on the window that projected a landing site using numbers passed by the guidance computer. Throughout this phase the LMP would read two-digit landing point designator values from the computer to the CDR who, using a set of window etchings (see Figure 5.2), would redesignate if necessary.

5.2.3 Terminal Descent

Terminal descent refers to the phase following the arrival at the "Low Gate" guidance condition (approx. 100 feet altitude, 36 feet ground range from the landing site [55])



(a) Inside (b) Outside

Figure 5.2: LPD Window Etchings

spanning all the way until touchdown (see Table 5.1). As the phase progressed, the view of the landing site became obscured by the structure of the LM as well as blow-back dust kicked up from the thrust of the main engine; hence, guidance was only based on nulling velocities and not position control [55]. The phase still allowed the human to assert himself over the craft when he deemed necessary; however, the system was programmed to land automatically in P65 [56, 58].

5.3 Controlling Apollo

The main manual control implementation in Apollo was Rate-Control/Attitude Hold with and incremental Rate-of-Descent (ROD), in which a deflection of the Rotational Hand Controller (RHC) would correspond to the rate-of-change in spacecraft attitude, while the rate-of-descent changed with each control click (1 fps). Other control modes based on the different orders of attitude control, both acceleration and position, were conceived of as well [60]. *Attitude Acceleration* commanded angular accelerations based on the deflection of the RHC. *Attitude Command* controlled angular attitude proportionally to the RHC

[1] Time from ignition of the DPS
[2] Horizontal velocity relative to surface

Table 5.1: Apollo 11 Premission Powered Descent Event Summary [56]

	Event	TFI[1] *min:sec*	Inertial Vel. *fps*	Altitude Rate *fps*	Altitude *ft*	Δ V *fps*
A	Ullage	-00:07	-	-	-	-
B	Powered Descent Initiation	00:00	5,560	-4	48,814	0
C	Throttle to maximum thrust	00:26	5,529	-3	48,725	31
D	Rotate to windows up position	02:56	4,000	-50	44,934	1,572
E	LR altitude update	04:18	3,065	-89	39,201	2,536
F	Throttle recovery	06:24	1,458	-106	24,639	4,239
G	LR velocity update	06:42	1,315	-127	22,644	4,399
H	High Gate	08:26	506	-145	7,515	5,375
I	Low Gate	10:06	55 ([2]68)	-16	512	6,175
J	Touchdown (probe contact)	11:54	-15 (0)	-3	12	6,775

position (i.e. a vertical RHC corresponded to a vertical spacecraft). These control modes were extensively tested in fixed-based simulators as well as free-flying mockups [61, 62, 63], focusing particularly on handling qualities (defined as the flight characteristics of a vehicle that describe the ease and precision with which a pilot is able to perform a task [70]) as a function of the control authority and power. The result of this testing was a lunar module in which the maximum angular rate command in a RCAH mode was 20 degrees per second [71, 72, 73], a value deemed as mandatory by astronauts [60, 71]. More recent studies have found that as control authority increases handling quality ratings improve [74], as do increases control power and reduction in the maximum-rate command. Such results depend highly on the dynamics of the vehicle being tested.

5.4 Lunar Landing Now

Fifty years later, the physics of lunar landing remain unchanged; however, mission goals have seen dramatic changes. In responding to President Bush's Vision for Space Exploration [75], NASA embarked on the Constellation Program (CxP), which was to carry humans toward to the moon, Mars, and beyond, with a number of technological and goal-based changes from the Apollo Program [76]. The Apollo Program sought to "land a man on the moon and return him to safely to the Earth", largely for the sake of national pride [51, 77]. The Constellation Program has shifted this focus to the concerns of lunar scientists and that of technology development for future Martian missions [78]. In order to gain further extraterrestrial ground experience relatively close to home, NASA is looking towards establishing an extended lunar presence [79]. Additionally, advances in flight deck technology will introduce considerable differences in the cockpit of any Constellation vehicle compared to that seen in Apollo [76].

The current Design Reference Missions (DRMs) for Constellation require global lunar access (NASA CxP 70007 5.8.1 [80]). The lunar poles are of particular interest since the recent Lunar CRater Observation Sensing Satellite (LCROSS) mission provided the first tangible evidence of water in some permanently shaded craters on the moon [81]. This desire for global access carries a host of new requirements and engineering challenges related to astronaut performance when evaluating landing sites and flying manually: a lack of atmosphere removes diffusive distance cues, the Non-Lamebertian regolith differs from terrestrial soil greatly in shadow generation and reflectivity, the lack of familiar objects removes comparative perceptual cues, and vestibular illusions result from the reduced lunar gravity [65, 82, 83]. Additionally, strict regulation of landing site topography and sun angle as done in Apollo will not be possible in locations such as the lunar poles [84]. In order to mitigate some of these effects, future landings will use specialized automation systems, such as the Autonomous Landing Hazard Avoidance Technology (ALHAT) System which will combat the problem of unknown terrain and landing hazards [85, 86]; however, flyijng without window visual cues immediately raises concerns: Apollo astronauts preferred to use out-the-window visual cues while in manual control [65, 66, 67, 68].

In addition to the global lunar access requirement, Constellation's new lunar lander is to also have both autonomous and human-in-the-loop flight capability for either crewed or cargo missions (NASA CxP 70007 [80]). This particular requirement will directly impact the design of any future lunar module and will create a significant human factors design challenge similar to, though distinct from, that which was faced during Apollo, where a highly complex three-phase landing was combined with a multi-modal Guidance, Navigation, and Control (GN&C) automation system to allow for several modes of human interaction (see Section 5.1). While it is likely that the nominal landing will be mostly automatic, the system must be capable of a manual takeover, in which the crew can gain immediate access to necessary data and controls (NASA CxP 70007 4.2.15 [80] and NASA CxP 70024 3.6.5 [87]). Additionally, the NASA Human Rating Requirements (HRRs) currently mandate that the crew have the capability to monitor, operate, and control the crewed space system and subsystems (NASA NPR 8705.2B 3.3.1) and be able to manually override higher level software control/automation (NASA NPR 8705.2B 3.3.2) [88]. Essentially, the role of the human in the sense of failure mitigation and handling has remained similar to that seen in Apollo:

> "Operations personnel should have the ability to intervene and override any onboard decision regardless of sensor indications. A central objective of the sensor systems is to facilitate the situational awareness of both the crew and of remote operators (be they on the Earth or another vehicle). The design should allow the operator to make a rapid assessment of the current situation, including the exposure and investigation of off-nominal states. The design of the crewed vehicles should allow for the crew to provide functional redundancy to the automated and Earth-in-the-loop systems where practical."
>
> (NASA CxP 70000 3.1.3.6.2 [89])

Hence, the new requirements have necessitated the increase in automation capability with systems such as ALHAT and were supported by the development of digital control systems and integrated computer displays (e.g. a glass cockpit) [76, 83, 90]. The small variety of modes used in Apollo was only a subset of a variety of possible control modes which were tested or could have been implemented (an Attitude Control Velocity Hold mode was included during testing [63]) and already new control modes are being considered, each of which offers a specialized mode with which the operator can achieve his or her goals [60, 91]. However, the history of automation development has shown that as the capability of automation is expanded, more modes of operation are introduced, creating complex multi-modal automation architectures that can easily confuse even the most experienced human operator [11]. A good example of this can been seen in the past development of aircraft, which saw a dramatic increase in the number of displays in the cockpits before the problem was addressed with integrated display systems (see Figure 5.3) [92].

This historical tendency of creating progressively opaque and incomprehensible systems was researched in a three year study of pilots in advanced technology transport aircraft, which found that pilot situational awareness with respect to the current operation mode of the aircraft, as well as all possible modes, was often deficient [1]. Aside from just understanding a single mode of operation, multi-modal architectures require understanding the interactions between modes when transitioning from one to another, a condition evident in Apollo which will most likely be a concern of Constellation. Further, in cases of extreme operational environments and high risk missions, this becomes an issue of great importance, as an unexpected mode interaction could lead to catastrophic failure. Somewhat ironically, these mode transitions are, by their nature, coupled with extreme operating environments and/or situations, as such circumstances often act as the triggers for mode transitions [93]. With such mission requirements and system concerns, understanding the transition to and between manual control modes will be of critical importance in any future lunar mission.

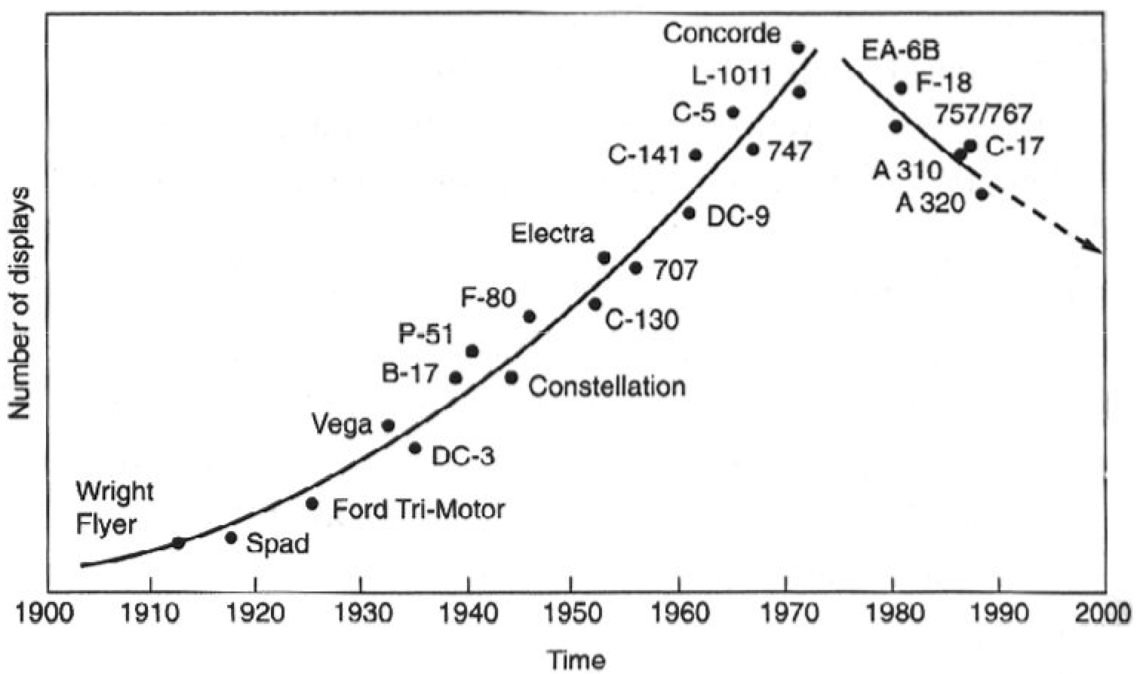


Figure 5.3: Trends in display development in aviation [92]

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Chapter 6

Experimental Background

6.1 Manual Control

The *crossover model* is the standard for human performance modeling in manual control applications: the human is modeled as a quasilinear controller that, when combined with the plant, tends towards a 1^{st} order integrator system – phase lags increase with the order of the plant (e.g. 0^{th} human-plant system had less phase lag than 2^{nd} order) [94]. As a corollary to the model, the human is nearly incapable of controlling high-order (greater than 2^{nd} order) without previewing of future states. Instead, the crossover model predicts the occurrence of Pilot Induced Oscillations (PIOs) and instabilities. Such events would occur when a pilot's input occurs with a 180° phase lag compared with system output, creating an potentially unrecoverable resonance in the system. Such phenomena are well known and have been observed and documented, occurring even in advanced systems such as the Space Shuttle Orbiter[95].

The model has been applied to both single- and two-axis control tasks, which have shown no difference in error tracking, but significant differences in lead time constants in two-axis tracking [96]; unfortunately, the adaptive nature of human control still escapes this model, which must include (1) input adaptation [97, 98], (2) controlled element adaptation [99] (3) task adaptation, and (4) programmed adaptation [100]. An investigation into human performance dealing with instantaneous "complex transitions" (transitions between different system orders of system dynamics) revealed that 3 phases can be identified as the *pretransition retention phase* in which the operator initially acts as if nothing happened, the *optimal control phase* in which a time-optimal control strategy is adopted (e.g. a bang-bang approach) until error is reduced to within a tolerable level, and the *adjustment to steady-state tracking phase* in which errors are further reduced and a new steady state operating point is achieved [101].

6.1.1 Jumping "In the Loop"

Recently, research attention has been directed to problems where the operator of a highly automated system has to suddenly "jump in the loop" and assume control [100, 102]. This phenomenon of degraded operator performance in the transient phase between two modes of control has been evident in numerous applications, not just within aeronautics [43, 44, 45, 46, 47, 48, 49, 103, 104]. This loss of operator performance has principally been linked to poor situational awareness, a symptom of difficulties in vigilance and complacency which reduce an operator's performance in error detection and mitigation within various applications of automation [23, 93, 105, 106]. This phenomenon was observed in some of the case studies (see Chapter 4).

6.2 Modes, Multi-modal Systems, and Adaptive Automation

The promises of improved performance and efficiencies in modern automation systems have had mixed results: operators must learn to interact with many of automation modes [93]. This has given rise to such problems as automation surprise [11], operator complacency [106], and skill degradation [93]. Additionally, multi-modal systems inherently demand the operator to be dynamically operating in and between modes, as is currently required in modern commercial aircraft [1] and multi-process control applications [107]. Some work has been directed at using display design in mitigating this issue [108, 109].

In the study of human-computer task allocation, a general distinction is made between *Supervisory Control* (human principally monitors and performs high level control functions) and *Manual Control*, with finer distinctions being described with *Levels of Automation* [14, 110]. These concepts have since been expanded and investigated [12], with one study showing that a mode transition between LOA (see Table 6.1) in an expert system had a significant effect on both transient performance as well as time-to-recovery: batch processing (level 3) and automated decision making (level 8) showed reduced performance during cases with mode switches in comparison to a cases without. Additionally, it was determined that batch processing (level 3) and automated decision making (level 8) had a significantly greater recovery time than manual control (level 1) and action support (level 2) [15, 111].

With improved computer capabilities and the widespread introduction of fly-by-wire systems [112], the scope of what is considered as Manual Control has expanded. It no longer is restricted to strictly mechanical systems, but encompasses dynamically augmented systems as well [49]. Augmented vehicle manual control modes such as Rate-Control-Attitude-Hold (RCAH) [71] are examples of modes which normally make the vehicle much easier for the human pilot to fly. Augmented vehicles can still have multiple control modes, ranging from relatively simple manual to a high level of supervisory control [113]); still, the problem of

Table 6.1: Endsley's Levels of Automation [15]

Level	Title	Description
1	Manual Control (MC)	The human performs all tasks including monitoring the state of the system, generating performance options, selecting the option to perform (decision making) and physically implementing it.
2	Action Support (AS)	At this level, the system assists the operator with performance of selected action, although some human control actions are required.
3	Batch Processing (BP)	Although the human generates and selects the options to be performed, they then are turned over to the system to be carried out automatically.
4	Shared Control (SHC)	Both the human and the computer generated possible decision options. The human still retains full control over the selection of which option to implement; however, carrying out the actions is shared between the human and the system.
5	Decision Support (DS)	The computer generates a list of decision options that the human can select from or the operator may generate his or her own options. Once the human has selected an option, it is turned over to the computer to implement.
6	Blended Decision Making (BDM)	At this level, the computer generates a list of decision options that it selects from and carries out if the human consents. The human may approve of the computer's selected option or select one form among those generated by the computer or the operator. The computer will then carry out the selected action.
7	Rigid System (RS)	This level is representative of a system that presents only a limited set of actions to the operator. The operator's role is to select from among this set. He or she may not generate any other options.
8	Automated Decision Making (ADM)	At this level, the system selects the best option to implement and carry out that action, based upon a list of alternatives it generates (augmented by alternatives suggested by the human operator).
9	Supervisory Control (SC)	At this level the system generates options, selects the option to implement, and carries out that action. The human mainly monitors the system and intervenes if necessary. Intervention places the human in the role of making a different option selection, thus effectively shifting to decision support LOA.
10	Full Automation (FA)	At this level, the system carries out all actions.

mode navigation exists as more modes are introduced, a problem that some have suggested might be mitigated through *adaptive automation* [109]. Recently, Sheridan [113] considered the distinctions between "adaptive automation", "adaptive control", and "supervisory control". Adaptive automation describes systems where the allocation of the primary control task to either human or computer changes with time to accommodate changes in environment or operational requirements. "Adaptive control" describes systems where the automation control laws change independent of the human role to accommodate changes in plant dynamics. "Supervisory control" describes cases where the human delegates lower control levels to automation. Issues in adaptive automation and time varying levels of supervisory control have been considered (e.g. [114, 115, 116, 117]), but many questions are unresolved so this area remains an important one for research.

6.3 Measurement of Gracefulness in Transitions

The following characteristics were distinguished when defining a graceful transition: the operator's maintenance of situational awareness, maintenance of control in system performance, and the reasonable workload levels; all maintenance must be accomplished in such a way that workload does not excessively increase or decrease. When considering situational awareness or workload, one can distinguish between subjective measurements (operator perceptions) and objective measurements (physical quantities that can be measured as surrogates). Such distinctions are not unheard of: measurement strategies of situational awareness focus on both a subjective (SART) and objective (SAGAT), as does workload measurement (side-task measurement vs. SWAT or NASA-TLX methods [118, 119]).

6.3.1 Situational Awareness

Situational awareness quantifies a human's understanding of his or her current situation objectively (or subjectively) described and is generally classified in three levels [22]:

1. Perception - awareness of the presence of a piece of information
2. Comprehension - understanding of information (by itself and in context of other information)
3. Projection - extension of information into the future by projecting future system states

While there have been varying opinions on situational awareness, both in its relevancy and definition [120, 2], the most widely accepted definition is "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the project of their status in the near future" [22]. A further distinction may be made to system awareness which includes such elements as system status, functioning and settings, fuel, time distance available on fuel, flight modes and automation entries and settings, and impact of malfunctions /system degrades and settings on system performance and flight safety [23].

In measuring situational awareness, two measurement techniques, SAGAT (Situational Awareness Global Assessment Technique) and SART (Situational Awareness Rating Technique), are generally used, each providing a particular sensitivity and diagnosticity to the measurement of situational awareness [121, 24, 122]. The is based on a comprehensive assessment of operator situational awareness requirements [123] and offers an objective measurement of situational awareness; however, its implementation is restricted to freezing during a trial for measurement purposes. The latter is based on the subject's own opinion of how aware of the situation they were [124] and was developed in the infancy of situational awareness concerns within aviation [22, 125]. This is a subjective measure and must accept the confounding influence of the subject's comprehension of the relevant information space of the problem. As such, traditional measurement of situational awareness provides the experimentalist a difficult trade-off, as detailed in Table 6.2

Table 6.2: SAGAT and SART: Pros and Cons

SAGAT	**SART**
Pros - Objective measurement and devoid of subjective confounding	Pros - Easy to implement and can be tailored to fit application (3-axis or 10-axis implementation)
Cons - Difficult to implement. Highly intrusive and requiring experimental freezes	Cons - Subjective confounding of measurement and difficulty in anchoring measurements

6.3.2 Workload

Workload describes the amount of work that a person is required to perfrom over a given period of time [126]. It can refer to two different quantities, both physical and cognitive, and the human is limited in the amount of workload that they can handle in either case. The limitations of cognitive workload are less obvious than those of physical workload and are quite relevant to human-computer design. It is important to understand how much information a human can handle.

The use of a secondary task, otherwise known as the Additive Factors Method, is a method of objective workload measurement that infers the remaining supply of operator attention resources based on response times to a purposefully conflicting secondary task [127, 128]. It has been used in the calculation of mental workload and has enjoyed much success [129, 130], though criticisms have been made of the specificity with which the the measurement can be used [18]; however, this becomes less of a concern when measuring gross workload.

Subjective measures of workload include SWAT (Subjective Workload Assessment Technique and NASA-TLX (Task Load Index) [118, 119]. The Modified Bedford Scale subjectively measures workload via the operator's judgement of their spare attention resources [131]. In order to improve the anchoring and sensitivity of the original Bedford scale, a Modified Bedford Scale was introduced which used a different adjective scaling. Being developed alongside scales such as the Cooper-Harper handling quality scale, such heritage is quite evident in the structure of the Modified Bedford Scale [132, 133], which is shown in Figure 6.1.

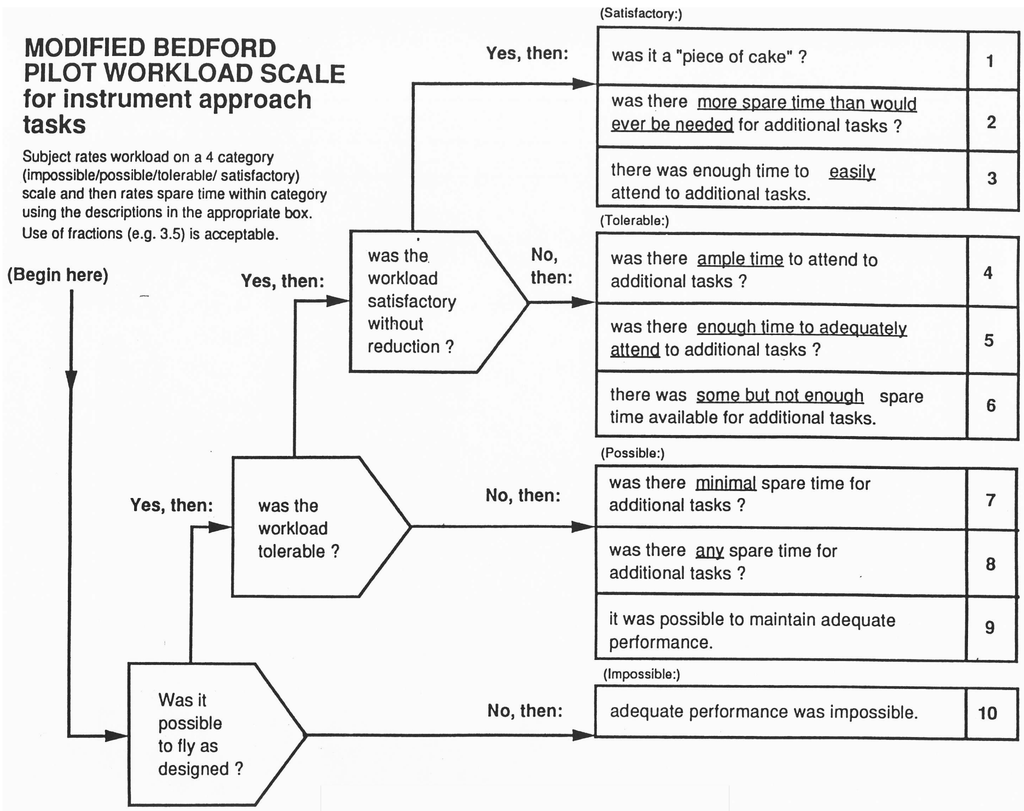


Figure 6.1: The Modified Bedford Scale

6.3.3 Performance

The objective measurement of control and performance, a quantity paramount to the success of any mission, will be contingent upon the context of the system. An aviation example might measure such performance using the Mean Square of the Error, referring to the pilot's deviation from the guidance targets. Other areas of application would necessarily measure different quantities, such as course tracking in maritime navigation or the accuracy of reactor core temperature in nuclear process management.

Chapter 7

Methods

In order to test several hypotheses related to the effects of Control Mode level of automation and the effect of large state errors on the grace of a transition we had 13 subjects fly the final stages of 48 simulated lunar landings (24 training runs, 24 experimental runs) in The Charles Stark Draper Laboratory, Inc. (Draper) Fixed-Base Simulator (Figure 7.1). All subjects gave informed consent in accordance with the MIT Committee on the Use of Humans as Experimental Subjects (see Appendix M). Runs were terminated before touchdown. During each run, subjects were instructed to give first priority to nulling guidance errors shown on the flight director and rate-of-descent indicator, second priority to responding to the "comm light", and third priority to providing verbal callouts of altitude, fuel and hazards. In 24 of the runs (12 training runs, 12 experimental runs) subjects were forced to null large state errors in the flight director which were introduced by a computer-determined landing point Redesignation.

Every run began in a fully automatic Control Mode and transitioned mid-run to one of three different manual Control Modes, in which the subject had to actively null the flight director errors. Each Control Mode operated at a different level of automation (depending on the number of control loops closed by the operator). The gracefulness of transition to the new Control Mode was measured by how well the subject maintained control and awareness of the situation without excessive workload or sacrificing system performance. Maintenance of control was measured by the counting the number of wrong control inputs; awareness was measured using a system of verbal callouts; workload was measured with response times to a secondary task and with the Modified Bedford rating scale; performance was measured by the flight technical error (mean square error) in the pitch axis (see Section 7.3 for full details). Subjects were also asked to rank order the gracefulness of transition for each combination of Control Mode and Redesignation condition – six in all. We expected that transition to a level of automation requiring a greater number of manual control loop closures would be increasingly less graceful, since it would impose a higher attentional workload, and potentially impair performance and some aspects of situational awareness not directly related to the loop closures. We also expected that runs without a Redesignation (low state errors) would be more graceful than runs with a Redesignation (large state errors).

Figure 7.1: The Draper Fixed-Base Lunar Simulator

7.1 Experimental Apparatus

The Draper Fixed-Base Lunar Simulator used two displays, a Primary Flight Display (PFD) and a Horizontal Situation Display (HSD). These displays were adapted from a similar NSBRI Project SA01604. The PFD was presented to the operator on a 16" Dell LCD monitor directly in front of the operator and contained information on vehicle attitude, heading, velocity, altitude, descent rate, fuel remaining, time-to-go, and Control Mode (see Figure 7.2). Flight director and guidance cues were provided for the roll and pitch axes, the descent rate, and the desired heading using magenta indicators. In primary flight task, subjects were instructed to keep the attitude indicator pip centered on the flight director needles within ±1 degree (less than the width of the attitude indicator pip) and to keep the descent rate within ±0.5 feet per second of the guidance (tick parks on the Vertical Speed Indicator are 1 foot per second). Subjects were instructed to disregard the heading flight director cue. Subjects also performed a tertiary task, making verbal callouts of the altitude and fuel levels using the altimeter and the fuel gauge on the PFD. They referred to the mode annunciator when a mode change occurred to determine the new mode of operation (see Section 7.1.1).

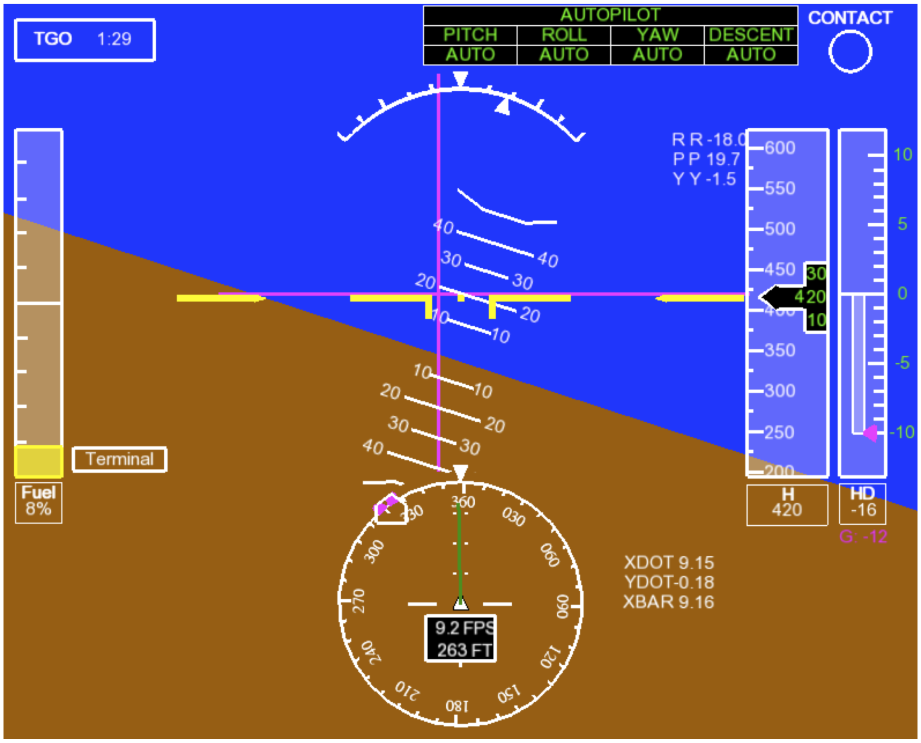


Figure 7.2: Primary Flight Display

The HSD (shown in Figure 7.3) was presented on a second 16" Dell LCD monitor to the immediate right of the PFD and showed a 2-D plan view (heading-up) of a map with marked hazards (red shading) and three predetermined landing points, overlaid on the lunar surface (see Section 7.1.3). The spacecraft ownship was fixed on the center and the map translated and rotated according to vehicle motion. Subjects were required to make verbal callouts using this display when they fully crossed over or exited a hazardous region as indicated by red shaded areas on the HSD terrain. Response time to the appearance of the comm light provided a secondary task performance objective measure of operator workload (see Section 7.3.1). While the comm light was meant to measure secondary task performance, it also functioned as surrogate for other system tasks an astronaut would be required to attend to. A full description of the PFD and HSD as was given to subjects during their training can be found in Appendix H.

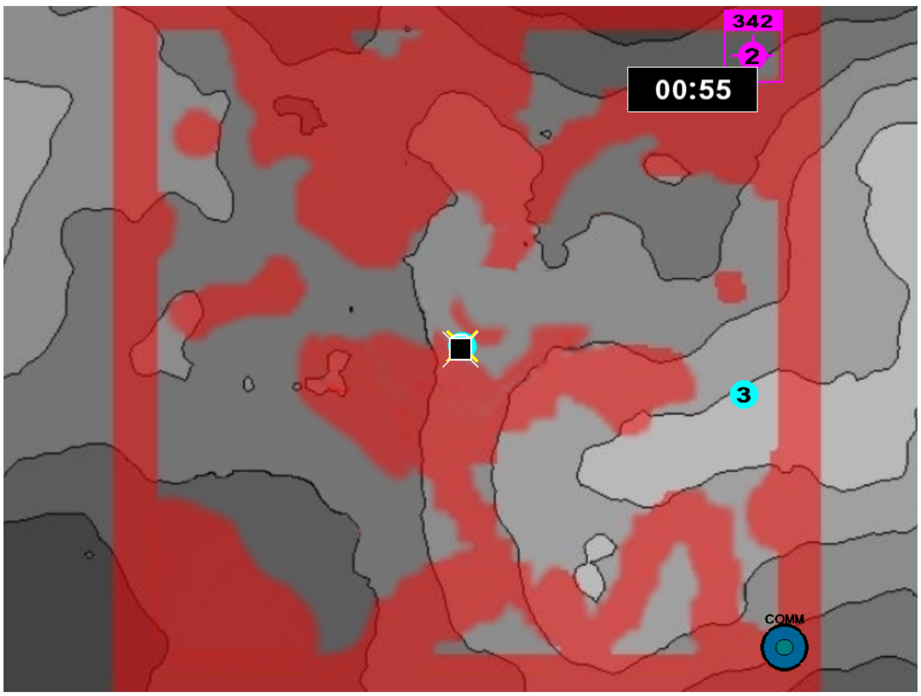


Figure 7.3: Horizontal Situation Display

Spacecraft states (roll-pitch-yaw angles, horizontal velocities, horizontal position, descent rate, altitude), guidance-desired values (roll, pitch, yaw, descent rate), and operator inputs (inceptor roll-pitch-yaw values, comm light button responses) were recorded at 10 Hz. Each data point was time-stamped with the simulation clock in seconds. The number of correct verbal callouts (see Section 7.3.2) were recorded by hand from a position sitting to the left of the subject, where both the PFD and HSD could be seen. Data was processed in Matlab and included the computation of flight technical error (mean square error in pitch, actual vs. guidance-desired), comm light response times, and the counting of the number of wrong inceptor inputs per run.

7.1.1 Dynamics and Control Modes

We used four Control Modes in the experiment: Full Automatic (FA), Single-axis RCAH (Pitch) with automatic rate-of-decent (SA), Triple-axis RCAH (Roll-Pitch-Yaw) with automatic rate-of-descent (TA), and Triple-axis RCAH (Roll-Pitch-Yaw) with Incremental Rate-of-Descent (TA-ROD). In FA modes, the guidance equations provided by Bilimoria [74] and described here closed all feedback loops (roll/pitch/yaw and rate-of-descent); guidance commands were shown via the flight director needles. All runs began in FA and then transitioned to either SA, TA, or TA-ROD. SA placed the subject in command of the rate of pitch while the computer maintained control over roll, yaw (maintained northern heading), and descent rate. TA placed the subject in complete command of attitude rate in roll, pitch, and yaw, and the computer in control of descent rate. TA-ROD placed the subject in complete command of attitude rate in roll, pitch, and yaw, with the addition of incremental control over rate of descent. TA-ROD is the analog of the P66 control used in the Apollo LM. We defined the levels of automation of the lander control modes, from highest to lowest, as FA, SA, TA, and then TA-ROD, based on the number of control loops the operator had to close manually (0, 1, 2, and 3 respectively.)

A conventional autopilot mode annunciator (Figure 7.4) was provided at the top of the PFD, and indicated the current operating mode. When operating in FA, all boxes below PITCH, ROLL, YAW, and DESCENT would read AUTO. When operation in one of the manual Control Modes, the appropriate boxes would change to reflect the new Control Mode (e.g. TA-ROD would read RCAH beneath PITCH, ROLL, YAW, and would read INC beneath DESENT). A auditory beep accompanied any Control Mode transition.

Figure 7.4: The mode annunciator (Mode FA)

The vehicle dynamics and control model was derived from the Altair LDAC-1 Delta vehicle parameters [60], and guidance laws were implemented to follow a reference trajectory [74]. In the RCAH control mode, the pilot commands an attitude rate which tilts the thrust vector and accelerates the vehicle laterally in the direction of the tilt (approximately first order control to attitude, and therefore third order control to position over the lunar surface). The commanded attitude rate was linearly proportional to the inceptor displacement with a maximum of 30 deg/sec in pitch and roll and 20 deg/sec in yaw at full inceptor deflection. When the pilot zeroed any inceptor deflection, the attitude rate was nulled and the tilt angle of the vehicle was automatically held constant. The control system was modeled to have a small (2 millisecond) time delay; the large moment of inertia of the vehicle and the sizing and placement of the LDAC-1 Delta vehicle reaction control system thrusters limited the maximum achievable attitude acceleration (control power) to 3.0 deg/sec^2 in pitch and roll and 2.0 deg/sec^2 in yaw [60]. This effectively resulted in the characterization of the innermost control loop as a first order system between inceptor input and commanded attitude rate, but with a variable lag which is short for small inputs, but can be as much as approximately five seconds for maximum pitch/roll rate commands. As a result, when large attitude rates were commanded, this variable lag increased the order of the control system to approximately fourth order (pilot commands attitude acceleration; fourth order to position). In addition, the modeled flight control system did not instantaneously achieve the maximum achievable control power; there was a first-order lag with a time constant of τ =160 milliseconds to reach the maximum attitude acceleration in each of the control axes.

The descent engine was assumed to be a fixed-gimbal and had a maximum thrust of 10,000 lbs, with a specific impulse of 300 seconds. Fuel consumption was modeled based on the thrust output and the specific impulse of the engine. The engine could be throttled between 10% and 60% of maximum thrust, below 10% there was no output and above 60% engine output was 100% thrust. Total fuel mass budgeted for the experimental profile was 50 slugs. The descent rate was regulated within +/- 1 ft/sec using a proportional feedback controller with a time constant of τ = 125 milliseconds. To maintain the descent rate when the vehicle was tilted from the vertical, the thrust was increased proportionally to the cosine of the tilt angle; larger tilt angles resulted in larger lateral accelerations. The dry vehicle mass was 493 slugs. Fuel slosh or a changing center of mass with fuel consumption was not modeled.

The guidance laws [74] were designed to follow a reference trajectory throughout the experimental scenario, and the resultant guidance cues were presented to the subject (via a flight director) as errors in pitch, roll, yaw and altitude rate from the desired vehicle state. The reference trajectory was calculated based on the range to target and the projected time until arrival at a point 150 ft above the selected landing point. The initial descent rate (guidance recommended and actual) was -16 ft/sec and decreased linearly to -3 ft/sec until the vehicle was below 150 ft (as specified by Bilimoria [74]) and within 15 ft horizontal range of the designated landing point. This effectively resulted in the vehicle being in a hover at approximately 90 ft altitude until it was within 15 ft of the landing point. This range criterion was kept regardless of mode, and if subjects descended below the reference height the computer would command an ascent to return the vehicle to the reference trajectory. As a result of the tilt of the vehicle from vertical, lateral accelerations were generated via the automatic control system (FA control mode) or via the pitch/roll commands (SA, TA, TA-ROD control modes) to null position errors relative to the reference trajectory in the horizontal plane. In the case where the vehicle was not on the reference trajectory, recommended pitch/roll and altitude rate were calculated and presented to the pilot via flight director cues to return to the reference trajectory. The gain within the altitude rate guidance algorithm was set to $K_h = 1/25$ [74], whereas it was $K_V = 1/1000$ for the calculation of the lateral acceleration guidance. These gains, applied to the difference between the actual and reference trajectory altitude and lateral velocity affected the calculation of altitude rate and lateral acceleration guidance along the reference trajectory. The recommended lateral velocity was proportional to the range to the selected landing point. Knowing the lateral acceleration, mass of the vehicle, and current thrust, the guidance recommended roll and pitch angles could then be computed (and presented) to the pilot to return to the reference trajectory.

The pitch and roll attitude guidance components provided the pilot with recommended tilt of the vehicle to null the position error from the reference trajectory. The flight director cues were presented as "fly to," which gave the pilot the direction of the recommended pitch and roll commands to null the error. These cues were computed as the difference between the guidance computed roll/pitch/yaw angles and the corresponding actual values [74], and would reflect the changing in the selected point during runs that required a landing point redesignation. The maximum guidance recommended pitch and roll angles were limited to +/- 45 degrees to limit the effect of large trajectory errors [74]. The subject was not given explicit feedback on position errors. Yaw guidance displayed the relative heading to the selected landing point; the subject was not required to null these heading errors during piloting task (TA or TA-ROD modes). The computer would maintain a northern heading in FA and SA modes. Altitude rate guidance was generated to maintain the vehicle on the reference trajectory in the vertical plane, and was presented on the vertical speed indicator as a recommended altitude rate flight director cue.

7.1.2 Landing Point Redesignation

Three possible landing points, labeled as 1, 2, and 3, were shown on the map in the HSD. This landing point display was derived from a previous experiment investigating human decision making in landing point redesignation [134]. The primary landing point was highlighted in magenta and surrounded by a box, with the range-to-target (in feet) just above (see Figure 7.5a). Alternate landing points were displayed in light blue with numbers (see Figure 7.5b). The landing points were prioritized by the automation system. Subjects were not allowed to redesignate to a new landing point: only the computer could redesignate. Preprogrammed Redesignations were used to create large state errors at the time of the

Control Mode transition in half of the runs. Rejected landing points were indicated by an "X" placed over the rejected landing point (see Figure 7.5c). All Redesignations were made directly down range from lander in the direction of travel, and were similar in magnitude for every Redesignation run. Redesignations occurred simultaneously with the transition to a manual Control Mode.

(a) Primary (b) Secondary (c) Rejected

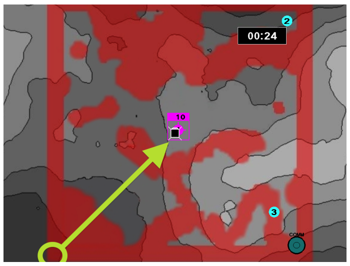
Figure 7.5: Landing points

7.1.3 Maps

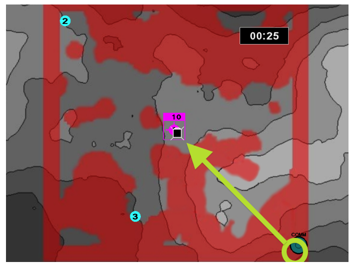
Eight Map types were used in the simulation, 4 for runs with Redesignations and 4 for runs without Redesignation. Each Map showed a hazard map overlaid on topographical map of the lunar surface, as might generated by a system such as the ALHAT [84, 85, 135, 136]. We designed each map so that the lander would cross between hazardous and non-hazardous regions at approximately the same time, regardless of map, when correctly following the guidance trajectory. This meant that the hazard callouts (see Section 7.3.2) would be required at the same time during a run with a Redesignation and a run without a Redesignation. Because the verbal callouts occurred at the same time, we could consider Map type as a set of 4 (SW, SE, NE, NW) instead of a set of 8 (SW, SE, NE, NW with Redesignation and SW, SE, NE, NW without Redesignation). Each Map type is shown in Figure 7.1.3. The primary landing point always appeared in the center of the hazard map.

7.2 Experimental Timeline

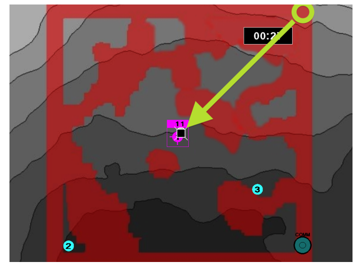
Subjects were trained prior to the 48 runs with a set of training slides (Appendix L) using a laptop (MacBook Pro) computer next to the simulator. Each slide was accompanied by an audio track to supplement and explain the information on the slides. The script



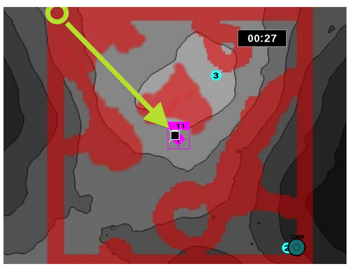
(a) Map SW (No Redesignation)



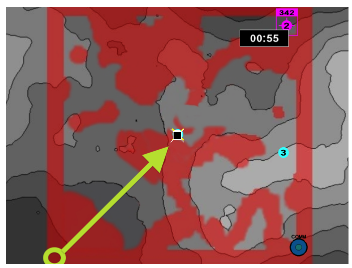
(b) Map SE (No Redesignation)



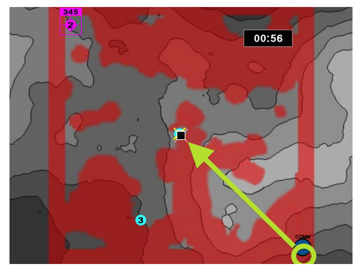
(c) Map NE (No Redesignation)



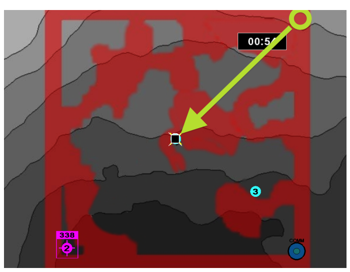
(d) Map NW (No Redesignation)



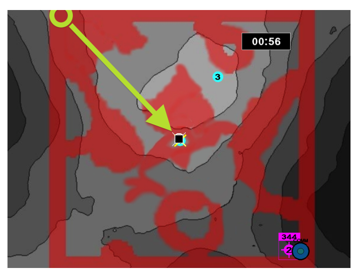
(e) Map SW (Redesignation)



(f) Map SE (Redesignation)



(g) Map NE (Redesignation)



(h) Map NW (Redesignation)

Figure 7.6: Experiment Maps. Circle represents point of origin. Arrow represents initial direction of travel. (SW = Southwest, SE = Southeast, NE = Northeast, NW = Northwest

of these audio tracks can be found in Appendix H. After completing the training slides subjects were allowed to take a break before beginning flight familiarization training. In the familiarization training, subjects reviewed the operation of each Control Mode without mode transitions or landing point Redesignations in the following order: FA, SA, TA, TA-ROD. See Appendix H for the familiarization training script. Subjects were allowed to fly each Control Mode to touchdown until they reported that they felt comfortable. Subjects were given the option of taking a break before continuing to main body of the experiment.

Each experiment session consisted of a number of mode familiarization runs, followed by 24 training runs, and finally 24 formal experiment runs. All runs were terminated after the final verbal callout (either 100 ft or 4% Fuel, depending on subject performance) and were only analyzed between 0 and 69 seconds (2 seconds following the forced extinguishment of the last comm light probe). During the first 24 runs subjects were instructed on how to make the verbal callouts, achieve the correct prioritization of tasks (Priority 1 - flying, Priority 2 - responding to the comm light, Priority 3 - verbal callouts), and rate their workload using the Modified Bedford Scale. This interaction was not scripted.

During the experimental trials the second set of 24 runs the interaction between subject and experimenter was kept to a minimum. All runs began in FA Mode at an altitude of 500 ft above the lunar surface with an initial descent rate of -16 fps, corresponding to the low gate condition used in Apollo (see Table 5.1). The lander began each approach at an attitude in opposition to the forward velocity (pitch angle of 19° and a roll angle of 19°), which is initialized at 15 fps in magnitude towards the center of the map. The descent rate decreased linearly from -16 fps at 500 ft to -3 fps directly over the landing site, accordingly to the equations provided by Bilimoria [74]. If the horizontal range to the landing point was not within 15 ft, the guidance commanded a hover until the range was closed.

The Control Mode transition was made by the computer between 20-25 seconds, a time which we varied randomly[1]to prevent operators from precisely predicting the transition. The operator was alerted to the Control Mode transition with a auditory beep, and was required to consult the mode annunciator to determine the new Control Mode (see Figure 7.4). Table 7.1 shows the sequence of runs, which was designed to balance the sequence of run type (Control Mode - Redesignation configurations).

[1]A time between 20 and 25 seconds was chosen using the Matlab rand() algorithm.

Table 7.1: Sequence of trials for training and experimental runs

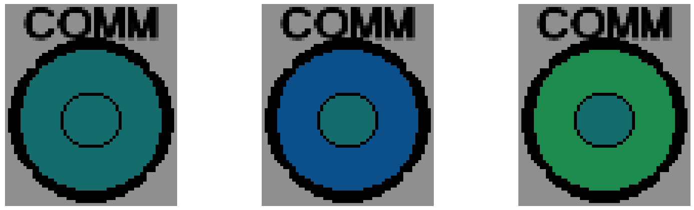
Trial	Mode	Redesign.	Map	Trial	Mode	Redesign.	Map
1	SA	No	SW - No LPR	13	SA	No	NE - No LPR
2	TA	No	NE - No LPR	14	TA-ROD	No	SE - No LPR
3	TA-ROD	No	NW - No LPR	15	TA	No	SE - No LPR
4	TA	Yes	SW - LPR	16	TA-ROD	No	SW - No LPR
5	SA	Yes	NW - LPR	17	TA-ROD	Yes	NW - LPR
6	TA-ROD	Yes	SW- LPR	18	TA	Yes	NW - LPR
7	SA	No	SE - No LPR	19	TA	Yes	NE - LPR
8	TA-ROD	No	NW - No LPR	20	SA	Yes	SE - No LPR
9	SA	Yes	NW - LPR	21	TA	No	SW - No LPR
10	TA	No	NW - No LPR	22	SA	Yes	SW - LPR
11	TA	Yes	SE - LPR	23	SA	No	NW - No LPR
12	TA-ROD	Yes	SE - LPR	24	TA-ROD	Yes	NE - LPR

7.3 Measurements

The gracefulness of transition to the new Control Mode was measured by how well the subject maintained control and awareness of the situation without excessive workload or sacrificing system performance. The number of pitch and roll control inputs in an inappropriate direction and axis was measured, and used as a measure of manual control performance and mode awareness; awareness was measured using a system of verbal callouts; workload was measured with response times to a secondary task and with the Modified Bedford rating scale; performance was measured by the flight technical error (mean square error) in the pitch axis.

7.3.1 Measuring Workload: Response Times & Bedford Ratings

Objective workload was measured using the response time to a “comm light”. This comm light appeared on the lower right of the HSD (see Figure 7.3). The various states of the comm light are shown in Figure 7.7. Throughout a run this comm light was illuminated either blue or green a total of ten times[2]. The illumination schedule of the comm light is shown in Table 7.2. The operator responded to the color of the outer circle (the color of the inner circle stayed constant as a reference) by pressing one of two buttons on the top of the inceptor, each marked with a corresponding color. If the operator ignored the comm light too long, after a few seconds (see Table 7.2) it would automatically extinguish



(a) Inactive (b) Blue (c) Green

Figure 7.7: The comm light

Table 7.2: Comm Light Illumination Schedule

Number *(#)*	**Illumination Interval**[3] *(sec)*	**Forced Extinguish Time** *(sec)*
1	[3,5]	9
2	[9,11]	15
3	[15,17]	21
4	[25,27]	31
5	[31,33]	37
6	[37,39]	43
7	[43,45]	49
8	[49,51]	55
9	[55,57]	61
10	[61,63]	67

Subjective workload was measured using the Modified Bedford Rating Scale. Following a run, subjects were asked to rate their workload *before*, *during*, and *after* the transition. *During* the transition was defined for subjects in training as the period beginning with the mode transition and ending when the flight director errors were nulled and the subject felt in control of the spacecraft. *After* the transition was the period following the *during* phase

[3]The default color of the comm light was turquoise in order to reduce the contrast between an illuminated or extinguished comm light. We used this to increase the sensitivity of the measure after pilot experiments showed an insensitivity when operators could rely on peripheral vision for this light.

[3]Color of comm light illumination was assigned randomly using the standard randomization package provided with MATLAB

(see Appendix H). We trained subjects to rate their transitions in this manner throughout the first 24 trials.

Hypothesis 1
The following was hypothesized regarding workload metrics:

> **Both subjective and objective workload would spike immediately following the transition to manual control and then decay to a steady state value. The magnitude of the spike would be greater in runs with a Redesignation than in runs without a Redesignation. The magnitude of the spike would become larger with decreasing level of automation in the Control Mode. Excessive workload characterizes one aspect of gracefulness: large increases and variability of the workload over time indicates a less graceful transition with respect to operator workload.**

7.3.2 Measuring Situational Awareness: Verbal Callouts

Subjects were instructed to make certain verbal callouts during each run (21 total: 14 altitude, 4 fuel level, 3 hazard crossings). We used verbal callouts of different states because they were a minimally invasive way of continuously measuring situational awareness, since pilots already use them to maintain situational awareness. During familiarization and the first 24 runs subjects were trained in making these callouts, which are shown in Table 7.3. This ordering in Table7.3 is a nominal ordering. If subjects did not perfectly follow guidance the ordering may be different.

Callouts referred to information from each of the displays and were directly relevant to the task. Approximately 6 of these callouts occurred before the transition (depending on the randomization of the Control Mode transition time). We measured an operator's situational awareness based on percentage of correct callouts a subject made each run (defined as occurring within 1-2 seconds of the event as determined by the experimenter). The nature of the callouts occasionally led to a clustering several callouts, which subjects had to quickly attend to. In these cases we recognized that not all of the callouts could be made within the space of 1-2 seconds, and so callouts in these clusters were afforded a certain amount of leniency: a series callouts with no pauses were counted as having been made correctly. A single experimenter conducted all experiments to reduce the uncertainty in judging correct callouts, which were recorded by hand during each run.

Hypothesis 2
The following was hypothesized regarding situational awareness metrics:

> **Situational awareness would follow the inverse trend of workload: awareness would drop immediately following the transition to manual control and would gradually return to a steady state value. The magnitude of the drop would be greater in runs with Redesignation and less in runs without a Redesignation. The magnitude of the drop would reduce with increasing level of automation in the Control Mode. Large drops and variability over**

Table 7.3: Situational awareness (verbal) callouts

Altitude	**Fuel**	**Hazard Crossing**
450 ft		
400 ft		
350 ft		
300 ft	7% Fuel	Cross to non-hazard
250 ft		
225 ft		
200 ft	6% Fuel	Cross to hazard
175 ft		
150 ft		Cross to non-hazard
140 ft	5% Fuel	
130 ft		
120 ft		
110 ft	4% Fuel	
100 ft		

time are characteristic of an ungraceful transition: a graceful transition requires the maintenance of situational awareness.

7.3.3 Measuring Performance: Flight Technical Error

We chose the mean square error (MSE) between the actual pitch angle and the guidance (flight director) pitch angle following the transition to manual control as a measure of human-system performance because it was an axis controlled by the operator in each Mode and allowed for direct comparison. In order to allow for comparison between runs with and with a Redesignation, we measured the error due to a Redesignation in FA Mode (no transition) separate from experimentation. A total of 4 runs were made (1 in each Redesignation Map), and these errors were averaged (there was variability introduced based on the time of redesignation. We subtracted this average from all runs with a Redesignation present. We considered increased MSE as a less graceful transition in the performance metric.

Hypothesis 3

The following was hypothesized regarding performance metrics:

> **The presence of a Redesignation and decreased level of automation in the Control Mode (SA $<$ TA $<$ TA-ROD) would negatively affect the performance. A reduction in performance characterizes an attribute of ungraceful transition: a graceful transition requires that performance be maintained.**

7.3.4 Measuring Control: Number of Wrong Inputs

We counted the number of wrong inceptor inputs for each run, which served to measure the appropriateness of control action. A wrong inceptor input was defined as any inceptor movement opposite the direction required for nulling the flight director errors. Any inputs into the roll axis when the operator was not controlling this axis were also counted as wrong inputs. Yaw and descent rate inputs were not considered in this measurement.

Hypothesis 4

The following was hypothesized regarding the number of wrong inceptor inputs:

> **The number of wrong inputs would be greater in runs with Redesignation and less in runs without Redesignations. The number of wrong inputs would also reduce with increasing level of automation in the Control Mode. Large numbers of wrong inputs suggest poor quality of control and describe another aspect of an ungraceful transition: a graceful transition maintains control of the system.**

7.3.5 Operator Rankings of Gracefulness

Following all 48 trials, subjects were asked to rank the transitions which they experienced (SA, No Redesignation; TA, No Redesignation; TA-ROD, No-Redesignation; SA-Redesignation, TA-Redesignation, TA-ROD-Redesignation) based on the definition of graceful transition as provided earlier in this thesis.

Hypothesis 5
The following was hypothesized regarding the pilot rankings of gracefulness:

> **Ratings would correspond to the level of automation in the Control Modes, with an offset based on the presences of a Redesignation. This will serve to validation for a subjective measure of gracefulness.**

7.3.6 Data Analysis

All analysis was performed with SYSTAT 13.0 (Systat Software Inc.). The analysis considered only the second set of 24 runs for each subject. Runs in which the subject crashed were omitted from analysis. A crash was defined as any contact with the ground occurring during the run (a nominal would have been terminated before landing). Runs with exceptionally large and erroneous control inputs due to fatigue were also omitted from analysis. If the experimentalist saw such an error, he asked the subject if they felt the input was due to fatigue. If fatigue was the cause subjects were given a quick break and then allowed to continue. In total, only 5 runs were omitted from analysis, due to fatigue or a crash.

Since many measures were non normally distributed or were inherently ranked data, we utilized nonparametric methods, particularly the Friedman Two-Way ANOVA for ranked data (Systat NPAR FRIEDMAN) to test the null hypothesis that our variables came from the same population. Systats Friedman analysis furnished p values, the Friedman Test Statistic, and multiple comparison test tables.

We calculated the average mean square deviation (MSE) in each Redesignation - Control Mode combination for each subject over the various replications of that combination. The average mean square deviation found in the FA Control Mode was measured in the non-Redesignation and Redesignation runs and subtracted from the corresponding measures in the manually controlled runs to estimate the MSE due to manual control alone. We used a Friedman analysis to test the difference in MSE before and after the transition, as well as the effects of Redesignation and Control Mode on the MSE after the transition.

We calculated the average response time for each comm light probe for each Map type and for each combination of Redesignation and Control Mode. Since the comm light probes are spaced in time, the analysis of their response times allows us to take time-profiles of responses under the fixed conditions of Redesignation and Control Mode, for six different combinations of those – a separate combination for each run of 69 seconds. Each combination is applied 4 times over the course of the experiment making, in all, 24 runs of 6 different types, each replicated 4 times.

We applied a Friedman analysis to see if subjects agreed on which probes were most challenging (gave highest response times.) The same test was applied to responses under Redesignation to see if subjects preferred one to the other condition, to Control Mode, and to workload ratings and situational awareness callouts at various fixed times within a run. These within-subject comparisons using the Friedman test allow us to use each subject as his/her own control.

Subjects occasionally did not perform the actions assigned to the portion of the experiment they were supposed to be performing. If they were assigned to perform single-axis control (Control Mode SA) they sometimes applied control in the roll axis (appropriate for Control Modes TA or TA-ROD). These were treated as errors of wrong input and the number of wrong inputs measures the maintenance of control. Those too were analyzed by Friedman test to see if subjects agreed on when their situational awareness was greatest and least, as measured against their own performances over other runs.

7.4 Subject Demographics

We recruited 13 subjects (10 males, 3 females) from the MIT/Draper community. All subjects gave informed consent in accordance with the MIT Committee on the Use of Humans as Experimental Subjects (see Appendix M). Their average age was 26.2±3.4 years The average age among female subjects was 25.7±3.8 years, among male subjects was 26.3±3.7 years. All subjects had flight simulator experience (Microsoft Flight Simulator or comparable). Four subjects (all male) having had actual flight experience; one was a licensed pilot.

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Chapter 8

Results

8.1 Objective Workload

We found no effect of Map type. There was, however, a significant effect (Friedman statistic = 82.291, df = 9, p = 0.0005) of probe sequence number over all probes. This suggests that subjects generally agreed on which probe instances were most and least demanding. A Friedman analysis found a significant effect of probe order on average response time over probes 4-10 (Friedman statistic = 14.11, df = 6 , p = 0.028). This means again, only that the subjects agreed on which probe positions were most challenging. Those were not consistently early or late in sequence, but the subjects' responses to the probes were concordant as measured by the Friedman test. As anticipated, Friedman pairwise comparisons showed that response times in probes 1-3 were significantly lower than in probes 4-10 (see Tables A.2 and A.3). This shows that the mode transition significantly increased the response times, our objective measure of workload.

We expected a spike in comm light response time after the transition to manual control which occurred just before probe 4 as an indication of increased workload. The size of that spike was expected to vary with Control Mode and Redesignation condition starting with probe 4 because those were expected to impose different workloads. Subjects only marginally agreed on the difficulty of runs with a Redesignation compared to those without a Redesignation in probe 4 (Friedman Statistic = 3.769, df = 1, p = 0.052) and probe 7 (Friedman Statistic, = 3.769, df = 1, p = 0.052). Figure 8.1 shows that response times increased after the transition, but additionally changing the landing point did not produce an additional large reliable change in workload lasting many seconds. A redesignation effect was expected, and may well exist, but it may have been obscured by the variability in our data.

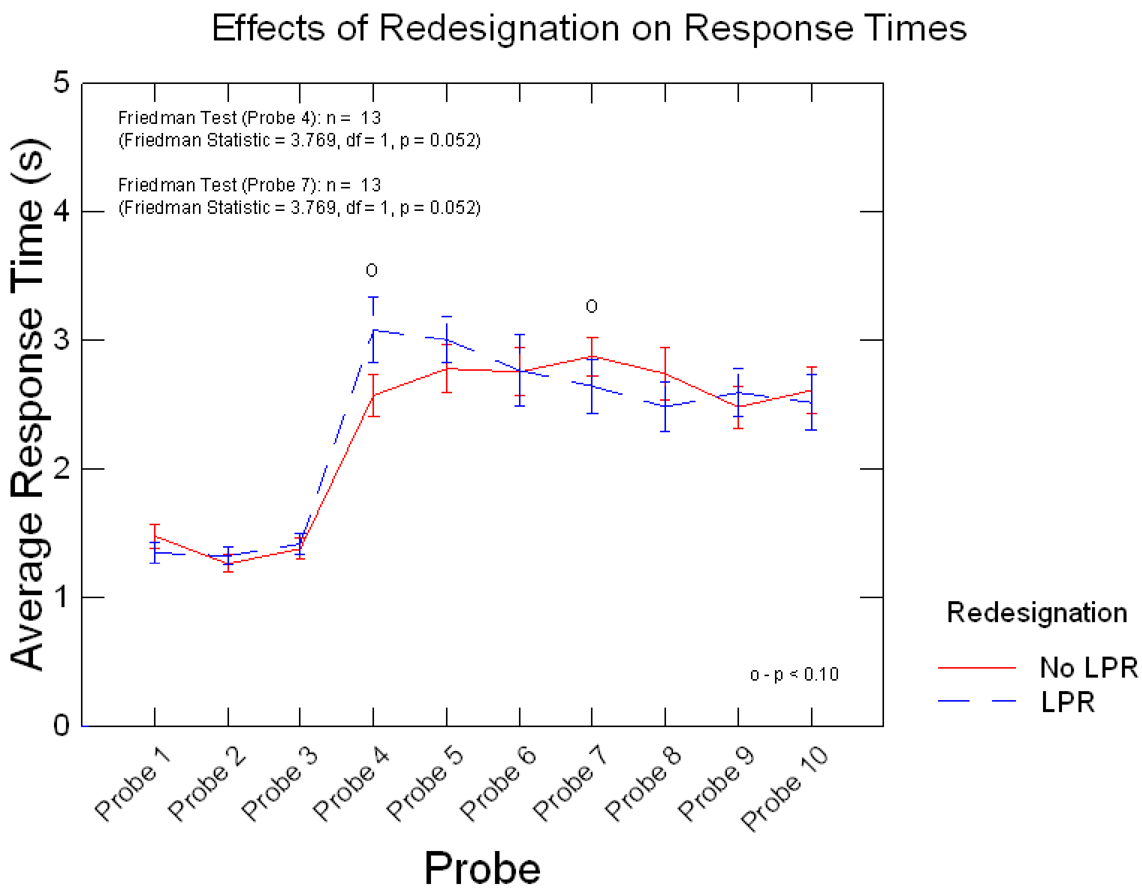

Figure 8.1: Effects of Redesignation on the average comm light response time (n = 13). Errors shown are the standard error of the mean.)

The subjects did not agree, however, as to the ranking of difficulty of Control Modes until after probe 4: the Friedman test on the average comm light response times in probe 4 did not give a significant result, but in in probe 5 it gave a marginally-significant result (Friedman statistic = 5.69, p=0.058, df=2). This suggests that in the interim the subjects' responses coalesced to the point where they agreed on the effects of the transition to manual control on their workload as by measured by their consistent rankings of comm light response times across Control Modes. The overall effect of Control Mode can be seen in Figure 8.2.

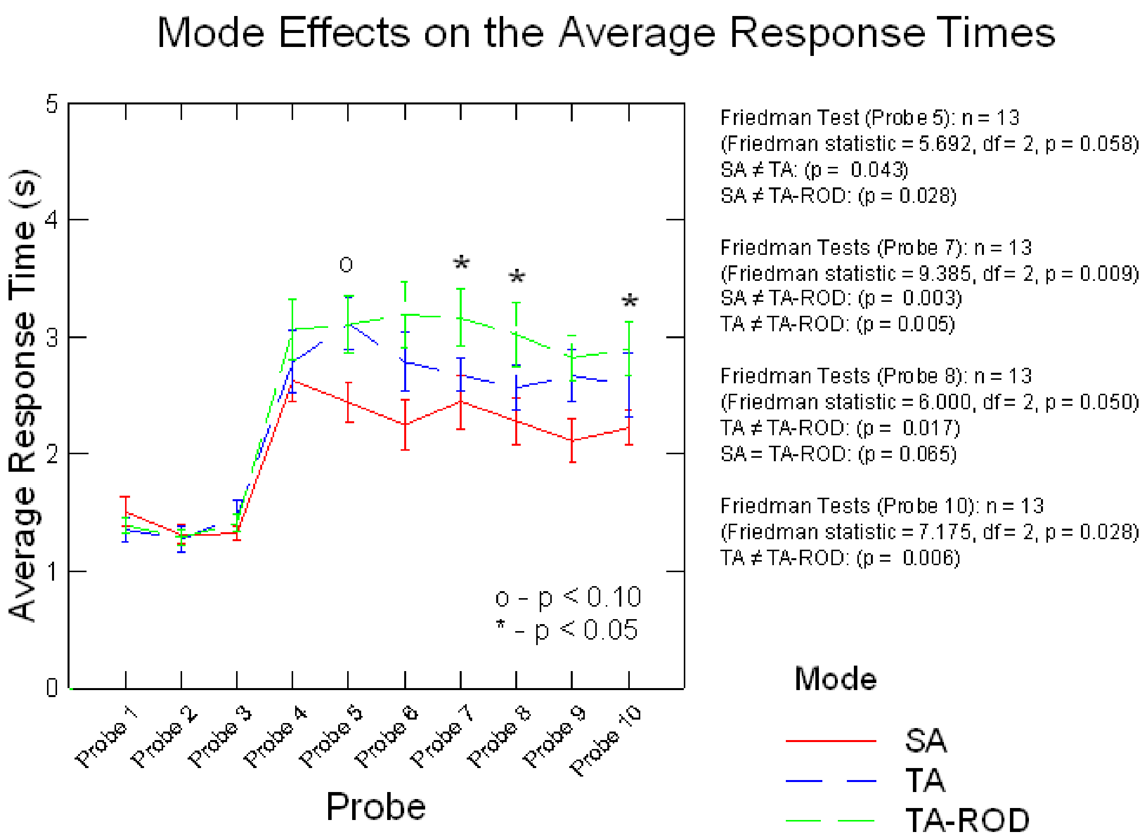

Figure 8.2: Effects of Control Mode on the average comm light response time (n = 13). Errors shown are the standard error of the mean. (SA = Single-axis RCAH in pitch, TA = Triple-axis RCAH, TA-ROD = Triple-axis RCAH with incremental rate-of-descent.)

Although Control Mode showed a large effect on secondary task response time (Figure 8.2), because the curves were essentially parallel in time after Probe 5 suggests that if an interaction between control mode and probe number exists, such that workload remains high for TA-ROD, but diminishes for TA and SA modes, the effect must be small, or masked by the variability in the data. The Friedman test on the average response time across probes 4-7 showed that Redesignation had no effect. The full analysis is shown, for this and the other analyses, in Table A.4-A.7.

8.2 Subjective Workload

Analysis showed no significant effect of Map type in any phase. We expected to see a spike in the subjective workload similar to the one observed in the comm light response times. Modified Bedford workload scores, when ranked, were completely consistent for all subjects for every combination of Mode and Redesignation. They ranked "Before" lowest, then, "After" and "During" Workload as highest. Not surprisingly, this ranking was significant (Kendall Concordance=1, Friedman statistic =14, df=2, $p = 0.001$). Redesignation had no significant effect on the average workload rating in "Before" or in the "After" phase. The subjective workload did vary with Redesignation in the 'During" phase (Friedman statistic = 8.333, df = 1, $p = 0.004$), as shown in Figure 8.3.

Subjects agreed on the ranking of the effects of Control Mode as measured by the average workload rating within the "During" phase (Friedman statistic = 26.000, df = 2, $p = 0.0005$) and the "After" (Friedman statistic = 23.804, $p = 0.0005$, df = 2); however, the effect of Control Mode was not significant in the "Before" phase. All pair-wise comparisons were significant ($p = 0.0005$) and rankings can be seen in Figure 8.4.

8.3 Verbal Callouts

A Friedman test found no significant effect of Map type on the percent of correct callouts made in a run. We expected a drop in the average percent of correct callouts made following the transition into a manual Control Mode, as shown in Figure 8.5. Subjects were concordant on the average percent of correct callouts (Friedman statistic = 177.635, df = 20, $p = 0.0005$) over all 21 callouts (rankings shown in Table A.8), and pairwise comparisons showed that 4 of the 6 callouts before the mode transition callouts (450 ft, 400 ft, 350 ft, 300 ft) had significantly higher percentages than those callouts after the transition (e.g. 300 ft pairwise comparisons are shown in Table A.9). All 6 callouts before the mode transition (450 ft, 400 ft, 350 ft, 300 ft, Hazard 1, 7% Fuel) had significantly higher percentages than callouts occurring after the transition and before the 120 ft callout (250 ft, 225 ft, 200 ft, Hazard 2, 6% Fuel, 175 ft, 150 ft, Hazard 3, 140 ft, 5% Fuel, 130 ft). This shows that the mode transition significantly reduced the percentage of verbal callouts which occurred afterwards. As will be shown later, the situational awareness measures follow the same pattern as the workload measures (when inverted).

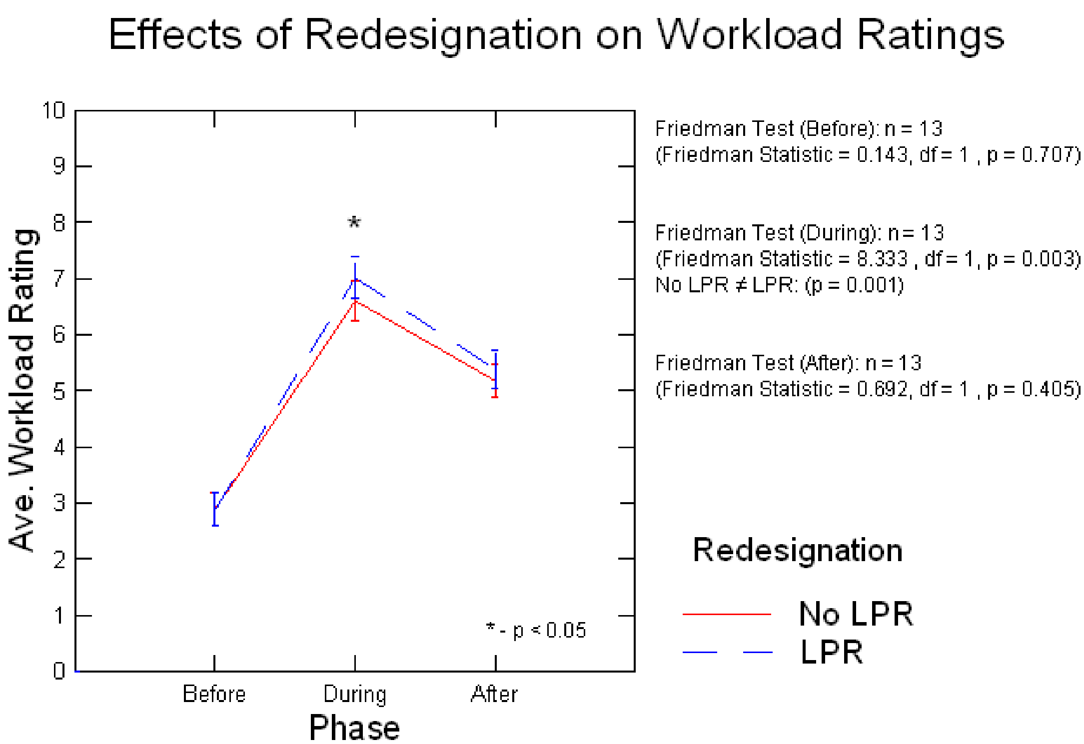

Figure 8.3: Effects of Redesignation on the average Modified Bedford workload ratings (n = 13 Subjects). Errors shown are the standard error of the mean.

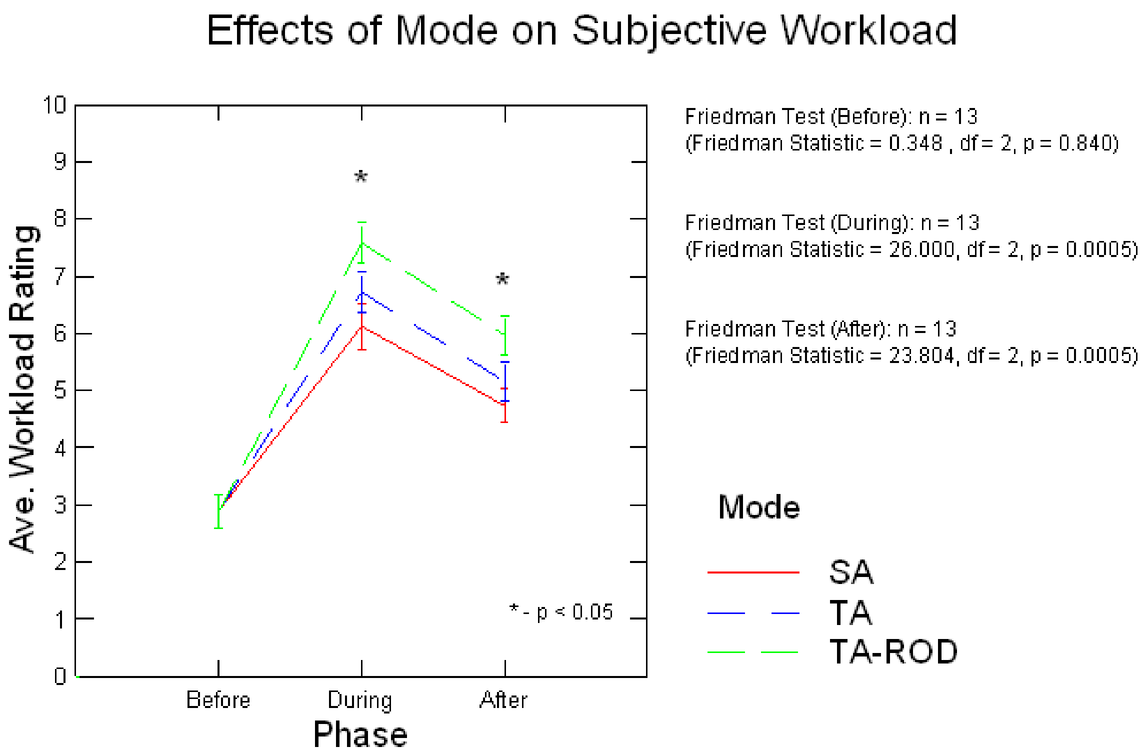

Figure 8.4: Effects of Control Mode on the average Modified Bedford workload ratings, within phases (n = 13). Errors shown are the standard error of the mean. (SA = Single-axis RCAH in pitch, TA = Triple-axis RCAH, TA-ROD = Triple-axis RCAH with incremental rate-of-descent.)

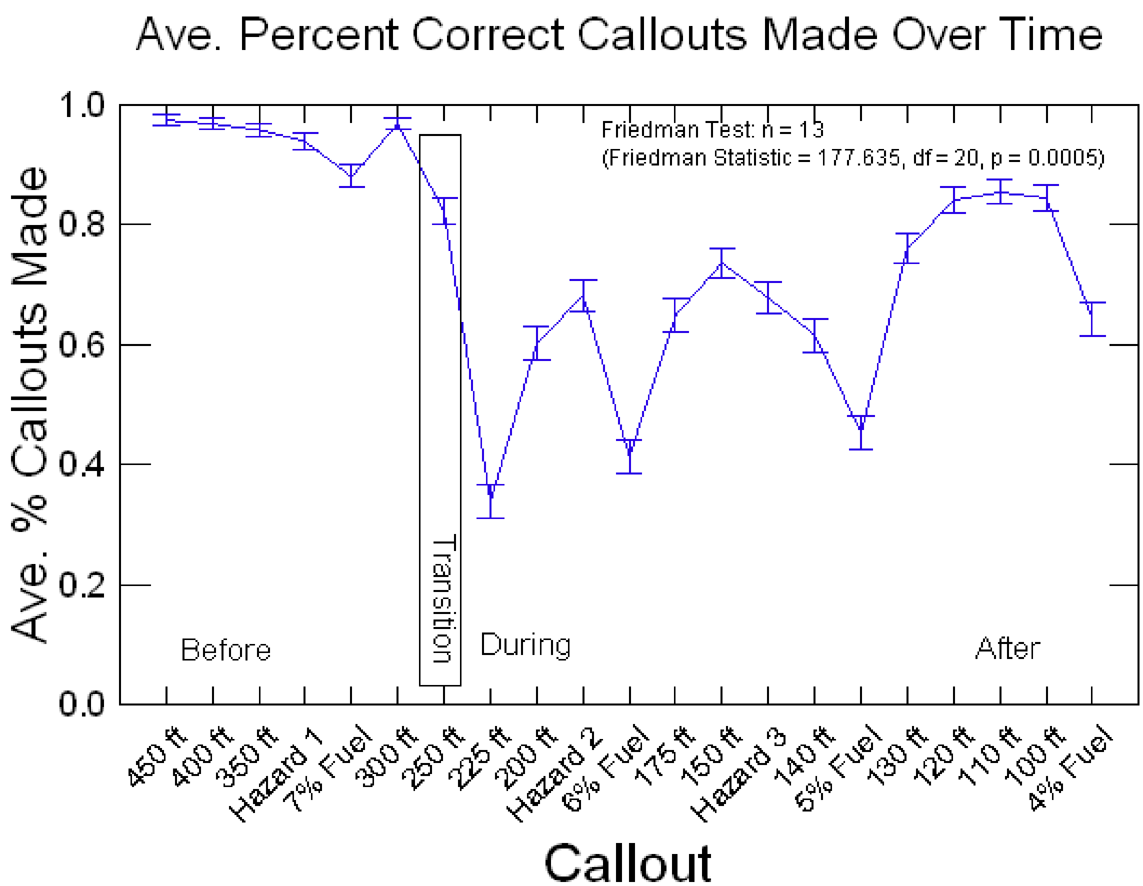

Figure 8.5: Average percent of correct callouts made against altitude (time), fuel level, and the appearance of hazards (n = 13). Errors shown are the standard error of the mean.

Figure 8.6 shows the effects of Redesignation on the percent number of callouts made. As shown in Table A.10, Friedman test results showed that subjects agreed on the rank effect of Redesignation at the 250, 225 and 200 foot altitudes immediately after the redesignation, and pairwise comparisons of percent correct showed that the percentage correct at 250 feet was significantly different than at 225 or 200 feet (see Table A.11).

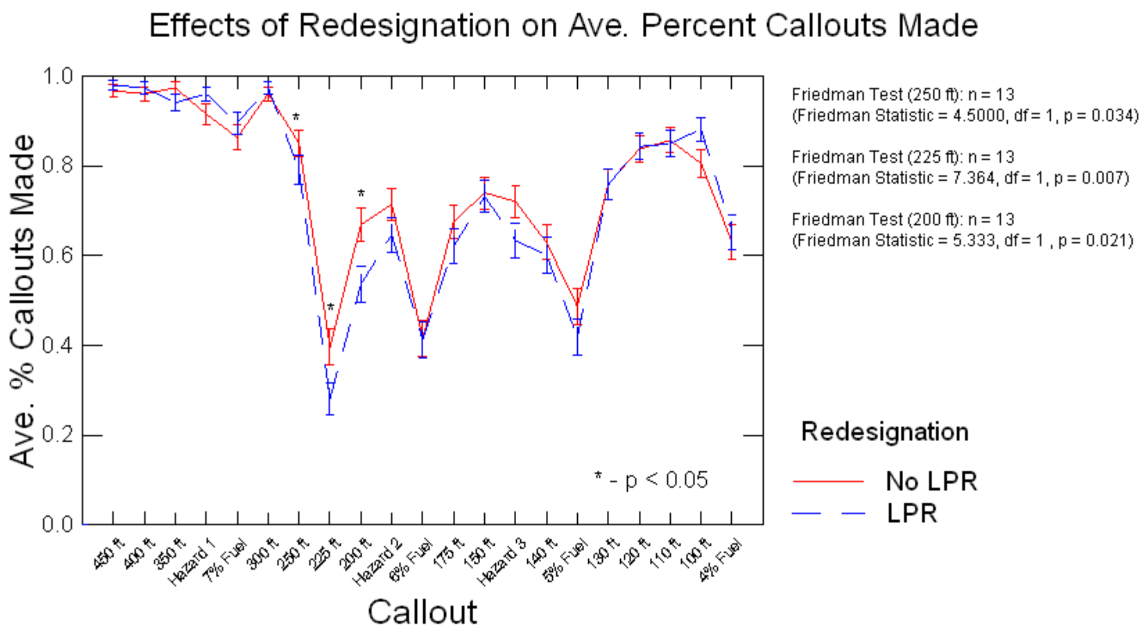

Figure 8.6: The effect of Redesignation on the average percent of correct callouts made (n = 13). Errors shown are the standard deviation of the mean.

We expected a transient returning to a steady state level of situational awareness and that it would be a function of both Control Mode and Redesignation. The relative ranks of the three Control Modes on the average percent of correct callouts were compared (over the 13 subjects) at 20 points and found concordant at 9 of the 15 by Friedman test, as shown in Tables A.12 - A.15. Figure 8.7 shows the effect of Control Mode on average percent of correct callouts. That the curves are approximately parallel shows that the effect of each Control Mode is consistent following the transition and does not change with time – the vertical heights between the curves is roughly consistent across time. The most striking feature of the verbal callouts is the seemingly periodic sequence of dips following the transition. Of those dips, four of the five are fuel level callouts and are most likely due to the difficulty subjects had in scanning that display element.

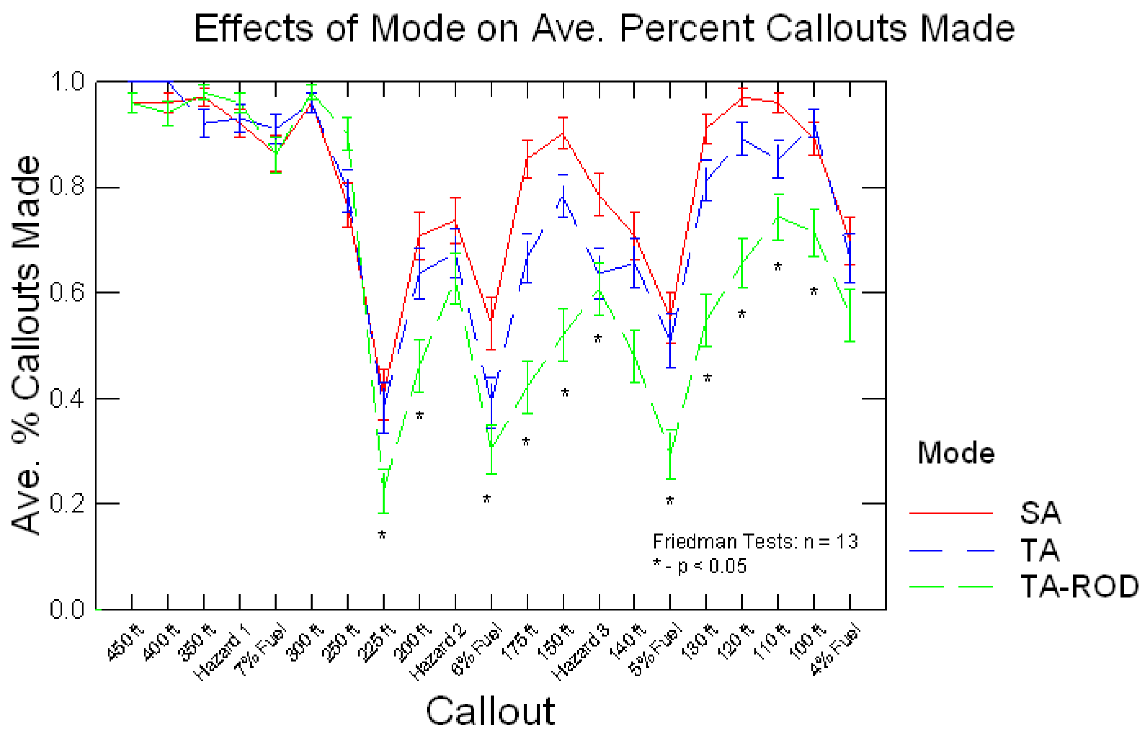

Figure 8.7: Effect of mode on the average percent of correct callouts made (n = 13). (SA = Single-axis RCAH in pitch, TA = Triple-axis RCAH, TA-ROD = Triple-axis RCAH with incremental rate-of-descent.)

8.4 Performance

We calculated the average mean square deviation (MSE) in each Redesignation - Control Mode combination for each subject over the various replications of that combination. The average mean square deviation found in the FA Control Mode was found to be 82.0±6.6 deg^2 in Redesignation runs. Those estimates were subtracted from the corresponding measures in the manually controlled runs to estimate the MSE due to manual control alone. With these corrections we found that the MSE was greater after the transition than before (Friedman statistic = 13.000, df = 1, p = 0.0005).

The MSE values were larger in runs with a Redesignation than in runs without in the "After" phase (Friedman statistic = 13.000, df = 1, p = 0.0005), shown in Figure 8.8. The values of MSE increased consistently from SA to TA to TA-ROD (Figure 8.9) when there was no Redesignation (Friedman statistic = 7.385, df = 2, p = 0.025), but not consistently in runs in which there was a Redesignation (Friedman statistic = 7.769, df = 2, p = 0.092). The lack of a significant result could be due to the increased variance in runs with Redesignations (F(12,12) = 0.028, p = 0.0005). This was an unexpected result and made it more difficult to clearly establish the effects of Control Mode for the Redesignation runs. We would expect a larger sample size to show a significant effect of Control Mode on MSE in Pitch for both Redesignation conditions.

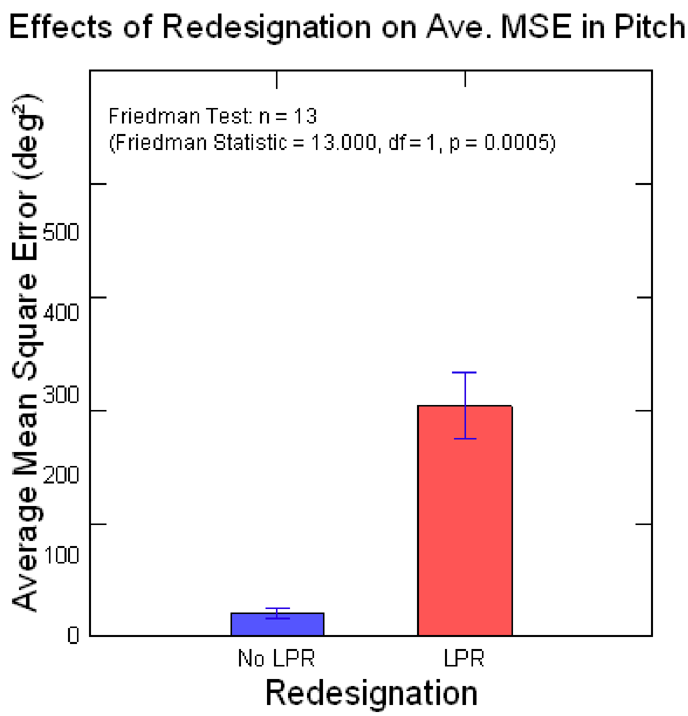

Figure 8.8: The effect of Redesignation on the Average MSE in Pitch. Errors shown are the standard error of the means.

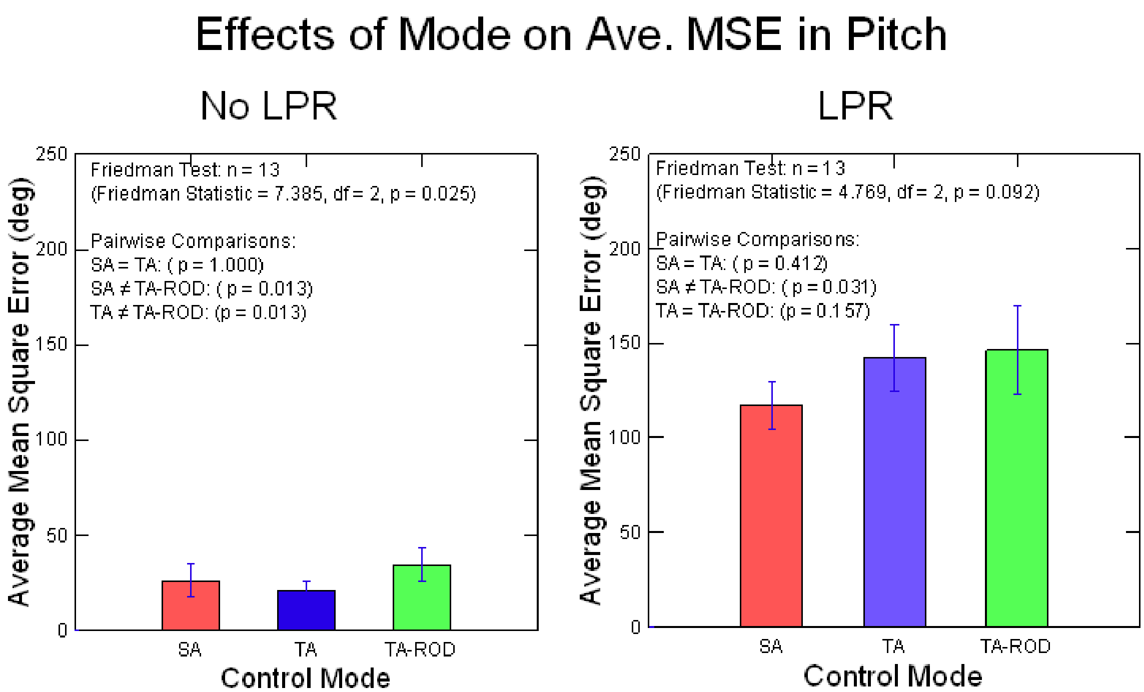

Figure 8.9: The effects of Control Mode on the Average MSE in Pitch. (SA = single-axis pitch RCAH, TA = triple-axis RCAH, TA-ROD = triple-axis with incremental rate of descent). Errors shown is the standard error of the mean.

8.5 Number of Wrong Inputs

There was no significant effect of Map type on the average number of wrong inputs by Friedman test. Subjects showed concordant effects of Redesignation on the average number of wrong inputs (Friedman statistic = 9.308, p = 0.002, df = 1). These effects and ranks are shown in Figure 8.10. No effect of Control Mode was seen by Friedman test.

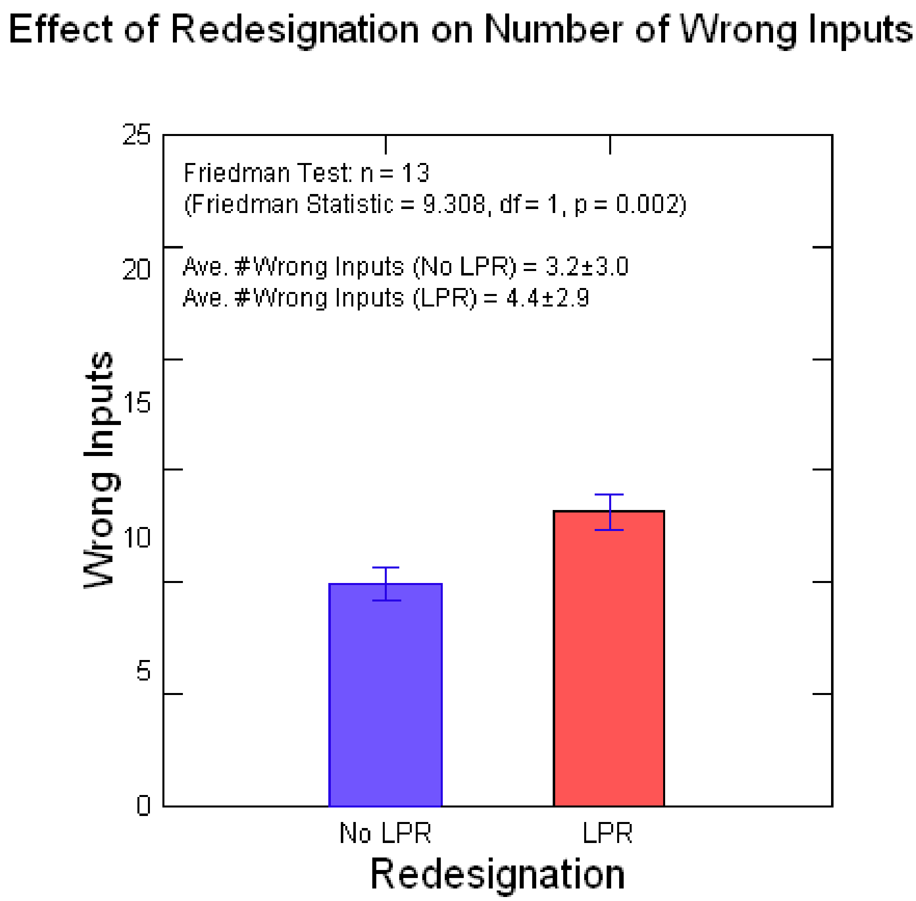

Figure 8.10: Effects of Redesignation on average number of wrong inputs (n = 13). Errors shown are the standard error of the mean.

8.6 Rankings of Gracefulness

Table 8.1 shows the rankings of gracefulness provided by subjects following the experiment. All subjects agreed that the gracefulness decreased from SA to TA to TA-ROD separately in each Redesignation category. As Table 8.1 and Figure 8.11 show, however, they did not agree perfectly on the full ranking of the six Redesignation - Control Mode configurations: an overlap existed between runs in SA Mode with a Redesignation and those in TA-ROD Mode without a Redesignation. The Friedman test on those six configurations was significant (Freidman statistic = 54.429, df = 5, p = 0.0005) and results are shown in Tables A.16 and A.17. Subject 4 gave equivalent ratings instead of singular rankings and was removed from this analysis.

Table 8.1: Subject rankings of gracefulness

Subject	**No Redesignation**			**Redesignation**		
	SA	*TA*	*TA-ROD*	*SA*	*TA*	*TA-ROD*
Subject 0	1	2	5	3	4	6
Subject 1	1	3	5	2	4	6
Subject 2	1	3	5	2	4	6
Subject 3	1	2	4	3	5	6
Subject 4	-	-	-	-	-	-
Subject 5	1	2	3	4	5	6
Subject 6	1	2	5	3	4	6
Subject 7	1	2	5	3	4	6
Subject 8	1	2	3	4	5	6
Subject 9	1	2	3	4	5	6
Subject 10	1	2	4	3	5	6
Subject 11	1	3	5	2	4	6
Subject 12	1	2	4	3	5	6

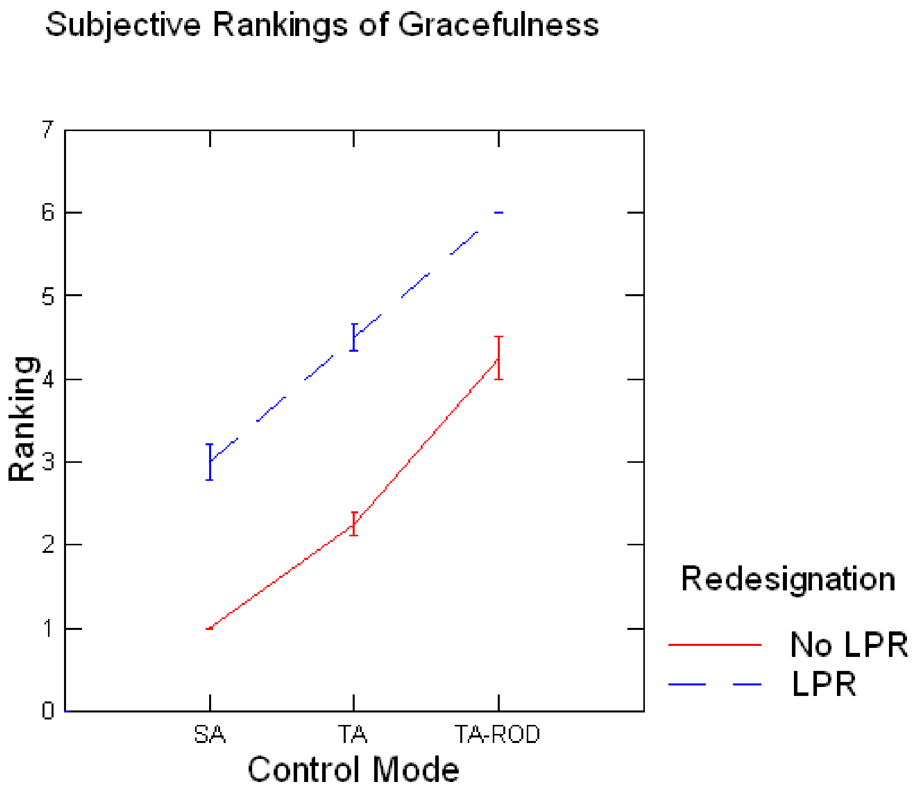

Figure 8.11: Subject rankings of gracefulness

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Chapter 9

Discussion

9.1 Workload & Situational Awareness

The response time to the secondary task (comm light) is an indicator of how much spare attention a subject had at particular points throughout a run. The comm light task was not just a simple response: it required both attention for visual scanning and attention for information processing and decision making (decide between 2 colors) and was, therefore, a very sensitive measurement of spare attention. Spare attention is assumed inversely related to workload (low spare attention = high workload), so these response times can be interpreted to indicate progression of workload over time. Additionally, the Modified Bedford ratings provide the subjects' estimates of their spare attention at three points of interest (before, during, and after the transition) during the runs. Both measures of spare attention were concordant in the trends that they observed, which increases the construct validity of separating a run into 3 phases for the subjective workload (before, during, and after).

Similarly, the verbal callouts (tertiary task) expressed how often a subject was aware of certain information relevant to the task for similar run types. The percentage of correct verbal callouts made was interpreted as an indicator of situational awareness. Verbal callouts such as these are often used by pilots in everyday operations, so the added workload of verbalizing the information represented by the callouts was considered minimal. This method of measuring situational awareness provides a unique way of measuring temporal changes in tertiary task situational awareness that is not available to methods like SART or SAGAT.

Verbal callouts do not provide the same resolution into the quality of the operator's situational awareness as SART or SAGAT: the information space of what is considered "situationally aware" is restricted. In this experiment, subjects could not be probed regarding any aspect of the situation: they had to be trained as to what pieces of information they would be expected to know. While this doesn't provide a complete measure of overall situational awareness, it does provide a great deal of information about the components of situational awareness that are lost when workload increases due to mode changes or a landing point redesignation. Subjects were trained to make nulling the guidance errors their first priority. Had they been asked questions about guidance errors, they probably would have scored very highly on that component of situational awareness. Typically when workload is increased, attention tunnels onto the primary task, and situational awareness as well as performance on secondary tasks decreases. Additionally, subjects were instructed to only make the callout when they *observed* the state that they were calling out. This made it unlikely that the subjects were unconsciously making callouts in a preprogrammed fashion. Foreknowledge of the callouts, at best, served to inflate the measure of situational awareness; not invalidate it (e.g. subjects could be expecting a callout, but they still needed to make it correctly).

In this experiment, the scope of the verbal callouts was limited to altitude, fuel level, and hazards because these occurred at approximately the same time in each run. This resulted in certain callouts being clustered into short time periods. However, any clustering effecting would have reduced the average percentage in each callout, and this was not observed.

The most striking feature in the callout data is the oscillatory nature that is observed following the transition. The first low point after the transition occurred at 225 ft, and this is taken as an indication of the increased workload due to the transition: subjects were observed as being preoccupied with determining the new Control Mode and responding to any observed guidance errors. Every other low point, including the one preceding the transition, was a fuel callout. These low percentages should not be taken to mean that subjects were completely negligent of the fuel callouts (subjects often made fuel callouts late), but rather that the fuel display was in a location that subjects did not scan as frequently. This result shows not only the sensitivity of these callouts in measuring situational awareness, but also shows the utility of its application in the design and evaluation of displays. Consistent low points indicate an inadequate scan frequency.

This continuous measurement technique provided by the verbal callouts presents a very practical way of understanding situational awareness. The SAGAT and SART both provide task-encompassing measures that dont easily give information on precisely when a subject is situationally aware or unaware. This experiment shows that situational awareness varies significantly with time (on the order of seconds) in these of a mode transition. Understanding the time-sequence of situational awareness can provide designers with an understanding of *when* operators are aware of something, and not just *what* they are aware of. A analysis using both verbal callouts and a measurement like SAGAT or SART would be provided with a complete picture of situational awareness: time-dependency and content.

Subjects were instructed to prioritize tasks in the following manner: (1) flight performance, (2) comm light, (3) verbal callouts. Reports from the subjects and the data suggest that this prioritization was achieved. Throughout training, subjects were reminded to correctly prioritize these tasks; all subjects reported that they felt they were correctly prioritizing by the end of the training runs. Additionally, the dropping of the fuel callout and not comm light response times provides additional evidence that subjects were prioritizing correctly.

It is likely that this experiment underestimates the effect that would be seen in an actual landing: in a real-world application the operator the operator would also have to designate a new landing location. Additionally, most landing redesignations will not be conveniently downrange of the craft. These would both be expected to increase the effect of a Redesignation, and so any direct application of this research to should take the effects of Redesignation seriously.

Objective workload data did show a large increase in workload at the time of the transition; however, it failed to show any significant recession in the period following the transition. Redesignation showed no effect immediately after the transition in the objective workload data. However, the subjective workload data did significantly show these effects (both of the mode transition and Redesignation) and the objective workload data displays trends which – though not statistically significant – resemble the same behavior. The inability to show such a recession was most likely hampered by the variance seen in the data. Situational awareness also showed significance: percent of correct callouts dropped immediately after the transition and then increased as a function of both landing point Redesignation (directly after the transition) and Control Mode. The apparent recession in workload might be related to the situational awareness recovery time; however, such an explanation is contingent upon the observation of a significant recession. This behavior was not observed due to variance of the data. Further experiments should investigate the existence of this phenomenon.

Time dependencies and intrinsic interdependencies of workload and tertiary task situation awareness has other interesting consequences for system design. It is possible that workload might become so high during the transient, or situational awareness so low, that operators find themselves constantly trying to catch up with the system and are never able to reach the steady state. Additionally, these spikes in the responses immediately after the transition should be considered when determining how much an operator should be responsible for during this time period: operators are overworked and uniformed immediately following the transition. Any input choices that need to be made at this time should be easy for the operator to determine and implement. Using a mode preview display or a trend display might help operators to prepare for the loss of situational awareness that they will experience during a transition. Additionally, the use of command displays which would indicate the direction of correct input could help mitigate the lack of situational awareness in the initial stages of transition.

These trends in workload and situational awareness data both support the predictions of Hypotheses 1 and 2. The effects of Control Mode level of automation are particularly consistent with the previous research in manual control and handling qualities discussed in Chapter 6. Further, the reduction in situational awareness measures the shows the time-progression of the out-of-the-loop effect on situational awareness as described in the literature [23, 93, 105, 106].

9.2 Performance & Wrong Inputs

Analysis showed that the average MSE in pitch was increased by the presence of a Redesignation. The level of automation in the Control Mode significantly affected the average MSE in pitch in runs without Redesignation: Mode SA had the least error and TA-ROD had the highest. Notably, there was no significant difference in MSE between SA Mode and TA Mode. This result is consistent with previous work considering single- and two-axis control tasks [96]; however, the difference recorded between SA Mode and TA-ROD Mode showed that there is a limit to the number of control axes which can be taken on in a mode transition before performance suffers. Runs with a Redesignation were only marginally affected by the level of automation in the Control Mode, which suggests an interaction between Redesignation and Control Mode. These findings support Hypothesis 3: the performance attribute of a gracefulness in a transition was reduced in runs with a Redesignation and in Control Modes of a lower level of automation. In consideration of their effect on gracefulness, the increased level of automation in the Control Mode (fewer control loops closed by the operator) led to a more graceful transition; the presence of a Redesignation also resulted in less graceful transition. These findings are also consistent with, and expand, the research of Kaber and Endsley investigating the effects of switching levels of automation on performance [23, 111].

The number of wrong control inputs also provide a measure of the operator's maintenance of control, as well as a gross estimate of situational awareness as it related directly to the flying task. The effect of a Redesignation on the number of wrong inputs was correlated with the drop in situational awareness (verbal callouts) immediately after the transition. The increased number of wrong inputs in runs with a Redesignation also correlates with the increased variance of the MSE in pitch compared to runs without a Redesignation. These measures together show that the certainty and accuracy of the subjects' control strategy was reduced in Redesignation runs. Trends of the number of wrong control inputs with Control Mode seem to be present; however, these were not conclusively proven due to a high variability in the data.

The trends of increased flight technical error following the transition and increased number of wrong inputs support Hypothesis 4 and should be considered when designing automation systems for graceful transitions: when transitioning into a more difficult mode certain fail-safes and command guidance features should be in place to help reduce the number of wrong inputs that an operator is prone to. For example, the use of a command display might reduce the uncertainty in the correct control input following a transition and improve gracefulness; however, command displays do increase issues related to automation trust. While the subject has a clear idea of what the automation thinks they ought to do, the question of how much this suggestion should be trusted, particularly in cases where transitions occur for failure mitigation. Further, increasing the level of automation of the manual mode that the operator is required to transition into would be advisable. An example would be to give preference manual modes with fewer control loops before requiring a transition to full manual; however, this should be done with caution. Such modes, by design, limit the pilot's input and could keep them from a novel control solution unforeseen by the automation.

9.3 Graceful Transitions

Subjects rankings corresponded directly with the level of automation in the Control Mode and were offset by Redesignation. Every subject reported SA as the most graceful Control Mode transition to, and TA-ROD as the least within Redesignation and non-Redesignation runs. This is shown by the overlapping effect shown in Figure 8.11: subjects did not agree on any ranking difference between non-Redesignation runs in TA-ROD and Redesignation runs in SA. This confirms the predictions of Hypothesis 5 and suggests that our definition of graceful transition provides a basis for the measurement of the gracefulness in transition.

In total, the results show that graceful transitions are more likely in cases where the Control Mode is at a higher level of automation. The effect of Mode shows that the workload attribute in a graceful transition is contingent upon the Control Mode. This result suggests that designers need to give careful consideration to what levels of automation they will be switching between: certain mode switches will be more prone to ungraceful transitions with respect to operator workload. Systems which operate at the extremes of the levels of automation violate this important design principle and are particularly prone to ungraceful transitions. Furthermore, workload is an extremely important quantity to operators: systems that transition gracefully will be preferred over those that do not.

The interactions of each of these measures is important when considering gracefulness. The quantities are naturally linked and the experimental data shows this. Workload increased when situational awareness was low, describing an operator who was attempting to either regain their awareness of the situation or was simply unaware because they were overworked. Performance dropped in cases of low situational awareness. Large numbers of wrong inputs described a poor quality of control and were consistent with low situational awareness. In essence, each of these measures are linked, and gracefulness describes their equilibrium. When a mode transition takes place, this equilibrium is disturbed and the operator must attempt to find their new operating point: systems which transition gracefully aid in this process.

The results of the experiment suggest that the system designer is in a key position to aid in the grace of a transition: levels of automation have a direct correspondence to how well a system will transition gracefully. If the mode to which operators are required to transition has a high level of automation the transition will most likely be graceful. It is important to note that these levels of automation refer specifically to levels within a manual control task; the results of this experiment cannot be generalized to transitions between purely supervisory tasks.

9.4 Limitations

The largest limitation of this experiment is its neglect of automation surprise. The case studies showed that this phenomenon is closely linked to the gracefulness of a mode transition; however, consistently replicating this phenomenon in an experimental setting is extremely difficult. Mode confusion may have existed in instances when operators mistook TA-ROD for TA; still, this phenomena could not be easily induced and its occurrence was too infrequent to measure. Hence, this experiment was intentionally limited to measuring the gracefulness of transitions in which subjects were fully trained and had recent experience with the Control Modes. Subjects also were aware of the approximate time that the transition would take place and could be certain that the transition would take place.

The second major limitation of this experiment was the length of the runs. In order to save time in the experiment, runs were cut short after the final callout. In many runs, particularly in those with a Redesignation and/or a lower level of automation in the Control Mode (e.g. TA-ROD), a steady state value was not reached for any of the measures, which did not allow for the definition of transition length.

In some of the trajectories being flown, subjects were actually flying backwards at the beginning of the run. This was by design to force subjects to operator the control stick in all four directions (forward, back, left, right) over the course of the 24 experimental runs. Similarly, the trajectories were all of a similar geometry (Redesignations in the direction of travel) to allow for comparison. A real lunar landing task with a Redesignation would most likely not be directly in front of the lander, nor would the astronaut ever find themselves flying backwards for long periods of time (they would yaw to see what was in front of them).

Chapter 10

Conclusion

10.1 Summary

In the beginning of this thesis, a graceful transition was defined as follows:

> The ability of a complex system to change between levels of automation/levels of supervisory control (including automation modes) with the operator maintaining control and awareness of the system without excessive workload or sacrificing system performance

An experiment investigating the effects of Control Mode and Redesignation on the gracefulness of a transition was performed and the results were presented and discussed in light of this definition. In general, it was shown that decreased level of automation in the Control Mode and the introduction of a Redesignation both served to reduce the gracefulness of the mode transition. The quantities of workload and situational awareness both showed a transient response which varied with Control Mode and Redesignation, as did the number of wrong inceptor inputs. The experiment demonstrated the important interdependencies between performance, workload, and situation awareness. These results showed that designers of multi-modal automation systems must consider the level of automation in the modes that they require operators to switch between and the time period in which such transitions occur: decreased levels of automation and large state errors will result in a less graceful mode transition.

Additionally, a set of 6 case studies were presented which investigated the question of graceful transitions in practice. Many of these case studies showed ungraceful transitions that flowed from a case of automation surprise and/or mode confusion. The gracefulness of a transition was distinguished from these phenomena; however, in many of these case studies it was intrinsically linked to the gracefulness of the transition. Two models of factors and mechanisms based on the work of Endsley in situational awareness were used in case studies to drive the development of a set of design principles for designing multi-modal automation systems for graceful transitions.

10.2 Future Work

Due to the multi-faceted nature of graceful transitions, there are many things to be investigated. The experiment only manipulated two variables: the mode following the transition and the presence of large state errors. All trials transitions were from a fully automatic mode. Future investigations should utilize modes other than fully automated prior to the transition, e.g. begin in SA mode and transition to TA-ROD. This could help determine if gracefulness in a transition is contingent on the specific modes being used, or if it is only the difference between the two modes that matters (e.g. 4 to 1 = 6 to 3).

The measurement of MSE in pitch here had a very coarse resolution: there was no distinction made between during the transition and after the transition. Using a finer grain measure in any future work concerning transitions would be recommended. The length of the runs did not consistently show the final steady state of all the measurements as time constraints required that the runs be cut short, and this was the driving factor of only analyzing "after" the transition with MSE. Any future experiment should increase the length of run time to sufficiently all of a settling of the quantities following the transition. This would allow for the MSE to be broken into phases similar to those used for the Bedford Workload ratings (before, during, and after). The time-dependency of the performance in comparison to that of workload and situational awareness would further illuminate the interactions between these quantities that lead to graceful transitions.

Further, automation surprise and mode confusion are both extremely difficult quantities induce in a controlled experimental setup; however, their relation to the gracefulness of a transition is not trivial. As the case studies showed, mode confusion is often a precursor to ungraceful transitions. When present, automation surprise can cause mode transition workload to increase and performance to decrease even more than seen in the present kind of experiment. Understanding how these particular phenomena interact with the other attributes of gracefulness would be an area of further development. Additionally, there is much to be gained in understanding how the other attributes of gracefulness, such as control maintenance, workload, and performance affect situations of mode confusion and surprise.

Now that the gracefulness of a transition has been found to depend on the number of manual control loop closures required, as well as the state errors present at the time of the transition, future experiments might consider the case in which subjects are not certain that a mode change will occur. Such an experiment could be designed as an extension of this experiment; however, subjects would complete two run sequences. In the first set of runs, subjects would complete an experiment similar to that presented here, with the computer always redesignating. In the second set, the computer would always redesignate, but the subjects would experience a mode transition in only half the runs. By comparing the workload, situational awareness, and performance measures between the two sets for each subject, many aspects of automation surprise could be simulated, since on any run, the subjects could not be certain that a mode transition would actually take place, and what the specific transition would be. On the other hand, the subjects would be aware that a sudden mode transition was possible and would have high recency in identifying the transition and responding to it – which is not always the case in real world situations. To completely simulate automation surprise subjects must be totally unaware of what is happening; this effect is lost the first time subjects experience the transition.

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Appendix A

Supplemental Figures

Table A.1: LOA within the OODA information processing model[21]

Level	**Description**			
	Observe	Orient	Decide	Act
1	The human is the only source for gathering and monitoring (defined as filtering, prioritizing, and understanding) all data	The human is responsible for analyzing all data, making predictions, and interpretation of the data.	The computer does not assist in or perform ranking tasks. Human must do it all	The human alone can execute decision.
2	The human is the prime source for gathering and monitoring all data, with computer backup.	The human is the source of analysis and predictions, with computer verification when needed. The human is responsible for interpretation of the data.	The human performs all ranking tasks, but the computer can be used as a tool for assistance.	The human is the prime source of execution, with computer backup for contingencies (e.g. deconditioned humans).
3	The computer is responsible for gathering and displaying unfiltered, unhighlighted, and unprioritized information for the human. The human is the prime monitor for all information.	The computer is the source of analysis and predictions as a calculator with human checks of the calculations. The human is responsible for interpretation of the data.	Both the human and the computer perform ranking tasks, the results from the human are considered prime	The computer executes decision after human grants authority-to-proceed. Human is backup for contingencies.
4	The computer is responsible for gathering the information for the human and for displaying all information. It highlights the relevant non-prioritized information for the user.	The computer analyzes the data and makes predictions as a trusted calculator. The human is responsible for interpretation of the data.	Both the human and the computer perform ranking tasks, the results from the computer are considered prime.	The computer allows the human a preprogrammed time-to-veto before execution. Human is backup for contingencies.
5	The computer is responsible for gathering the information for the human. It filters out the unhighlighted data and shows the remaining data in a non-prioritized fashion.	The computer overlays predictions with analysis and interprets the data. The human is the backup for interpreting the data in contingencies.	The computer performs ranking tasks. All results, including "why" decisions were made, are displayed to the human.	The computer allows the human a context-dependent time-to-veto before execution. Human is backup for contingencies.
6	The computer gathers, filters, and prioritizes information display to the human.	The computer overlays predictions with analysis and interprets the data. The human is shown all results for potential override.	The computer performs ranking tasks and displays a reduced set of ranked options while displaying "why" decisions were made to the human.	The computer executes automatically, informs the human, and allows for override ability after execution. Human is backup for contingencies.
7	The computer gathers, filters, and prioritizes data without displaying any information to the human. Though, a "program functioning" flag is displayed.	The computer analyzes, predicts, interprets, and integrates data into a result which is only displayed to the human if result fits programmed context (context dependent summaries).	The computer performs final ranking and displays a reduced set of ranked options without displaying "why" decisions were made to the human.	The computer executes automatically and only informs the human if required by context. Override ability after execution is allowed.
8	The computer gathers, filters, and prioritizes data without displaying any information to the human.	The computer predicts, interprets, and integrates data into a result which is not displayed to the human.	The computer performs final ranking, but does not display results to the human.	The computer executes automatically and does not allow any human interaction.

Table A.2: Friedman ranking of averaged response time to the comm light probes 1-10 (n = 13)

Probe	**Rank Sum**
Probe 1	31.000
Probe 2	19.000
Probe 3	28.000
Probe 4	101.000
Probe 5	108.000
Probe 6	93.000
Probe 7	97.000
Probe 8	80.000
Probe 9	76.000
Probe 10	82.000

Table A.3: Friedman pair-wise comparisons of averaged response times to comm light probes (n = 13)

Probe	**Compared to:**	**Statistic**	**p-value**	**(p < 0.05)**
Probe 1	Probe 2	1.371	0.173	
	Probe 3	0.343	0.732	
	Probe 4	7.998	0.000	**Yes**
	Probe 5	8.798	0.000	**Yes**
	Probe 6	7.084	0.000	**Yes**
	Probe 7	7.541	0.000	**Yes**
	Probe 8	5.599	0.000	**Yes**
	Probe 9	5.142	0.000	**Yes**
	Probe 10	5.827	0.000	**Yes**
Probe 2	Probe 3	1.028	0.306	
	Probe 4	9.370	0.000	**Yes**
	Probe 5	10.169	0.000	**Yes**
	Probe 6	8.455	0.000	**Yes**
	Probe 7	8.913	0.000	**Yes**
	Probe 8	6.970	0.000	**Yes**
	Probe 9	6.513	0.000	**Yes**
	Probe 10	7.199	0.000	**Yes**
Probe 3	Probe 4	8.341	0.000	**Yes**
	Probe 5	9.141	0.000	**Yes**
	Probe 6	7.427	0.000	**Yes**
	Probe 7	7.884	0.000	**Yes**
	Probe 8	5.942	0.000	**Yes**
	Probe 9	5.485	0.000	**Yes**
	Probe 10	6.170	0.000	**Yes**

Table A.4: Friedman ranking of averaged response time to the comm light probes 4-10 (n = 13)

Probe	**Rank Sum**
Probe 4	62.000
Probe 5	69.000
Probe 6	54.000
Probe 7	58.000
Probe 8	41.000
Probe 9	37.000
Probe 10	43.000

Table A.5: Friedman pair-wise comparisons of averaged response times to comm light probes 4-10 (n = 13)

Probe	Compared to:	Statistic	p-value	($p < 0.05$)
Probe 4	Probe 5	0.675	0.502	
	Probe 6	0.771	0.443	
	Probe 7	0.385	0.701	
	Probe 8	**2.024**	**0.047**	**Yes**
	Probe 9	**2.409**	**0.019**	**Yes**
	Probe 10	1.831	0.071	
Probe 5	Probe 6	1.446	0.153	
	Probe 7	1.060	0.293	
	Probe 8	**2.698**	**0.009**	**Yes**
	Probe 9	**3.084**	**0.003**	**Yes**
	Probe 10	**2.506**	**0.014**	**Yes**
Probe 6	Probe 7	0.385	0.701	
	Probe 8	1.253	0.214	
	Probe 9	1.638	0.106	
	Probe 10	1.060	0.293	
Probe 7	Probe 8	1.638	0.106	
	Probe 9	**2.024**	**0.047**	**Yes**
	Probe 10	1.446	0.153	
Probe 8	Probe 9	0.385	0.701	
	Probe 10	0.193	0.848	
Probe 9	Probe 10	0.578	0.565	

Table A.6: Friedman ranking of average comm light response times by probe and Control Mode (n = 13). (SA = Single-axis RCAH in pitch, TA = Triple-axis RCAH, TA-ROD = Triple-axis RCAH with incremental rate-of-descent.)

Friedman Rankings		Rank Sums						
df = 2		Probe 4	Probe 5	Probe 6	Probe 7	Probe 8	Probe 9	Probe 10
Friedman Statistic		*4.145*	*5.692*	*3.846*	***9.385***	***6.000***	***7.176***	*8.000*
p-value		*0.125*	***0.058***	*0.146*	***0.009***	***0.050***	***0.028***	*0.308*
Mode	SA	20.000	19.000	21.000	**21.000**	**21.000**	**19.500**	18.000
	TA	29.000	29.000	26.000	**22.000**	**24.000**	**25.500**	28.000
	TA-ROD	29.000	30.000	31.000	**35.000**	**33.000**	**33.000**	32.000

Table A.7: Friedman pair-wise comparisons of the average response times in each Control Mode for each comm light probe (n = 13). (SA = Single-axis RCAH in pitch, TA = Triple-axis RCAH, TA-ROD = Triple-axis RCAH with incremental rate-of-descent.)

Mode	Compared to:	p-values						
		Probe 4	Probe 5	Probe 6	**Probe 7**	**Probe 8**	**Probe 9**	Probe 10
SA	TA	0.077	0.043	0.318	**0.816**	**0.525**	**0.192**	0.033
SA	TA-ROD	0.077	0.028	0.052	**0.003**	**0.017**	**0.006**	0.004
TA	TA-ROD	1.000	0.833	0.318	**0.005**	**0.065**	**0.107**	0.374

Table A.8: Friedman ranks of the average percent callouts made by time-sequence (n =13).

Callout	Rank Sum	Callout	Rank Sum
450 ft	237.000	175 ft	115.500
400 ft	229.500	150 ft	132.000
350 ft	230.500	Hazard 3	109.000
Hazard 1	214.000	140 ft	88.000
7% Fuel	189.500	5% Fuel	45.500
300 ft	229.500	130 ft	137.500
250 ft	158.500	120 ft	175.500
225 ft	30.000	110 ft	182.500
200 ft	80.000	100 ft	170.500
Hazard 2	116.500	4% Fuel	94.000
6% Fuel	38.000		

Table A.9: Friedman pair-wise comparisons of 300 ft callout (n = 13)

Probe	**Compared to:**	**Statistic**	**p-value**	**(p < 0.05)**
300 ft	450 ft	0.407	0.684	
	400 ft	0.000	1.000	
	350 ft	0.054	0.957	
	Hazard 1	0.842	0.401	
	7% Fuel	2.173	0.031	**Yes**
	250 ft	3.856	0.000	**Yes**
	225 ft	10.835	0.000	**Yes**
	200 ft	8.120	0.000	**Yes**
	Hazard 2	6.137	0.000	**Yes**
	6% Fuel	10.401	0.000	**Yes**
	175 ft	6.192	0.000	**Yes**
	150 ft	5.295	0.000	**Yes**
	Hazard 3	6.545	0.000	**Yes**
	140 ft	7.685	0.000	**Yes**
	5% Fuel	9.994	0.000	**Yes**
	130 ft	4.997	0.000	**Yes**
	120 ft	2.933	0.004	**Yes**
	110 ft	2.553	0.011	**Yes**
	100 ft	3.204	0.002	**Yes**
	4% Fuel	7.359	0.000	**Yes**

Table A.10: Friedman results of the effect of LPR on the percent callouts made (n = 13)

Friedman Results		Callout Rank Sum		
df = 2		250 ft	225 ft	200 ft
Friedman Statistic		*4.500*	*7.364*	*5.333*
p-value		*0.034*	*0.007*	*0.021*
Redesignation	No LPR	22.500	24.000	23.500
	LPR	16.500	15.000	15.500

Table A.11: Friedman results of the effect of LPR on the percent callouts made after the transition (n = 13)

No Redesignation				Redesignation			
Probe No.	Compared to	Statistic	p-value	Probe No.	Compared to	Statistic	p-value
250 ft	225 ft	6.663	0.0005	250 ft	225 ft	6.582	0.0005
	200 ft	2.473	0.018		200 ft	3.118	0.004

Table A.12: Friedman rankings of mode for percent callouts made (n = 13). (SA = Single-axis RCAH in pitch, TA = Triple-axis RCAH, TA-ROD = Triple-axis RCAH with incremental rate-of-descent.)

Callout	250 ft	225 ft	200 ft	Hazard 2	6% Fuel	175 ft	150 ft	Hazard 3	140 ft	5% Fuel	130 ft
Statistic	*8.629*	*7.818*	*7.875*	*3.511*	*15.167*	*21.565*	*14.244*	*7.511*	*4.409*	*14.913*	*13.064*
p-value	*0.013*	*0.020*	*0.019*	*0.173*	*0.001*	*0.0005*	*0.001*	*0.023*	*0.110*	*0.001*	*0.001*
SA	21.500	32.000	32.000	29.500	36.000	36.000	34.000	33.500	30.000	33.000	34.500
TA	23.500	27.000	27.500	27.500	25.000	28.000	27.000	22.000	27.500	29.500	26.500
TA-ROD	33.000	19.000	18.500	21.000	17.000	14.000	17.000	22.500	20.500	15.500	17.000

Table A.13: Pair-wise comparisons of mode rankings for average percent callouts made (n =13). (SA = Single-axis RCAH in pitch, TA = Triple-axis RCAH, TA-ROD = Triple-axis RCAH with incremental rate-of-descent.)

Mode	Compared to:	250 ft		225 ft		200 ft	
		Statistic	p-value	Statistic	p-value	Statistic	p-value
SA	TA	0.562	0.579	1.225	0.233	1.057	0.301
SA	TA-ROD	3.231	0.004	3.184	0.004	3.171	0.004
TA	TA-ROD	2.669	0.013	1.960	0.062	2.114	0.045

Table A.14: Pair-wise comparisons of mode rankings for average percent callouts made (n =13). (SA = Single-axis RCAH in pitch, TA = Triple-axis RCAH, TA-ROD = Triple-axis RCAH with incremental rate-of-descent.)

Mode	Compared to:	6% Fuel		175 ft		150 ft		Hazard 3	
		Statistic	p-value	Statistic	p-value	Statistic	p-value	Statistic	p-value
SA	TA	3.342	0.003	3.881	0.001	2.209	0.037	2.762	0.011
SA	TA-ROD	5.773	0.000	10.672	0.0005	5.365	0.0005	2.642	0.014
TA	TA-ROD	2.431	0.023	6.791	0.0005	3.156	0.004	0.120	0.905

Table A.15: Pair-wise comparisons of mode rankings for average percent callouts made (n =13). (SA = Single-axis RCAH in pitch, TA = Triple-axis RCAH, TA-ROD = Triple-axis RCAH with incremental rate-of-descent.)

Mode	Compared to:	5% Fuel		130 ft	
		Statistic	p-value	Statistic	p-value
SA	TA	1.074	0.294	2.248	0.034
SA	TA-ROD	5.369	0.000	4.917	0.000
TA	TA-ROD	4.295	0.000	2.669	0.013

Table A.16: Friedman test of subject rankings of gracefulness (n = 12).

Run Type	Rank Sum
SA, No LPR	12.000
TA, No LPR	27.000
TA-ROD, No LPR	51.000
SA, LPR	36.000
TA, LPR	54.000
TA-ROD, LPR	72.000

Table A.17: Friedman test pair-wise comparisons of run types for subject rankings (n = 12).

Run Type	Compared to:	Statistic	p-value
SA, No LPR	TA, No LPR	5.142	0.000
SA, No LPR	TA-ROD, No LPR	13.370	0.000
SA, No LPR	SA, LPR	8.228	0.000
SA, No LPR	TA, LPR	14.398	0.000
SA, No LPR	TA-ROD, LPR	20.569	0.000
TA, No LPR	TA-ROD, No LPR	8.228	0.000
TA, No LPR	SA, LPR	3.085	0.003
TA, No LPR	TA, LPR	9.256	0.000
TA, No LPR	TA-ROD, LPR	15.427	0.000
TA-ROD, No LPR	SA, LPR	5.142	0.000
TA-ROD, No LPR	TA, LPR	1.028	0.308
TA-ROD, No LPR	TA-ROD, LPR	7.199	0.000
SA, LPR	TA, LPR	6.171	0.000
SA, LPR	TA-ROD, LPR	12.341	0.000
TA, LPR	TA-ROD, LPR	6.171	0.000

Appendix B

Case Study: The Crown Princess

B.1 General Description

The following case study refers to the Heeling Accident of the *Crown Princess* in the Atlantic Ocean off of Port Canaveral, FL on July 18th, 2006 [45, 137]. The cruise ship *Crown Princess* heeled at a maximum angle of about 24 degrees due to a number of factors, chiefly being misguided input from the 2nd officer into control system that was too slow to respond. These control inputs followed the disengagement of the ship's autopilot, which was operating in a regime unsuited for its operational environment. No casualties were sustained in this accident.

The following instances of mode transitions were identified and analyzed within this case study:

1. Transition from manual steering to heading mode in the trackpilot by the captain.
2. Change in status of the 2nd officer from monitoring to supervising.
3. Transition back to manual steering from heading mode by the 2nd officer

B.2 Transition Case 1

The NTSB report describes that on orders from the captain, the crew engaged the trackpilot (the autopilot) function of the vessel's integrated navigation system (INS). This is the transition which will be considered here.

B.2.1 The Modes

Sheridan & Verplank LOA

The mode transition being considered here is one between manual steering and autopilot (specifically heading mode, or NACOS-1 as referred to by the Crown Princess crew). Heading mode, aside from having several parameters, such as rudder limit and rudder economy, maintained the input heading from the crew. This manual steering would be classified as a level 1 on the Sheridan and Verplank scale [14]. Essentially, the NACOS-1 system was functioning at level 7 on the Sheridan and Verplank scale; however, given the very slow nature of cruise liner control, it could be considered a level 6 on the Sheridan and Verplank scale. This mode switch is shown in Figure B.1 and Table B.1.

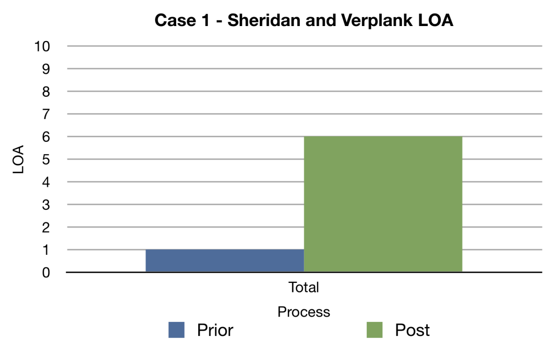


Figure B.1: Crown Princess Transition Case: Sheridan and Verplank Scales

Table B.1: Case 1 - Sheridan and Verplank LOA

Case 1 - Sheridan and Verplank LOA	
Prior	*Post*
1	6

Proud and Hart LOA

In terms of the levels of automation as suggested by Proud and Hart [21], the modes can be considered in terms of four separate functions: observe, orient, decide, act. These levels of automation can be assigned based on the descriptions provided by Schuffel [138] of bridge operations in the the 1990's.

Based on the OODA model, the following levels can be described within the transition:

Observe Phase - Prior to this transition, the system was operating at Level 7 via the NACOS system trackpilot. Out the window information was still available, allowing for two parallel observing processes to be taking places; however, with respect to the navigation task, the information which was being used as all handled at Level 7. Following the transition, the system began to operate at Level 4, in which the human became much more heavily involved in the observation of utilized information.

Orient Phase - Prior to the transition, the system was operating at Level 7, in which the result was displayed but rationale was suppressed. Following the transition, the system was operating at Level 3, in which the computer integrated the information visually integrated the information using displays for the human to use.

Decide Phase - Prior to the transition the system was operating at Level 7, in which selections were displayed but reasons were suppressed. Following the transition, the system was operating at Level 1, in which the operator (the 2nd officer) was now in charge of all decisions.

Act Phase - Prior to the transition, the system was operating at Level 7, in which the operator had override capability only. By exercising this override capability, the user reverted to Level 1, in which they were solely responsible for all actions of the system via gain mediation through the computer.

These OODA levels are shown in Figure B.2 and Table B.4

Table B.2: Case 1 - Proud and Hart LOA

Case 1 - Proud and Hart LOA							
Observe		Orient		Decide		Act	
Prior	Post	Prior	Post	Prior	Post	Prior	Post
4	7	3	7	1	7	1	7

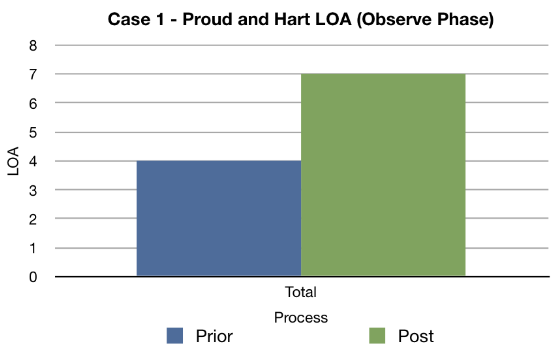
B.2.2 The Trigger

The major triggers seen here was the mission goals and procedures. Having cleared port and reached open water, it was standard for the activation of the NACOS system for autonomous navigation. This can be summarized then as follows:

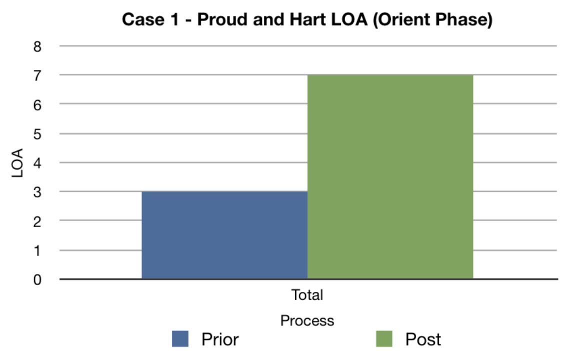
- Goals and Procedures
- Environment State
- Performance of Actions

Goals and Procedures - These called for the switch to automatic navigation on reaching open water.

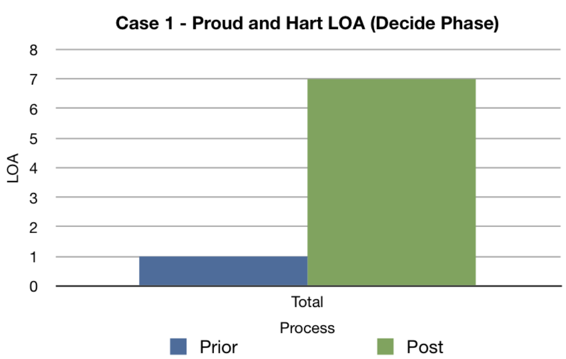
Environment State - This provided the conditions which the procedures specified.



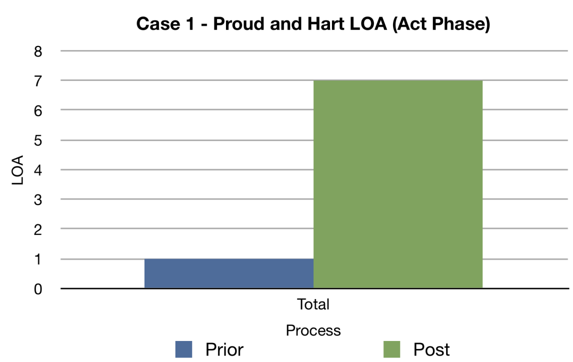
(a) Observe



(b) Orient



(c) Decide



(d) Act

Figure B.2: Case 1 - Proud and Hart LOA

Performance of Actions - While the procedures and the environment state suggested the transition, it still fell to the human to make the transition.

See Figure B.3 for an illustration.

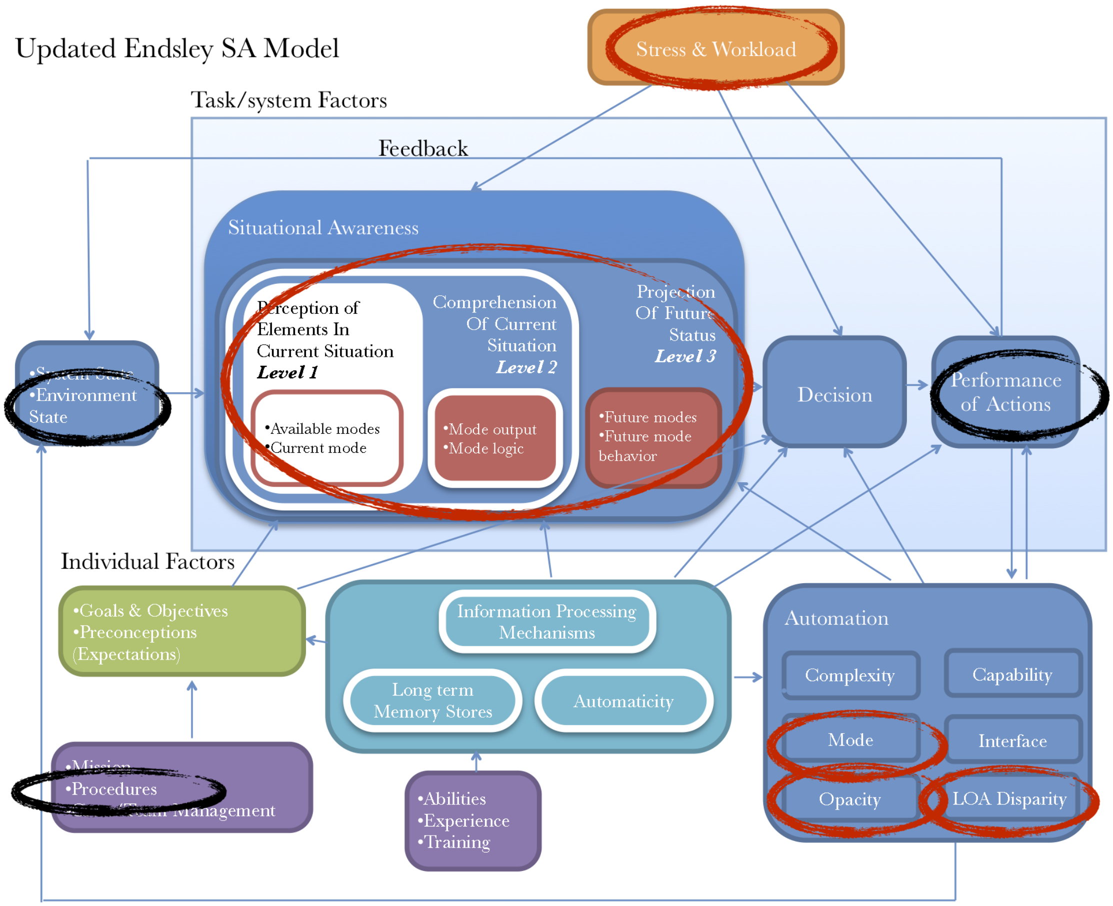


Figure B.3: Case 1 - Factors

B.2.3 Factors, Mechanisms, and Design Lessons

Factors in the Transition

This transition was quite graceful, in that situation awareness was not immediately or discernibly lost, workload did not increase or decrease in excess, and performance was maintained. Hence, all factors influencing this transition can be seen as positively influencing this transition. The following are particularly noticeable and can be considered in contrast with other ungraceful transitions:

- Stress & Workload
- LOA Disparity
- Automation Opacity
- Mode
- General SA
- Mode SA

Stress & Workload - During this transition the stress and workload were quite manageable by the operator and were kept at levels that did not detrimentally affect the transition.

LOA Disparity - While the transition was over a relatively large direction, it was in a positive direction (from low automation to high automation). This directionality in the transition is inherently easier, because the human is starting with what might be consider and excess of involvement in maintaining SA and performance. Unless stress and workload are sufficiently high at the time of such a transition, it is unlikely that these will be can a immediately loss of either of these quantities.

Automation Opacity - As the operation was manual prior to the transition, the operator was intimately aware of how the automation was acting and what it was acting on. Hence, in entering a new mode, there was little opacity in the "automation" prior to the transition; the operator new on what it was acting and how it was acting.

Mode - The mode being transitioned to requires significantly less workload in operating.

General SA - The operator knew what the situation was in which they were operating.

Mode SA - The operator knew the way in which the system would behave following the transition and had a knowledge the way in which it accomplished this (this will not be the case in a future transition case).

See Figure B.3 for an illustration.

Mechanisms of Gracefulness
The transition, as mentioned previously, was a graceful one. Therefore it is impossible to identify any one mechanisms as contributing significantly to the gracefulness observed. The entire mechanisms model functioned correctly.

Design Principles and Lessons
From this transition case, the following design lessons can be learned:

- Operator understanding of the prior mode of operation is just as important as understand the mode into which they are transitioning. In understanding the states currently being controlled by the mode, the operator can more easily determine the changes that will be forced during the transition and what processes he or she will be required to drop, take on, or maintain.
- The disparity of levels of automation most likely have a more detrimental effect when the direction is negative, i.e. moving from a high level of automation to a lower level of automation.
- Low stress and workload levels enable, but do not explicitly cause, graceful transitions.

B.3 Transition Case 2

The NTSB reports that the captain turned the conn over to the second officer. While this is not a mode transition in terms of the automation, it is a subjective mode change from the vantage point of 2^{nd} officer. The 2^{nd} officer essentially switched from a fully automatic mode where the system (ie. the ship and captain system) was performing the task to a supervisory mode, where he was monitoring and intervening if necessary.

B.3.1 The Modes

Sheridan and Verplank LOA

This transition, as stated above, involves the switch from fully automatic (what would be considered a Level 10 by Sheridan and Verplank) to slightly lower level of Supervisory Control, roughly being an 8 on the Sheridan and Verplank scale. This transition is illustrated in Figure B.4 and Table B.3.

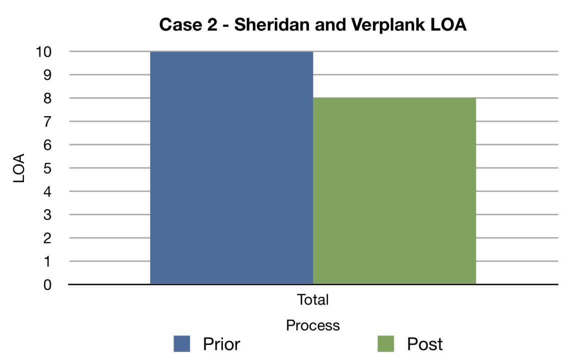


Figure B.4: Case 2 - Sheridan and Verplank LOA

Table B.3: Case 2 - Sheridan and Verplank LOA

Case 2 - Sheridan and Verplank LOA	
Prior	*Post*
10	8

Proud and Hart LOA
The following levels based off of Proud and Hart can be observed in this transition:

Observe Phase - Prior to the transition, the 2^{nd} officer was operating, relative to the system, at Level 6, as any information which he was made aware of was highly filtered by the system before it presented it. When he was put in charge he assumed the LOA which the captain had been functioning at now for some time, which was Level 7. The operator was always immersed in the environment and had cues other than the automation.

Orient Phase - The 2^{nd} officer before the transition is seen to have been operating at Level 7, as only context dependent summaries were being received. Following the transition, this remained the case.

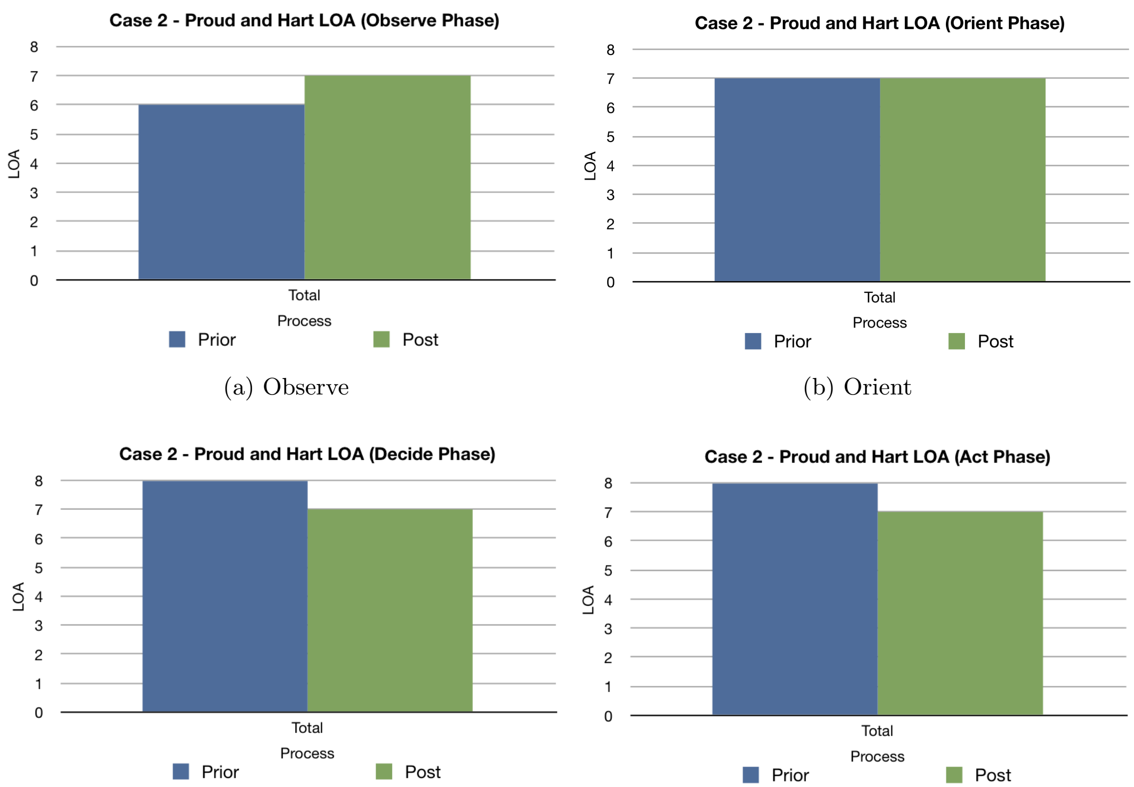
Decide Phase - The system was operating at Level 8 before the transition, as none of the decisions were being displayed to the second officer. Following the transition, the system was operating in the realm of Level 7, in which the computer's solution was displayed without any rationale.

Act Phase - Prior to the transition, the system was operating with respect to the 2^{nd} officer at Level 8, with absolutely no control interaction. Following the transition, the system began to operate at Level 7 with respect to the 2nd officer, giving him override capability.

The OODA transition levels are illustrated in Figure B.5 and Table B.4.

Table B.4: Case 2 - Proud and Hart LOA

Case 2 - Proud and Hart LOA							
Observe		Orient		Decide		Act	
Prior	Post	Prior	Post	Prior	Post	Prior	Post
6	7	7	7	8	7	8	7



(a) Observe (b) Orient

(c) Decide (d) Act

Figure B.5: Case 2 - Proud and Hart LOA

B.3.2 The Trigger

This transition occurred on the order of the captain, who was now going off duty. The captain, who had been acting as the supervisor called for the system now required that the 2^{nd} officer take the conn. If the analog is drawn to the ship and captain as an automated system, the system reached a state where it required certain amount of involvement from the operator. Hence the following can be summarized has having been involved in triggering this transition:

- Crew/Team Management

Crew/Team Management - The crew/team management was the major triggering mechanisms of this “mode transition”. As one member of the team left the bridge the other took over those functions, effecting the transition.

See Figure B.6 for an illustration.

B.3.3 Factors, Mechanisms, and Design Lessons

Factors in the Transition

This transition was particularly graceful as well, hence only the major factors seen as worthy of note are will be considered:

- Stress & Workload
- LOA Disparity
- System State
- Environment State
- General SA
- Mode SA

Stress & Workload - Both of these were manageable, allowing for the officer to effectively handle jumping into the loop and fulfilling his control input requirements.

LOA Disparity - The number of LOA that were traversed in this transition was relatively low, even though it was in the negative direction. Hence, at these levels and given the other surrounding circumstances, it can be concluded that such transitions can be accomplished with reasonable gracefulness. Such a conclusion would only hold for a situation of comparable control loops: an aviation analog would be difficult as there are significantly more loops being controlled in that application.

System State - The system reaching a state which was manageable enabled this mode transition. The bridge officer leaving would not have occurred until the system was in a state which was able to be easily handed over to the next operator.

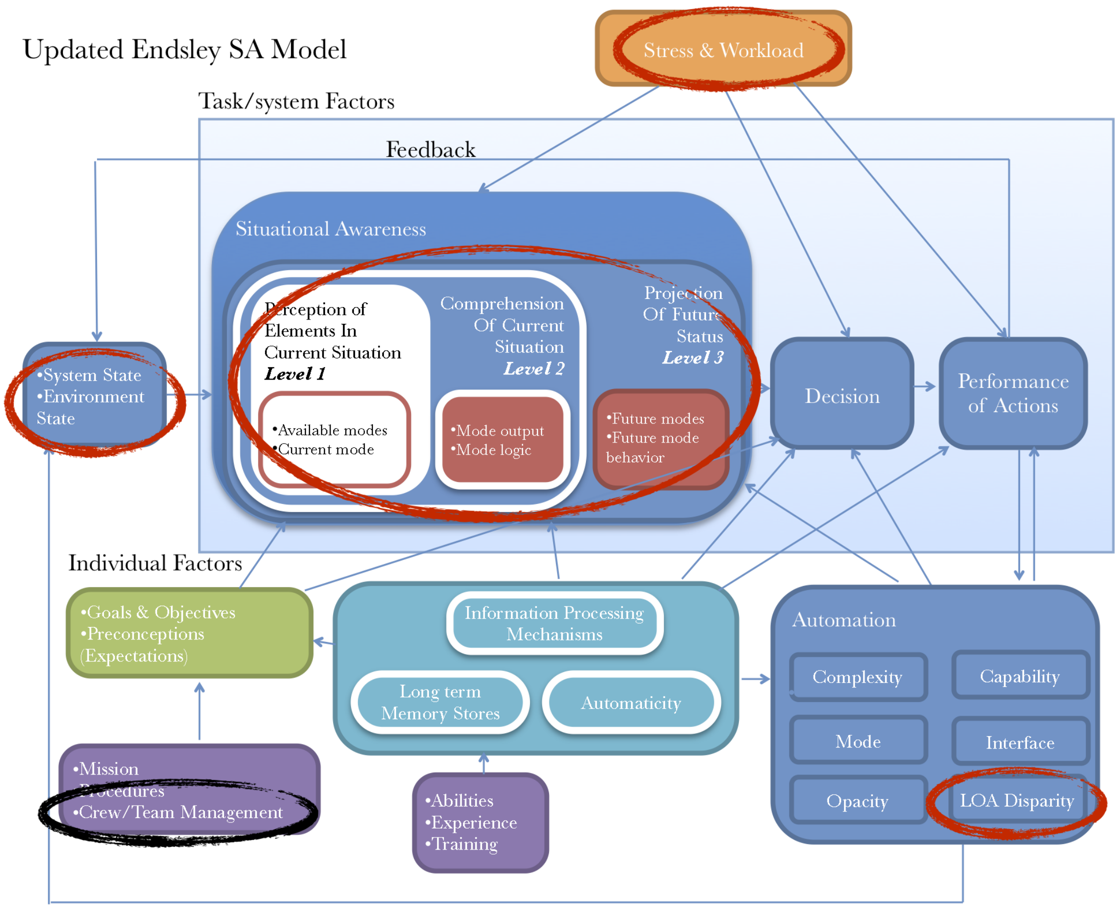


Figure B.6: Factors in The Crown Princess Transition Case 2

Environment State - In the same manner, the environment state allowed for this transition to take place: no significant stressors were present during the transition. This is worthy of note, as it is the habit of a human operator to obtain a graceful transition; the system state and environment state as enablers then suggests these as major factors in allowing for graceful transitions.

General SA - The operator knew the situation into which he was being inserted that he was able to adequately make the transition in a graceful fashion.

Mode SA - The operator also understood the mode in which he was operating and would be operating. This also enabled a graceful transition.

See Figure B.6 for an illustration.

Mechanisms of Gracefulness
Again, as with the first transition case, none of the mechanisms within the Endsley model can be picked out easily. All functions in the model are functioning in an adequate capacity. A major enabling of this is that attention resources are adequate for all process; this is only an enabling factor and not a cause.

Design Principles and Lessons
From this transition, the following can be learned for future automation architecture design:

- The preferred method of transition by operators is when the handoff takes place in a stable situation. While this seems rather obvious at first glance, such a principle is violated often. One such case will be seen as blatant within the STS-3 PIO case study. Additionally, operators wait until the last minute to begin a mode transition, when the system has already exceeded such bounds. Hence, if this were perceived as a future possibility, beginning the transition at the early stages would improve the gracefulness of at transition.

B.4 Transition Case 3

The NTSB report on the *Crown Princess* accident states that "At 1524, the 2^{nd} officer disengaged the trackpilot and, because he was closer to the wheel than either of the helmsmen, took manual control of the steering." Immediately following this transition, the 2^{nd} officer made a control input in the wrong direction, which worsened the situation. It is this transition that will be considered here.

B.4.1 The Modes

Sheridan and Verplank LOA

The transition was one from a relatively high level of automation to that of manual steering, where the 2nd officer was directly controlling the ship, albeit via hydraulics. The mode which the operator began in was level 8 and moved directly to level 1. This can be seen in Figure B.7 and Table B.5.

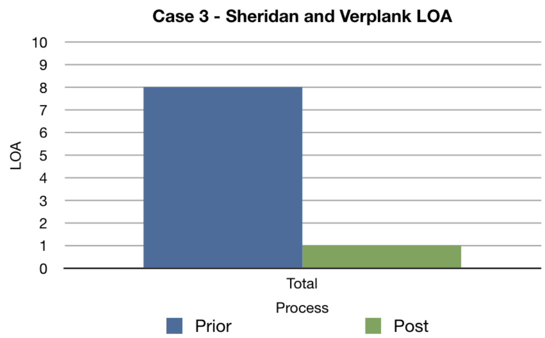


Figure B.7: Case 3 - Sheridan and Verplank LOA

Table B.5: Case 3 - Sheridan and Verplank LOA

Case 3 - Sheridan and Verplank LOA	
Prior	*Post*
8	1

Proud and Hart LOA

Based on the OODA model, the following levels can be described within the transition:

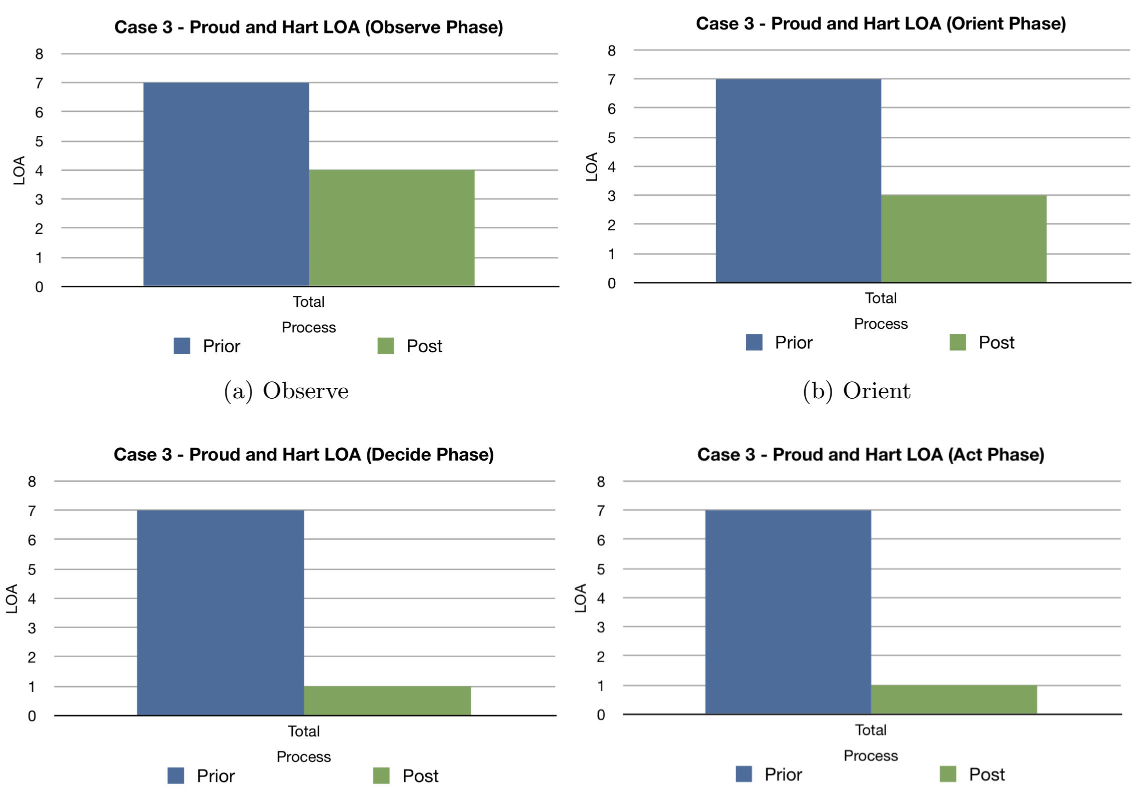
Observe Phase - Prior to this transition, the system was operating at Level 7 via the NACOS system trackpilot. Out the window information was still available, allowing for two parallel observing processes to be tak place; however, with respect to the navigation task, the information which was being used was all handled at Level 7. Following the transition, the system began to operate at Level 4, in which the human became much more heavily involved in the observation of utilized information.

Orient Phase - Prior to the transition, the system was operating at Level 7, in which the result was displayed but rationale was suppressed. Following the transition, the system was operating at Level 3, in which the computer integrated the information visually using displays.

Decide Phase - Prior to the transition the system was operating at Level 7, in which selections were displayed but reasons were suppressed. Following the transition, the system was operating at Level 1, in which the operator (the 2nd officer) was now in charge of all decisions.

Act Phase - Prior to the transition, the system was operating at Level 7, in which the operator had override capability only. By exercising this override capability, the user transitioned to Level 1, in which they were solely responsible for all actions of the system via gain mediation through the computer.

The OODA transition levels are illustrated in Figure B.8 and Table B.6.



(a) Observe

(b) Orient

(c) Decide

(d) Act

Figure B.8: Case 3 - Proud and Hart LOA

B.4.2 The Trigger

In this case the 2nd officer disengaged the autopilot because he needed to regain control of a syste, which he had determined was no longer in control of itself. The NTSB report

Table B.6: Case 3 - Proud and Hart LOA

Case 3 - Proud and Hart LOA							
Observe		Orient		Decide		Act	
Prior	Post	Prior	Post	Prior	Post	Prior	Post
7	4	7	3	7	1	7	1

supports this. In reference to his decision to revert to manual control the second officer is recorded as saying,"I just saw the rate of turn and instinct took over, I thought...we're going to be swinging to port really fast here and I've got to get hand steering... [to] try to stop the swinging."

Hence the following factors, based on the updated Endsley model, were identified as active during this mode:

- System State
- Automaticity
- General SA (All Levels)
- Performance of Actions
- Automation Capability

System State - The system state going out of bounds was the origin of the transition trigger. Had this not gone into such an extreme off-nominal state, the operator would not have made the transition to a manual mode.

Automaticity - The reaction of the 2nd officer was an automatic response; it wasn't extremely thought out, but was more along the lines of "any manual input is better than this."

General SA (All Levels) - The operator's understanding of the overall situation, while obviously inadequate because of his erroneous input, was adequate enough to allow for him to sense and comprehend the states of the system and its environment as requiring intervention.

Performance of Actions - As this was an operator implemented transition (not an scripted control transition), the performance of actions was the active trigger of the transition (it originated from system states and was realized by the performance of an action.

Automation Capability - The cause of the off-nominal system states was the incapability of the automation to deal with the state of the environment based on its current parameters.

See Figure B.9 for an illustration.

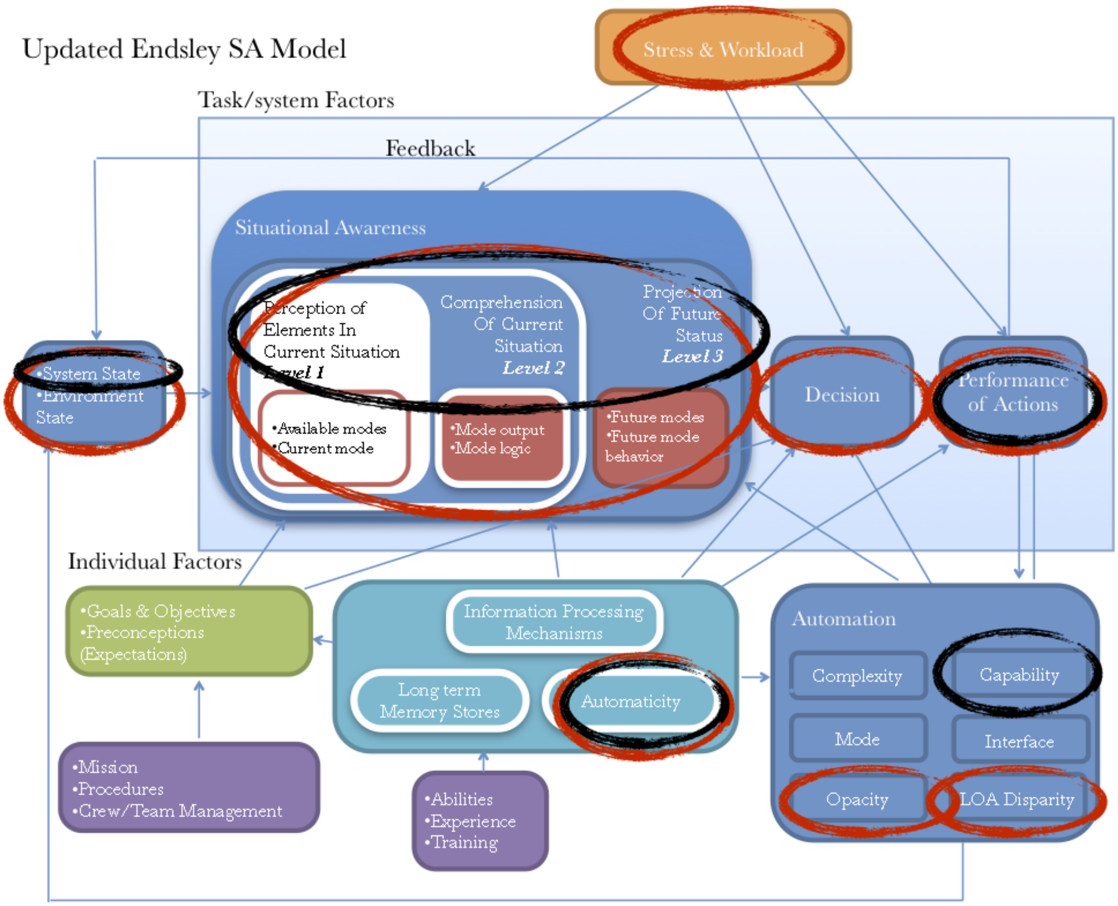


Figure B.9: Factors in The Crown Princess Transition Case 3

B.4.3 Factors, Mechanisms, and Design Lessons

Factors in the Transition

Based on the updated Endsley model of factors influencing SA, the following factors were identified as active during this transition:

- Environment States
- System States

- General Situaitonal Awareness
- Mode Situaitonal Awareness
- Operator Automaticity
- Automation Opacity
- Stress & Workload
- Operator Decision
- Performance of Actions

Environment States - The unknown nature of the environment (shallow water effect) was what caused the automation to be incapable of effectively handling the situation. This was a significant stressor, allowing it to become uncontrollable more readily than in a nominal environment.

System States - The system states were highly dynamic, making it all the more difficult for the operator to gain an understanding of the internal variables for proper control intervention.

General SA - Aside from the ship being in a relatively extreme operating condition (shallow water effect), the operator was not aware of the this particular effect on operating requirements. Had this been known any control inputs would most likely have been tempered given the increased sensitivity of the system in such conditions.

Mode SA - The operator was unaware prior to the transition of why the automation was having difficulty controlling the system. This lack of basic mode SA (mode operation) may have biased the operator in a way that effected his first control input immediately following the transition.

Operator Automaticity - The operator's only concern was making some input, whatever that input may have been. In this case, the input was in the wrong direction, which only exacerbated an already bad situation. The operator's comments on his input, as well as the action itself, suggest that the input was purely an automatic reaction requiring no premeditation.

Stress & Workload - The stress and workload induced by the extreme operating environment and the oscillating system states in this case negatively effected the operator, pushing them to rely on "instinctual" reactions, rather than reasoned reactions.

Operator Decision - It is difficult to determine where the operator error was made: either in the decision making block or the performance of actions block. It is possible that the operator, based on inadequate situational awareness, high stress, high workload, and operator automaticity, made the wrong decision on what the initial control input ought to be. The wrong decision would have then effected the performance of actions block and significantly contributed to the gracelessness seen in this transition (loss of performance).

Operator Performance of Action - Conversely, it is possible that the operator made the correct decision but the wrong action was taken for whatever reason. This, again, would have led to the wrong control input and would have significantly contributed to the graceless seen here.

See Figure B.9 for an illustration.

Mechanisms of Gracefulness
Based on the updated Endsley model of mechanism in SA, the following mechanisms can be identified making this transition less than graceful:

- Attention Resources
- Action Guidance
- Mode Setting
- Schema
- Script
- Interpretation, Comprehension, and Projection
- Action Guidance

Attention Resources - Due to the extreme environment in which this transition took place, the operator was placed in charge of monitoring a large number of variables. This depleted the operator's attentional resources are removed his ability supply the transition process completely.

Action Guidance - By some effect, the wrong action was made, and this was either due to a wrong decision or the misapplication of a script based on the operators current schema. As this particular transition was described as an almost automatic reaction from the operator, it is most likely the misapplication of a script feeding into the action guidance block.

Mode Setting - This block, as well as perception, feeds into the Schema construct, which in this transition was most likely misapplied. As perception seems to have been functioning properly (the off-nominal case was recognized enough to trigger the transitions), Mode Setting is the most likely next source. It is quite quite possible that attention resources were not allocated adequately to allow the user to completely comprehend the required inputs to the computer for a particular action, suggesting a misapplication of an operator schema.

Schema - In some way, the operator misapplied the schema to the situation. The type of action was correct, how the direction and magnitude were incorrect.

Script - The misapplication of schema provide an incorrect scrip for driving the operators automatic response to the situation.

Interpretation, Comprehension, and Projection - Based on the perception of urgency of the situation and the current schema in use by the operator, this block was, in some senses, bypassed, allowing for an automatic reaction from the operator to be generated from the script construct (instinctual reaction). Had this block been utilized (i.e. had time-pressure not forced such a suppression) this transition may have been much more graceful.

Action Guidance - The flow down effect from all the other blocks resulted in the wrong action guidance.

See Figure B.10 for an illustration.

Design Principles and Lessons
From this transition case, the following design lessons can be learned

- Reduce the demands on attentional resources during any transition.
- It cases of high workload, stress, and time pressures, the decision making block can and will be bypassed by the operator script which is derived from his or her schema for the selected situation. This schema will be dependent upon (1) the operator, (2), their perception, and (3) the mode setting. In effect, their mental model of the situation will react to the situation in one of three ways: wrong action, right action, and no action. These three options are not equally weighted: the right action is often singular, as is the no action category, whereas their are a multitude of wrong actions. A system which can equalize the salience of these options, by highlighting a suggested action or warning against certain control actions prior to or during the transition would improve the gracefulness of a transition in the area of performance and situaitonal awareness.
- Reduced automation opacity (while a good principle to strive for in general) prior to a transition is extremely crucial. An operator who doesn't understand the processes which they are taking over and how the automation had been handling them to begin with will not be able to graceful transition into a new mode. Particularly in cases such as the one discussed here, if the automation is not able to control the situation it is important the operator know how the automation was attempting to control the situation so that they can adapt their control strategy accordingly.
- Large control inputs should not be required immediately at a transition, such as seen in this case. The salience of such a requirement disposes the operator to any kind of action, rather than first confirming control of the craft and then correcting any errors.

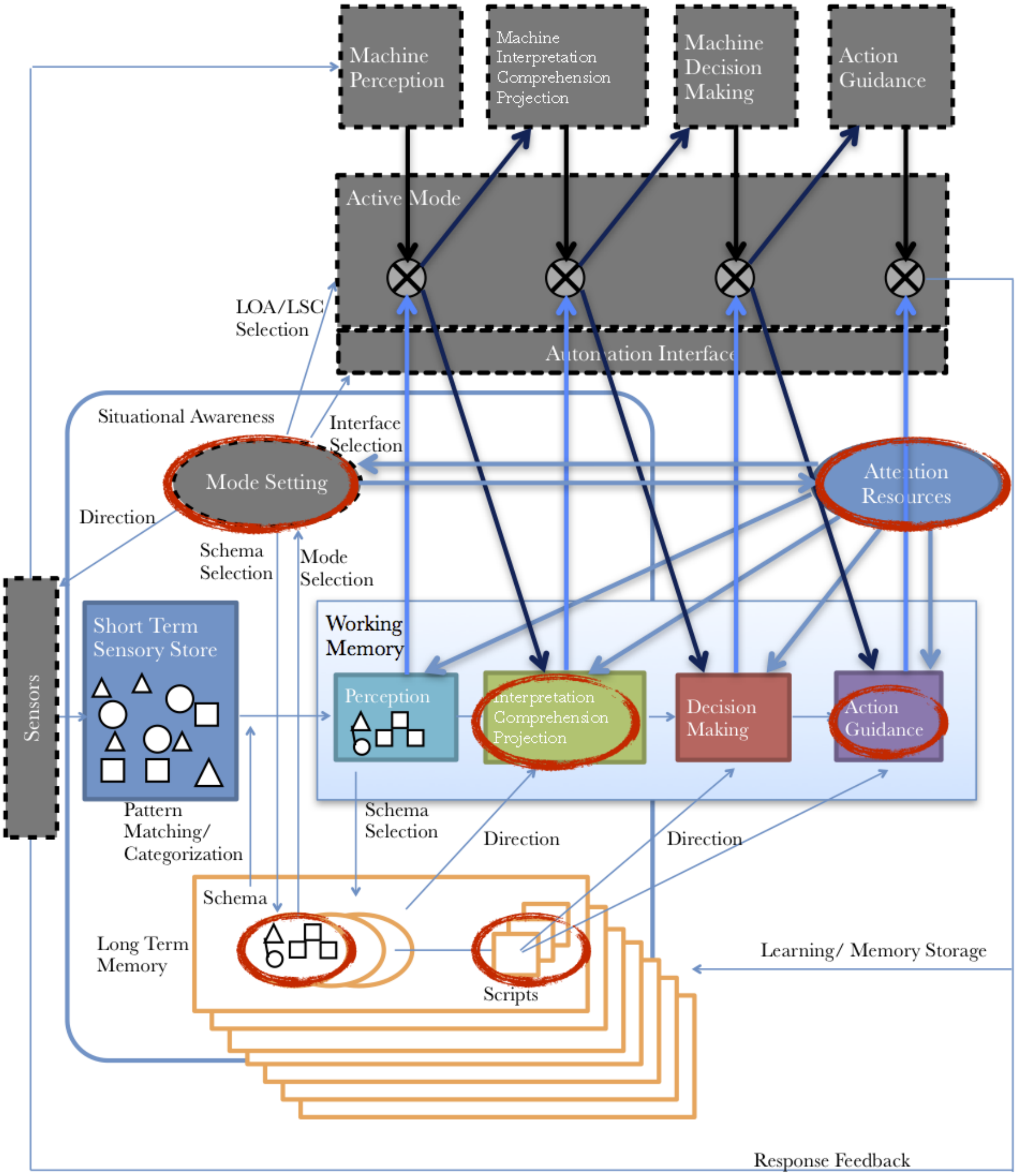


Figure B.10: Mechanisms in The Crown Princess Transition Case 3

Appendix C

Case Study: The Royal Majesty

C.1 General Description

As described in the NTSB report [46]:

> On June 10, 1995, the Panamanian passenger ship Royal Majesty grounded on Rose and Crown Shoal about 10 miles east of Nantucket Island, Massachusetts, and about 17 miles from where the watch officers thought the vessel was. The vessel, with 1,509 persons on board, was en route from St. George's, Bermuda, to Boston, Massachusetts.

The major cause of the accident was the result of a loss of GPS data input into the NACOS of the ship, resulting in a transition to Dead-Reckoning. The bridge crews' failure to observe this mode change, which had been caused by a disconnected cable, ultimately resulted in the NACOS steering the ship off course due to a lack of current, wind, and sea data.The following instances of transition were identified within this case study:

1. The navigator set the navigation and command system (NACOS) 25 on the navigation (NAV) mode
2. The transition of the position data from GPS to Dead Reckoning (DR) mode
3. The second officer switched from autopilot to manual when the *Royal Majesty* unexpectedly veered to port

C.2 Transition Case 1

The NTSB report [46] describes that "the NACOS 25 autopilot was engaged and operating in the NAV mode from the time the vessel departed St. George's (1400 on June 9) to before the grounding." Additionally, the report describes that "shortly after departure [the navigator] set the navigation and command system (NACOS) 25 autopilot on navigation (NAV) mode." No direct discussion could be found of the mode prior to the setting of the autopilot; however, if prior information on the operation of cruise liners is to be taken as standard, this mode would have been manual steering.

C.2.1 The Modes

Sheridan and Verplank LOA

This particular transition describes one from manual to the engagement of the NACOS 25 in NAV mode. Manual steering in this case can be considered level 1, perhaps level 2 or 3 depending on the interpretation of the operator interface. The NAV mode of the NACOS 25 automatically compensated for the effect of gyro errors, wind, current, and sea, while using programmed information (latitude and longitude of waypoints and the vessel's maneuvering characteristics), gyro and speed data, and position data from the GPS or the Loran-C, to steer the vessel along a preprogrammed track. Dekker [139] gives the explanation that the NAV mode "kept the ship within a certain distance of a track, and corrected for drift caused by wind, sea, and current." Such a mode would be considered a level 8 on the Sheridan and Verplank scale. The levels of automation are shown in Figure C.1 and Table C.1.

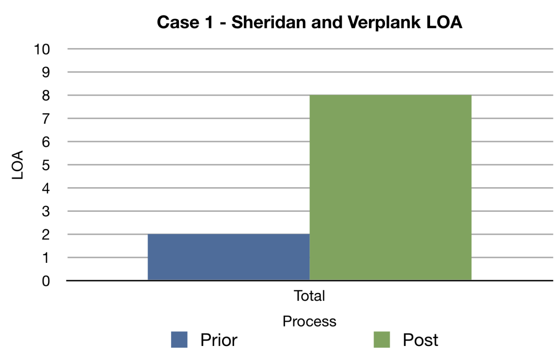


Figure C.1: Case 1 - Sheridan and Verplank LOA

Proud and Hart LOA

Based on the OODA model, the following levels can be described within the transition:

Table C.1: Case 1 - Sheridan and Verplank LOA

Case 1 - Sheridan and Verplank LOA	
Prior	*Post*
2	8

Observe Phase - Prior to the transition, the system was operating at a Level 4, as the navigation system presents a filtered picture of the environment based on the data perceived as pertinent by the system designer. Since the operator still has access to the out the window view, this filtering is not complete, hence this is only a level 4 and not a level 5. Following the transition, the system was operating at level 7 essentially. Level 7 suggests is described as “the computer gathers, filters, and prioritizes data without displaying information to the human. Though a ‘program functioning’ flag is display.” This is not entirely true, as the operator does have access to this information outside of just a “program functioning”; however, this is only when the human is actively seeking the information. otherwise to the knowledge of the human, the automation is either functioning or not. Hence, a more descriptive characterization would be a human-driven choice between a level 7 or level 6 at any given time.

Orient Phase - Prior to the transition, the system was operating at operating at Level 3, given that the human was responsible for all interpretation; however, there are some general predictions displayed to the human via the display consoles. Following the transition, the system was operating at Level 7.

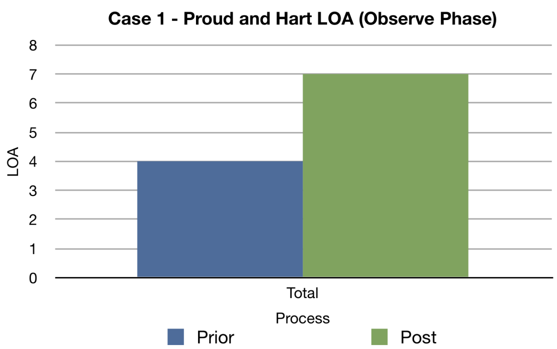
Decide Phase - Prior to the transition, the system was operating at Level 1. Following the transition, the system was operating at system was operating at level 8.

Act Phase - Prior to the transition, the system was operating at Level 1. Following the transition, the system was operating at Level 7.

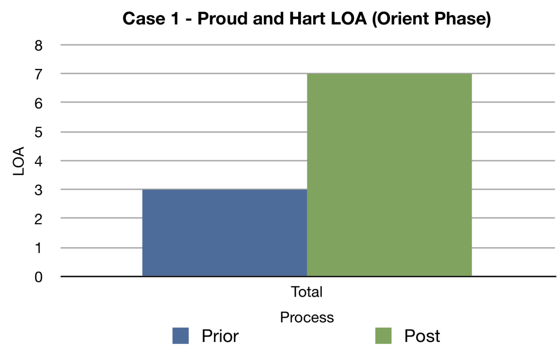
Thes levels are shown in Figure C.2 and Table C.2.

Table C.2: Case 1 - Proud and Hart LOA

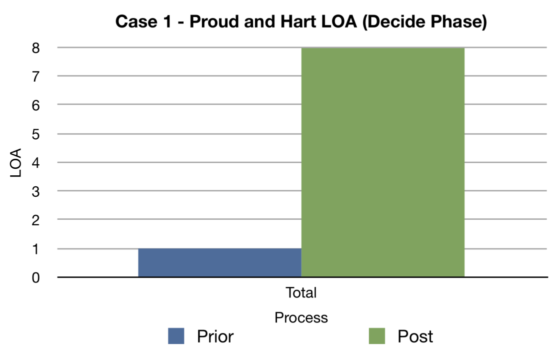
Case 1 - Proud and Hart LOA							
Observe		Orient		Decide		Act	
Prior	Post	Prior	Post	Prior	Post	Prior	Post
4	7	3	7	1	8	1	7



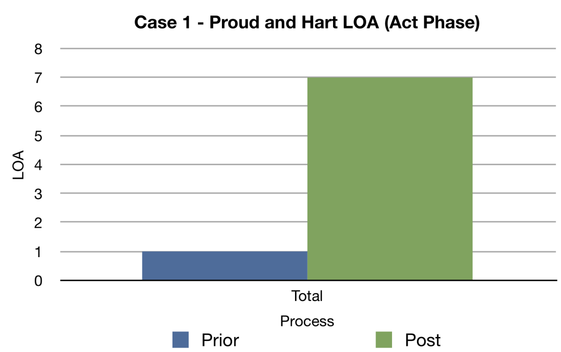
(a) Observe



(b) Orient



(c) Decide



(d) Act

Figure C.2: Case 1 - Proud and Hart LOA

C.2.2 The Trigger

This particular transition is almost identical to that which was described in Section B.2. Refer to this section for a full consideration of the triggering of such a transition.

C.2.3 Factors, Mechanisms, and Design Lessons

Factors in the Transition

This particular transition is almost identical to that which was described in Section B.2. Refer to this section for a full consideration of the factors involved in the transition.

Mechanisms of Gracefulness

This particular transition is almost identical to that which was described in Section B.2. Refer to this section for a full consideration of the mechanisms involved.

Design Principles and Lessons

This particular transition is almost identical to that which was described in Section B.2. Refer to this section for a full consideration of the particular lessons learned. The similarity suggests that this transition type may be quite common. The influence of mission procedures over mode transitions should not be underestimated or understated: used incorrectly it can lead to horribly ungraceful transitions. Used correctly, mission procedures could be large factor in enabling graceful transitions.

C.3 Transition Case 2

This NTSB report states that "the GPS receiver antenna cable connection had separated enough that the GPS switched to DR mode, and the autopilot, not programmed to detect the mode change and invalid status bits, no longer corrected for the the effects of wind, current, or sea."

C.3.1 The Modes

The modes involved here are encompassed within essentially the same autopilot mode; however, the position data source changed modes. On the surface it would appear that there was no traverse between the levels of automation as described by Sheridan and Verplank. The key to understanding the mode transition here lies in the report's note that "the mode no longer corrected for the effects of wind, current, or sea."

These corrections can be thought of as separate tasks from that of pure course navigation. Prior to the data source change, these all were being automatically controlled via GPS coordinates, effectively placing the automation at a level 8 on the Sheridan and Verplank scale. Following the data change, these tasks were reduced to a level near full manual. The closest level on the Sheridan and Verplank scale that would describe this is level 2, but this particular delineation seems to be lacking in specificity with respect to how such corrections are determined and made. These levels are illustrated in Figure C.3 and Table C.3.

Sheridan and Verplank LOA

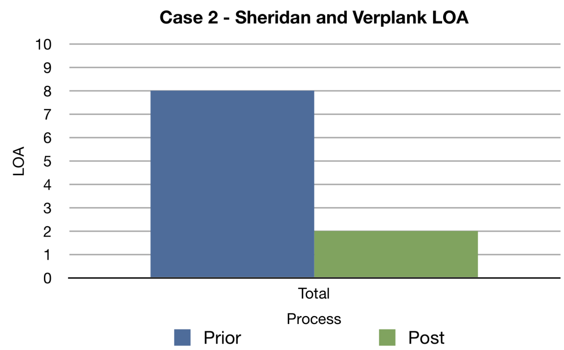


Figure C.3: Case 2 - Sheridan and Verplank LOA

Table C.3: Case 2 - Sheridan and Verplank LOA

Case 2 - Sheridan and Verplank LOA	
Prior	*Post*
8	2

Proud and Hart LOA
Using the Proud and Hart LOA, the following breakdown of the transition can be made:

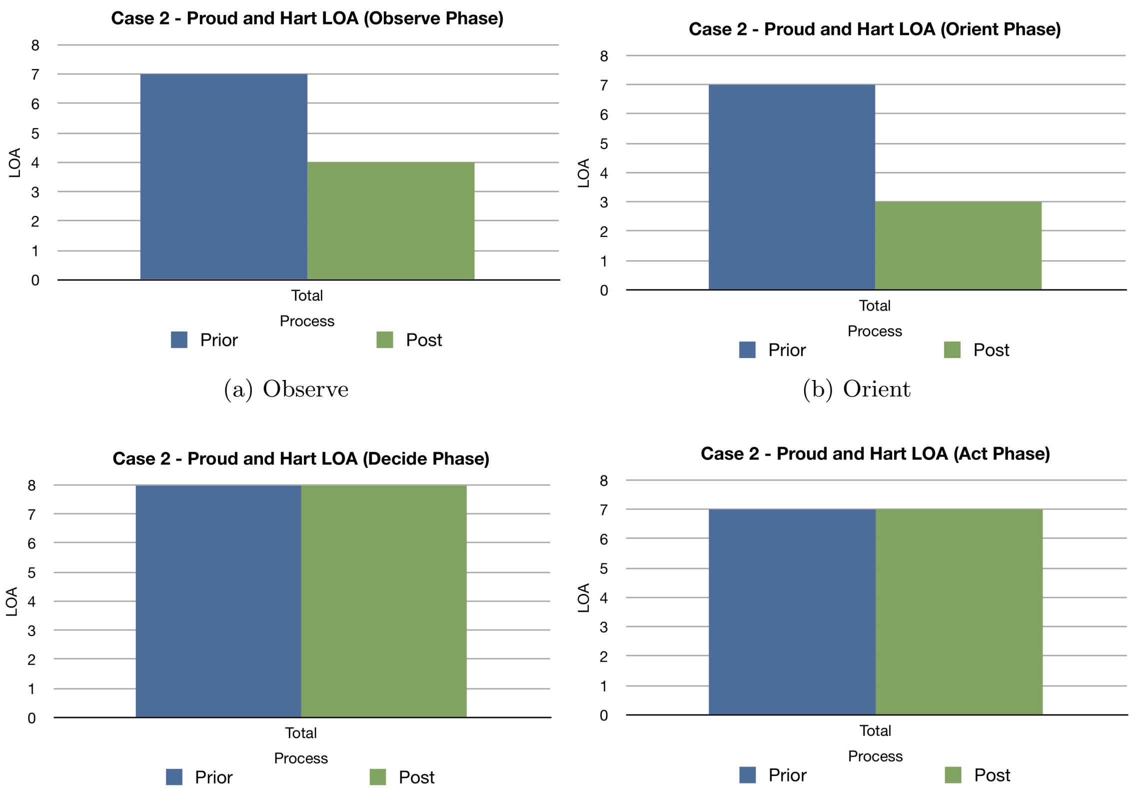
Observe Phase - Prior to the transition the system was operating at Level 7 within the observe phase. Following the transition, the system, though unperceived by the operator, was operating at Level 4 (inherent filtering of the environment). The user was immersed in the environment and so there was a secondary source of unfiltered information.

Orient Phase - The system prior to the transition was operating at Level 7 within the orient phase. Following the transition the system, though unbeknownst to the operator, was operating at Level 3.

Decide Phase - The system prior to the transition was operating at Level 8 within the decide phase. Following the transition, the system was still operating at Level 8. No ranking of the possible option is given to the operator, as the operator feeds in the correction data and the computer takes it from there.

Act Phase - The system prior to the transition was operating at Level 7. Following the transition, the system was still operating at Level 7.

These levels are shown in Figure C.4 and Table C.4.



(a) Observe (b) Orient

(c) Decide (d) Act

Figure C.4: Case 2 - Proud and Hart LOA

C.3.2 The Trigger

The trigger in this was the failure of the GPS data as an input into the system. In essence, the loss of input disable a mode and so in order to keep functioning, the system had a preprogrammed secondary mode to revert to. Such a transition is a prime example of an adaptive control system.

The following can then be identified as active in triggering this transition:

- Mode
- Environment State

Mode - The adaptive control style of the automation architecture was the primary trigger of the transition here. In the event that the GPS was somehow made inactive, the system

Table C.4: Case 2 - Proud and Hart LOA

Case 2 - Proud and Hart LOA							
Observe		Orient		Decide		Act	
Prior	Post	Prior	Post	Prior	Post	Prior	Post
7	4	7	3	8	8	7	7

would transition into a different mode.

Environment State - As opposed to a system state changing (in the sense of state variables) it was an variable within the surrounding environment which activated the pre-programmed behavior from the automation. Hence, the environment state can be mapped as triggering the mode response, which then activated the mode transition.

See Figure C.5 for an illustration of these triggering factors.

C.3.3 Factors, Mechanisms, and Design Lessons

Factors in the Transition

At the outset, this transition may not seem entirely ungraceful, as performance was maintained within acceptable parameters at and immediately following the transition. Additionally, workload was not increased. However, situation awareness and mode situational awareness were both lost during this transition. As such, the following factors are identified as contributing to ungraceful nature of this transition:

- Mode situational awareness (All Levels)
- General situational awareness (All Levels)
- Interface
- Opacity
- Information Processing Mechanisms
- Environment State
- Preconceptions

Mode situational awareness (All Levels) - This is the major descriptor of the lack of grace in this transition. During and following the transition the operator(s) were not aware of the new mode of operation, and were in fact operating under the assumption that no transition had taken place.

General situational awareness (All Levels) - A lack of awareness of the state of the environment (the disconnection of the GPS) before and after the transition, as well as a general

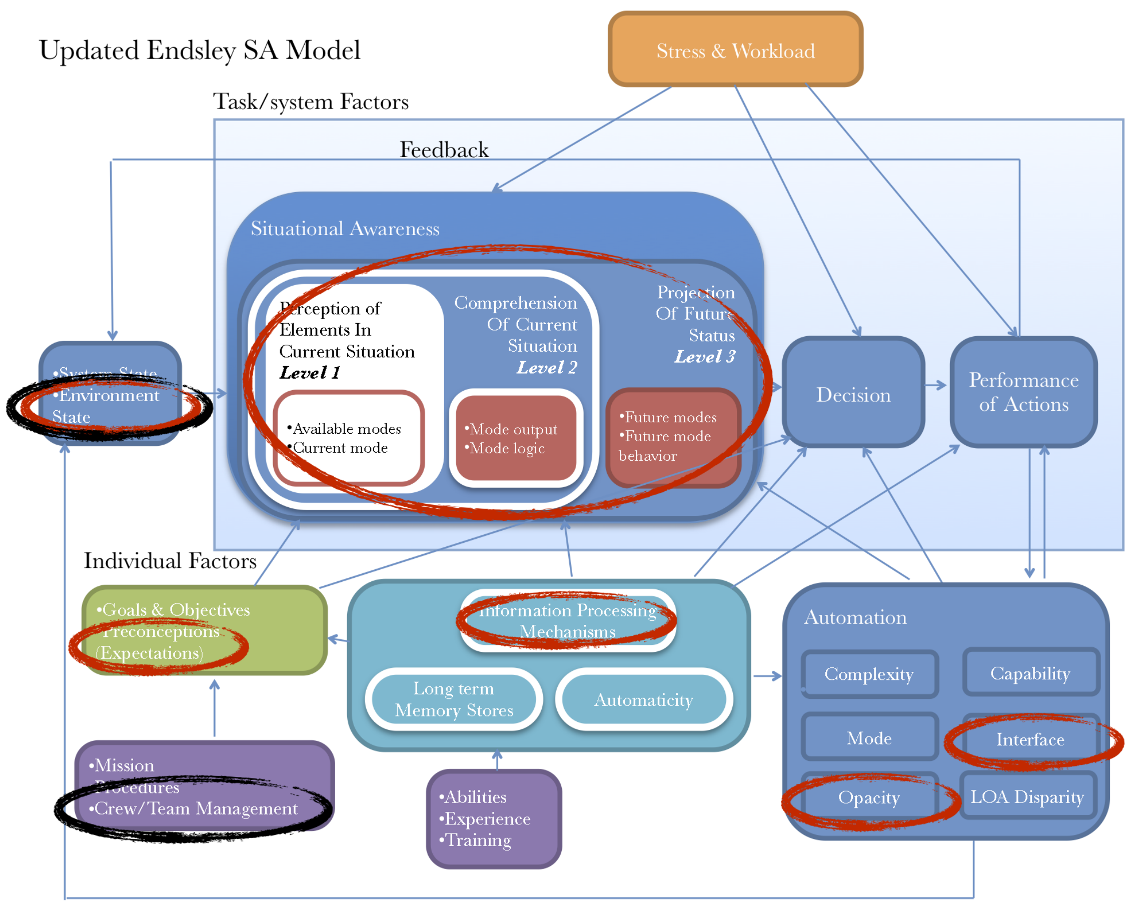


Figure C.5: Factors in The Royal Majesty Transition Case 2 lack of how the system was acting following the transition is another descriptor of the lack of gracefulness in the transition. This is particularly notable, as the dynamics of the system are so slow that recognizing any different in the system behavior would take a significant amount of time to become salient enough for the operator to detect them.

Interface - The interface, which has been the subject of another independent study [140], was completely inadequate in alerting the operator to the transition when it took place.

Opacity - The opacity of the automation is a secondary description of the poor interface design; the operation of this automation is particularly complex or difficult to understand by the operator. The relatively unannounced mode switch, along with the operator's ignorance of the system's limited adaptive capability for a GPS dropout, shows a system which is not transparent in its operation to the operator.

Information Processing Mechanisms - The mode switch, both in its effects and its announcement was too subtle for the operator to catch. Additionally, if it were to be argued that their normal monitoring procedures should have sensed the transition, the vigilance limits on human information processing was clearly enough to make this not feasible.

Environment State - As mentioned, the cue in the environment were extremely subtle, to the point that the human was able to remain ignorant.

Preconceptions - The operator(s) were not expecting a mode transition. This preconception combined with low salience of any cues from the system or the environment and the limits of information processing due to vigilance limits ultimately resulted in the loss of situational awareness, and by extension, grace throughout the transition.

See Figure C.5 for an illustration of these factors.

Mechanisms of Gracefulness
In examining the loss of grace in this transition, the following mechanisms can be identified from the update Endsley situational awareness model:

- Machine Perception
- Machine Interpretation, Comprehension, and Projection
- Machine Decision Making
- Operator Schema
- Operator Perception
- Interface

Machine Perception - A failure in the machine perception (GPS failure) can be considered as the root of the ungraceful nature of the transition. The adaptive control scheme of the automation essentially replaced the output of the GPS with the of the dead-reckoning system; however, the dead-reckoning system was unable to perceive elements like current and wind drift which can, in some sense, be considered as a failure in machine perception.

Machine Interpretation, Comprehension, and Projection - Based on the inputs to the system, the system attempted to fulfill these functions. This was not completed adequately. And led to a the slow drift off course experience following the transition. While SA was by far the major descriptor of the lack of grace in this transition, a gradual loss in performance also describes it as, though this was slow developing performance loss.

Machine Decision Making - The adaptive control decision made by the computer, though preprogrammed, was the wrong control decision. The computer continued to operate as if under control by the GPS while in fact operating under dead-reckoning readings. Hence, the decision made was compromised by the faulty nature of its inputs. It can be argued that this was a programming error and not a true automation error; however, automation error (more specifically software error) if classified in this manner will rarely ever occur, which is simply a false notion. An automation failure occurs when it acts in opposition to its design's intent, not its programming actuality.

Operator Schema - The operator's initial schema of the situation biased the mode setting to have little feedback to the operator's schema, hence when the mode actually changed, the schema did not change. This failure of schema resulted in the failure of the operator to correctly perceive and interpret the situation.

Operator Perception - Due to the subtle nature of the cues and the bias from the operator's schema, the operator failed to perceive the cues which would have prompted them to change their schema to fit the new system mode.

Interface - The automation did attempt to alert the operator to the new operating conditions; however, this alert was too subtle to be detected by the operator and was ineffectual.

See Figure C.6 for an illustration of these mechanisms.

Design Principles and Lessons
The following design lessons can be learned from this transition:

- Salience in mode transition alerts, particularly in slow systems is crucial. Nothing in the immediate operation of the *Royal Majesty* would have suggested such a mode change. While procedure did call for the monitoring for the mode change, from prior experience the crew schema was dominated by the bias that such a transition never occurred and did not to be guarded against. This should not be considered as entirely a crew error: this is a reasonable (and often good) human behavior in dealing with highly reliable systems.

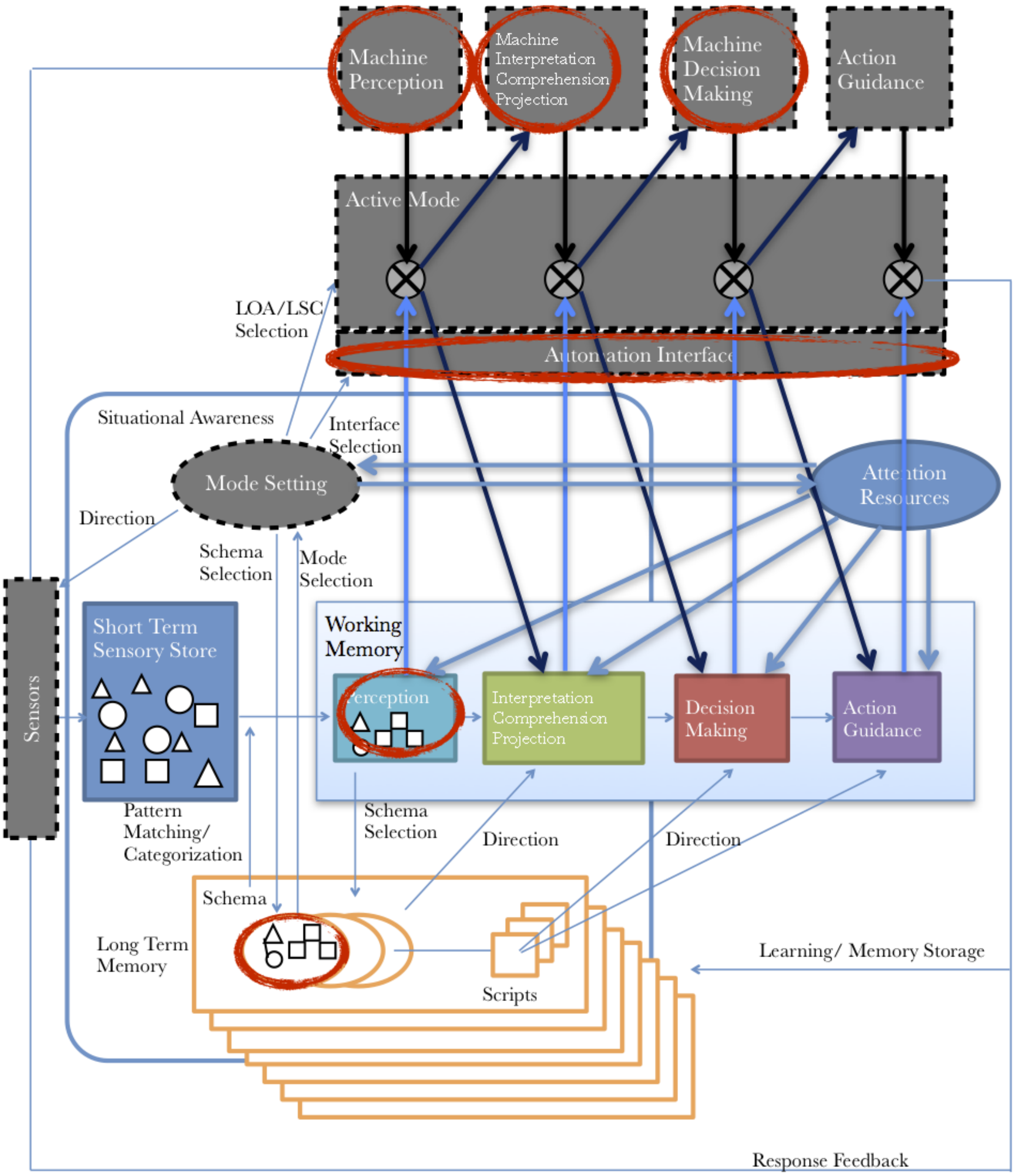


Figure C.6: Mechanisms in The Royal Majesty Transition Case 2

- Humans will allocate attention to the systems which are more likely to fail, suggesting that any mode in a highly reliable system due to failure will need increased salience to alert the human.
- An adaptive control system should be used with caution, especially in a slow-dynamics system. If it is used, the same suggestions as before hold: emphasize the salience of the mode switch cue.
- Unless time-pressure or other limiting circumstances don't allow for human intervention and judgement in the system, the replacement of a faulty sensor system should not be automatically made without the direct consultation and affirmation of the operator. Had such a programmed requirement been in place, situational awareness would not have been lost at the time of the transition, nor would performance have gradually degraded in the manner that it did.

C.4 Transition Case 3

The NTSB investigation reports the following: "The second officer testified that about 2220, the Royal Majesty unexpectedly veered to port and then sharply to starboard and heeled to port. The second officer stated that because he was alarmed and did not know why the vessel was steering off course, he immediately switched from autopilot to manual steering." This is the reversion which will be considered here.

This reversion involves the transition between the NACOS 25 NAV mode and manual steering. However, this transition has two particular viewpoints from which it can be considered: the autopilot's and the operator (the 2nd officer).

C.4.1 The Modes

Sheridan and Verplank LOA

The second officer, as well as everyone else on the bridge, was unaware of the previous mode change (see Section C.3) and was, as such, operating under the assumption that he was dealing with a system that was functioning in NAV mode with GPS data. Thus, the perceived mode was level 8 on the Sheridan and Verplank scale; however, this was not the true mode of the automation system. In fact the automation was attempting to function as a level 1 on the Sheridan and Verplank scale. These levels are shown in Figure C.7 and Table C.5. This particular problem associated with automation has been recognized as mode confusion and has been documented and investigated by numerous scholars [3, 139, 141, 142, 143].

Proud and Hart LOA

Observe Phase - Prior to the transition, the system was operating at Level 4 within the observe phase. Following the transition, the system was operating at Level 4.

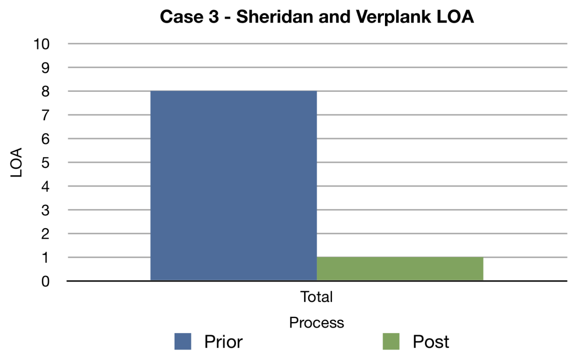


Figure C.7: Case 3 - Sheridan and Verplank LOA

Table C.5: Case 3 - Sheridan and Verplank LOA

Case 3 - Sheridan and Verplank LOA	
Prior	*Post*
8	1

Orient Phase - Prior to the transition, the system was operating at Level 3. Following the transition, the system was still operating at Level 3.

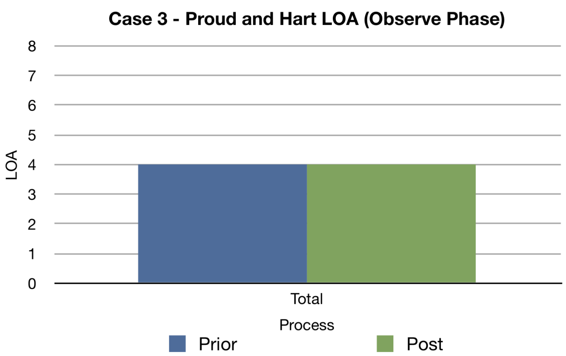
Decide Phase - Prior to the transition, the system was operating at Level 8. Following the trnaistion, the system was operating at Level 1.

Act Phase - Prior to the transition, the system was operating at Level 7. Following the transition, the system was operating at Level 1.

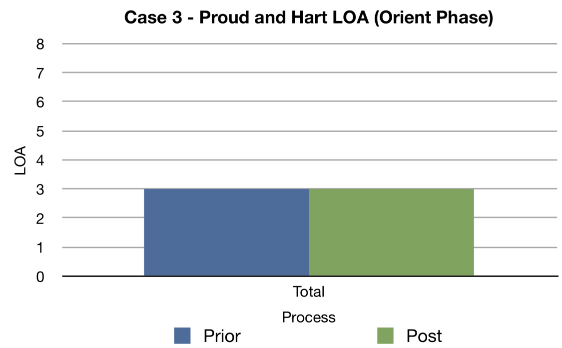
These levels are shown in Figure C.8 and Table C.6.

Table C.6: Case 3 - Proud and Hart LOA

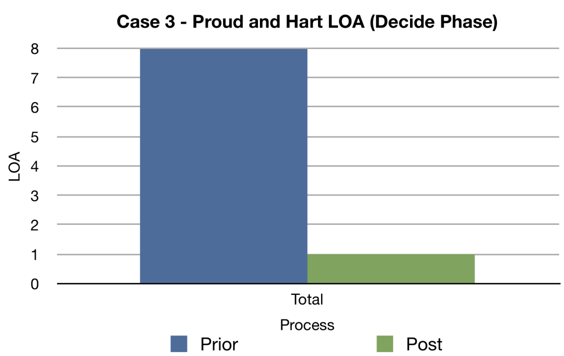
Case 3 - Proud and Hart LOA							
Observe		Orient		Decide		Act	
Prior	Post	Prior	Post	Prior	Post	Prior	Post
4	4	3	3	8	1	7	1



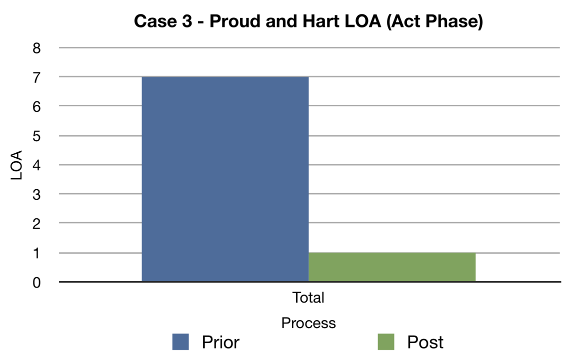
(a) Observe



(b) Orient



(c) Decide



(d) Act

Figure C.8: Case 3 - Proud and Hart LOA

C.4.2 The Trigger

The trigger which caused the transition was specifically stated by the 2nd officer, when he said that he "was alarmed and did not know why the vessel was steering off course." As such, his intention could be construed as a gut reaction to automation surprise, an intention to gain more control over the situation, or a mix of both.

This gut reaction to the off-nominal situation follows suit with that described in Section B.4. Refer to this section regarding a similar trigger.

C.4.3 Factors, Mechanisms, and Design Lessons

Factors in the Transition

This particular transition exhibits the same characteristics seen in the transition analyzed in Section B.4. Refer to subsection B.4.3 for further details regarding the factors involved in this transition.

Mechanisms of Gracefulness

This particular transition exhibits the same characteristics seen in the transition analyzed in Section B.4. Refer to subsection B.4.3 for further details regarding the mechanisms leading to the loss of grace in this transition.

Design Principles and Lessons

This particular transition exhibits the same characteristics seen in the transition analyzed in Section B.4. Refer to subsection B.4.3 for further details regarding the design lessons which are pertinent to this transition.

Additionally, this transition suggests the importance of understanding the mode of operation prior to the mode transition. In this case the transition occurred in the fashion that it did because of the remnants of the previous mode transition. Had this mode been understood and the correct schema been adopted by the user, this transition, if still necessary, would have been more graceful as it would have occurred under less time-pressures.

Appendix D

Case Study: Aeroflot-Nord Flight 821

D.1 General Description

The following case study investigates the transitions which took place on Aeroflot-Nord flight 821, a Boeing 737-500 which crashed outside of the Perm Airport in Russia on September 14th, 2008. Prior to the approach to the runway, the system experienced a large number of mode transitions, much of which was exacerbated by a pre-existing assymetric thrust split in the engines. On approach to Perm airport, the pilots attempted to execute a missed approach, during which the airliner lost radio contact and impacted the ground. There were no survivors [48].

The performance suggests that neither of the pilots had the skill or experience required to fly such a craft, which inevitably dominates any discussion of grace in mode transitions. Additionally, the pilot in command (PIC) was reported as being inebriated, greatly reducing his ability to cope with changes in the system. While it should be understood that no high-performance system such as a passenger airliner be able to operate gracefully with an impaired operator, the condition of this operator gives a unique look at the consequences of an "off-nominal" operator case and can provide incite into how to make a system more robust in terms of gracefulness in mode transitions.

The following cases of transition were identified in this accident base on the report by the Russian Interstate Aviation Committee (MAK):

1. Prior to the approach, the autothrottle was disengaged at 22:59:23. The transition was preprogrammed, classifying it an adaptive control function.

2. In entering the approach, a switch to "Altitude Hold" (ALT HOLD) was made at 23:06:30. Prior to the transition, the aircraft had been operating in "Level Change " (LVL CHANGE) mode.
3. In entering the approach, a switch was made to "Lateral Navigation" (LNAV) at 23:06:44, with the report describing it as most likely mistaken input by one of the pilots.
4. In entering the approach a transition was made from "Lateral Navigation" to Control Wheel Steering in both roll (CWS ROLL) and pitch (CWS PITCH). This took place at 23:06:48.
5. During the approach a transition was made to full manual control by the disengagement of the autopilot at 23:07:08.

D.2 The Flying Task

When considering the flying task, it is important to define "the whole" task, particularly because Sheridan and Verplank refer to "the whole task" in their LOA taxonomy. In this study, the flying task refers specifically to the maintaining and pursuit of selected states in the vehicle. As such, the selection of states (e.g. determining desired airspeed or altitude) is not what will be considered. Instead, the "options" referred to in Sheridan and Verplank's scale will describe all possible options that would be considered, either consciously or subconsciously, by the pilot.

Such an example would be seen in the case of the LEVEL CHG mode. The user specifies the desired airspeed of the climb and the desired altitude of the climb. The selection of these parameters is outside the scope of what is being considered within the LOA. What is being considered is how these external parameters are achieved: does the human generate all possible flying options, does the computer, or is there a team effort involved? Manual flying describes the case in which the human does this entirely. A full autopilot with no display of functions to the human would be considered fully automatic (Level 10). Level 7 describes a highly automated system which necessarily requires that the human be informed of the state of the system, its actions, and the environment.

Additionally, as the system becomes more complex, the macro-application of Sheridan and Verplank's LOA becomes less beneficial. Instead, it becomes necessary to break the job down into tasks with each of these tasks then being considered on Sheridan and Verplank's Scale. In the case of flying an airplane, the following task set can be derived from a general list of available inputs to the pilot as well as the goal states:

- Attitude Control

- Thrust Control
- Lateral Flight Path Control
- Vertical Flight Path Control
- Airspeed Control
- Descent/Ascent Rate Control

The first two, attitude and thrust control, represent loops which are more internal to the system dynamics. In essence, these loops are closed by the pilot in order to (1) affect changes in the other control domains, and (2) keep the the plane in a controllable state. As such, these loops are included when automation modes handle the outer loops, such as lateral flight path and airspeed; in fact, good automation design guards against these loops not being monitored, as some of the accidents have arisen from unmonitored inner loops. The example of the Crown Princess is a case and point: the computer sacrificed heeling angle control for heading control, resulting in a hazardous 70 degree heeling angle.

There are other various tasks that are present in the cockpit which indirectly affect the flying task, such as communication with ATC and health and status monitoring. These tasks do not directly relate to the modes offered in modern cockpits and are neglected in this analysis. In general, the imposition of these tasks could be assumed to raise the overall level of workload of a pilot during any transition, as they add to the attention drain on the pilot.

D.3 Transition Case 1

The first transition to be considered is the autothrottle disengagement at 22:59:23. This particular transition was built into the system as a preprogrammed mode change:

> ...the autothrottle disengagement was as per design, as the following conditions were met simultaneously at 22:59:23...: flaps less than 12.5°, thrust split more than 700 lbs, and spoiler on any wing deflected more than 2.5°.

Additionally, the report explains the following:

> The aircraft, being in the LVL CHG mode, was reaching the assigned flight level of 6900 ft (2100 m). Laterally, HDG SEL mode was active, and the aircraft was turning with a bank of 20°. Both engines were operating at idle. This was set by the autothrottle before starting descent from 2700 m. According to the logics of the joint operation of the autopilot and the autothrottle, idle mode is maintained until LVL CHG is changed to ALT ACQ. After the autopilot mode was changed, the autothrottle switched to SPEED mode. To maintain

the speed when reaching the assigned flight level, the autothrottle starts moving the throttles synchronically to increase thrust. When both engines N1 reach 40%, the autothrottle starts automatically matching them, by staggering the throttles. If during this matching for some reason the N1 of one engine drops lower than 40%, the matching stops. With regard to this portion of the accident flight, the ALT ACQ mode was activated at 22:59:09. Simultaneously, the autothrottle SPEED mode was activated and both throttles started advancing. At 22:59:13 the N1 of both engines reached 40% and the autothrottle started matching them, independently moving the throttles. However, after 3 seconds left engine N1 dropped lower than 40%, so the matching stopped. By that time the N1 split was about 20%, which led to a significant left banking moment (created because of right sideslip) and forced the autopilot to apply right wheel to maintain the roll angle established during the turn. The right wheel caused the deflection of ailerons and spoilers on the right wing. Finally, at 22:59:23, after the spoiler deflected more than 2.5°, the autothrottle was automatically disengaged, which is confirmed by recording of the OnOff signal on the FDR. It should be noted that in previous flights the autothrottle was also disengaged several times in similar conditions.

D.3.1 The Modes

Sheridan and Verplank LOA

Attitude Control - In terms of attitude control, prior to this transition, the system was operating in HDG SEL mode. This mode is meant to control the lateral component of the flight path. At the same time it closes the inner attitude control loop in order to do this. As such, the vehicle was operating at Level 7 on the Sheridan and Verplank Scale. Following the transition, the vehicle was operating at Level 7 with respect to attitude control, as the system was still operating in HDG SEL mode and ALT ACQ.

Thrust Control - Prior to the transition, the system was operating in SPEED mode. This mode controls an outer loop state, in this case, airspeed. Essentially, it placed the system at Level 8, where the computer was automatically controlling the engines. This control process was hidden from the pilots unless it was requested (the pilots may navigate to the engine display screen in order to view the engine status). Following the transition the system was operating at Level 2.

Lateral Flight Path Control - Lateral flight path control in multi-engine aircraft is effected by the thrust split of the engines. As such, lateral flight path control cannot be reduced solely to a function of attitude control. With this in mind, prior to the transition the system was operating at Level 7. Following the transition, the system was operating in a regime that might be considered Level 4. The vagueness of this classification is a result of the Sheridan and Verplank scale only describing cases in which either the human does the whole job or the computer does the whole job; there is no explicit case in which the human and the computer affect the system through distinct, but parallel, mechanisms.

Vertical Flight Path Control - Prior to the transition, the system was operating in ALT ACQ mode, placing the system at Level 7. Following the transition, the system was still operating in ALT ACQ mode, meaning that it was still operating at Level 7.

Airspeed Control - Prior to the transition, the system was operating in SPEED mode, placing it at Level 7. Since airspeed is controlled jointly by attitude and thrust (one of which was now being controlled fully manually) this placed the system at Level 4 (again, with the same difficulty in that no room is made for distinctly parallel controlling processes within Sheridan and Verplank's LOA).

Descent/Ascent Rate Control - Prior to the transition, the system was operating in ALT ACQ mode, which sets the desired altitude. This process controls its inner loop of descent/ascent rate to acquire the desired altitude. As such, the system was operating at Level 7 prior to the transition. Following the transition, the system was operating still at Level 7.

These leves are shown in Figure D.1 and Table D.1.

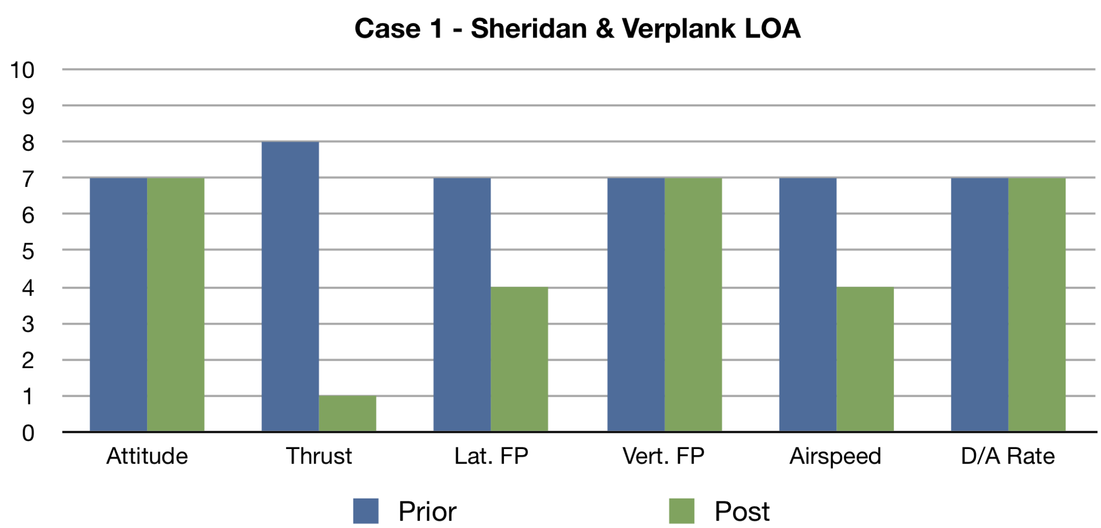


Figure D.1: Case 1 - Sheridan and Verplank LOA

Proud and Hart LOA

The system can be analyzed based on Proud and Hart's LOAs; a breakdown into the individual tasks becomes necessary for the Orient, Decide, and Act phase.

Observe Phase - Prior to the transition, the automated system was displaying a filtered

Table D.1: Case 2 - Sheridan and Verplank LOA

Case 1 - Sheridan & Verplank LOA		
Control Task	*Prior*	*Post*
Attitude	7	7
Thrust	8	1
Lat. Flight Path	7	4
Vert. Flight Path	7	7
Airspeed	7	4
Descent/Ascent Rate	7	7

picture of the environment and the system. This information, by the vary nature of the display and its multilayered interface is prioritized to the user. Hence, the system is operating at Level 6, and following this transition the system is still operating at Level 6, as the display has not changed in any appreciable way.

Attitude Control:

- Orient - Prior to the transition, the plane was operating in HDG SEL and ALT ACQ mode, both of which control the outer loops of flight path control by controlling the inner attitude and thrust control loops. In order to do this, the system orients itself automatically given the information passed to it by its sensors. It then interprets this data in context with these two modes, "predicts" future system behavior, and will eventually provide output (given output from the Decide and Act phases) to control the system. While the human can be doing this in parallel, this parallel orientation process does not feed into the Decide phase, and is thus irrelevant with respect to this analysis. Hence, the system is operating at Level 7 prior to the transition. As the system remains in HDG SEL and ALT ACQ modes following the transition but takes on the contingency of thrust management and delegates it to the human, the system is operating at Level 5. The thrust split affects the vehicles attitude.
- Decide - Based on the output of the Orient phase, the computer selects automatically the desired action disregarding the human. The human is allowed to be monitoring the system in parallel, but their decision is not factored into the automation when linking with the Act phase. This decision is directly linked to the action phase, and the only knowledge that the operator gains of this decision comes from its implementation during the action phase. Hence, prior to the transition the system is operating at Level 8. Following the transition, the system is still operating at Level 4 (HDG SEL and ALT ACQ), but the human is handling thrust management decision tasks.

In particular the computer control decisions outweigh the human inputs to the system in terms of gains from each output.

- Act - Prior to the transition, the human is allowed to intervene in the system at any time, substituting what had been his or her background orientation and decision processes for that of the computer. However, this intervention is solely contingent on the human, and the system will automatically execute its decision without requiring human approval. The operator is automatically informed of this decision via the display, which will show a change using the attitude indicator. Additionally, vestibular cues to the pilot will inform them of the action of the system. As such, prior to the transition, the system is operating at Level 6. Following the transition the system is still operating at Level 6, as any action from the human via thrust management can be considered "contingent overrides".

Thrust Control:

- Orient - Prior to the transition the system is operating in SPEED mode, which automatically integrated the information from the engines to determine the thrust. Additionally, based on the required thrust levels to obtain desired states, future predictions are made in this mode which are then used to generate the eventual future control decisions. As such, prior to the transition the system was operating at Level 7. Following the transition, the system is operating at Level 2. This can be considered as such because with the autothrottle disengaged, the pilot was now in complete control of the thrust system. This required that all data and information presented to the pilot both by the automation and by external cues be integrated by the pilot to generate the control decision and output; however, the display thrust information does incorporate some automated interpretation and integration of information.
- Decide - Prior to the transition, the system generated its own control decision regardless of the human. The only output given to the human was via the Act phase, in which the pilot directly observed the action output. As such, the system can be described as operating at Level 8. Following the transition, the system is operating at Level 2, in which the human is required to weigh all of the integrated data and the predictions made about future system states to determine the decision for the control output, using the computer as an aid tool.
- Act - Prior to the transition, the system automatically executed its control decision and informed the human via engine output display and other various gages. This particular engine display is part of a multilayered display and is not necessarily always being viewed by the pilot, and as such can be considered as a "context dependent" display. Hence, the system is operating at Level 7. Following the transition, the system is operating at Level 1, as the pilot is solely responsible for executing the decision passed by the Decide phase.

Lateral Flight Path Control:

- Orient - Prior to the transition the plane was operating in HDG SEL mode. This means that following a heading input into the computer, the plane automatically oriented itself using sensor input, predicted system activity, and then generated the correct control decision and output. This first process describes a system operating at Level 7. Following the transition, the system is operating at Level 5, since HDG SEL was still active, but the human is responsible for the contingency of thrust management.

- Decide - Prior to the transition, the system is operating at Level 8. Following the transition, the system is operating in a region best described as Level 4. While HDG SEL is still active, the thrust split is being managed by the human, and as such two decisions are essentially being made resulting in separate control outputs during the action phase. In some ways the system is operating at Level 7 because the computer alone is managing raw attitude, but in some senses the system is operating at Level 1 as well. Level 4 comes the closest to describing this situation: Both the human and the computer perform ranking tasks, and the results from the computer are considered prime (these are always automatically passed to the act phase).

- Act - Prior to the transition, the system is operating at Level 6. Following the transition, the system is still operating at Level 6; both the human and the computer are affecting the process through separate means. However, the human actions are purely contingency-based because of the thrust split.

Vertical Flight Path Control

- Orient - Prior to the transition, the plane was operating in ALT ACQ mode – the system orients and predicts future states in order to determine control decisions and inputs. As such the system is operating at Level 7. Following the transition, the system is still operating at Level 7, as nothing has changed in this regard.

- Decide - Prior to the transition, the system is operating at Level 8, in that all decision are made by the computer and the human is not informed of any of the "options" and is only aware of the automations decision following the action phase. Following the transition, the system is still operating at Level 8, as nothing has changed in this regard.

- Act - Prior to the transition, the system is operating at Level 6, with the computer providing all control actions, with the human operating only as a contingency back-up with override capabilities. Following the transition, the system is still operating at Level 6, as this has not changed.

Airspeed Control:

- Orient - Prior to the transition, the system was completely in charge of orienting itself and predicting future vehicle states. Hence, it was operating at Level 7. Following the transition, this did not change and the system is still operating at Level 7
- Decide - Prior to the transition, the system is operating at Level 8, in which is generates its own decision without informing the human. Following the transition, the system is still operating at Level 8.
- Act - Prior to the transition, the system implemented its own decision with the human acting solely as a contingency. Hence, it was operating at Level 6. Following the transition, the system is still operating at Level 6, as this has not changed.

Descent/Ascent Rate Control:

- Orient - Prior to the transition, the system is operating at Level 7 as it oriented and predicted system states without human input. Following the transition this did not change and the system is still operating at Level 7.
- Decide - Prior to the transition the system made decision neglecting the human or the necessity to inform the human of such decisions. Hence, the system is operating at Level 8. Following the transition this did not change and the system is still operating at Level 8.
- Act - Prior to the transition, the system was operating at Level 6, with the computer automatically implementing all control decisions with the human as a contingency. Following the transition this did not change and the system was still operating at Level 6.

It should be noted that in all cases of observation, the pilot(s) had access to an out-the-window view and were also immersed in the system which was being controlled. As such, no matter how much filtering the display of the plane provide, there was were still unfiltered vestibular and visual cues to the pilot presenting themselves in parallel with automation's display.

These levels are shown in Figures D.2 - D.5 and Table D.2.

D.3.2 The Trigger

The trigger mechanism is described in great detail by the report. Given the shear verbosity of the description, it is obvious that this trigger involves a number of different factors. The immediate triggers programmed into the system consisted of the following logic: if the system to reach a state in which flaps [where] less than 12.5°, thrust split more than 700 lbs, and spoiler on any wing deflected more than 2.5° the autothrottle would disengage.

Hence, the trigger can be mapped to the following sources within the updated Endsley model, shown in Figure D.6.

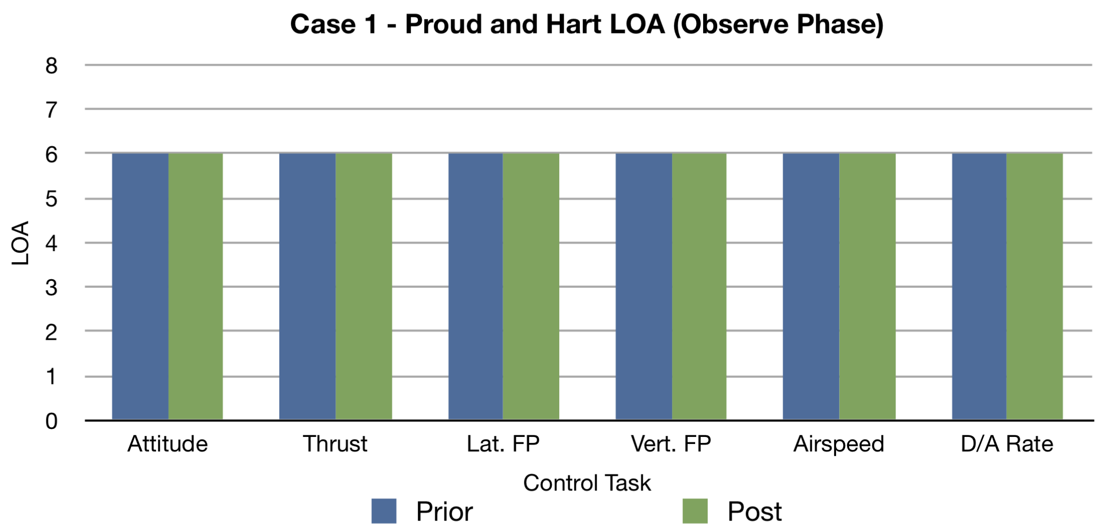


Figure D.2: Case 1 - Proud and Hart LOA (Observe Phase)

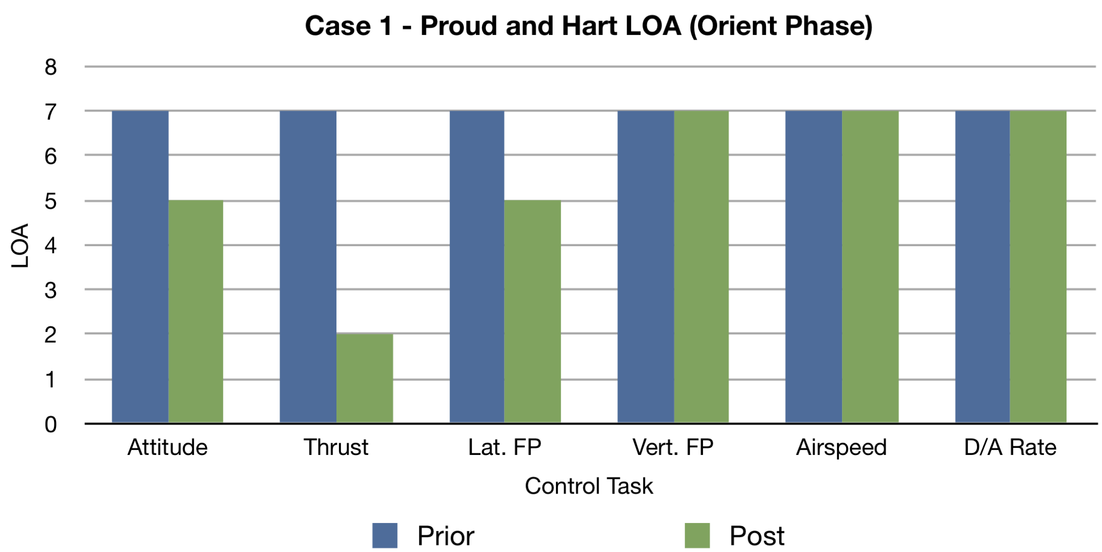


Figure D.3: Case 1 - Proud and Hart LOA (Orient Phase)

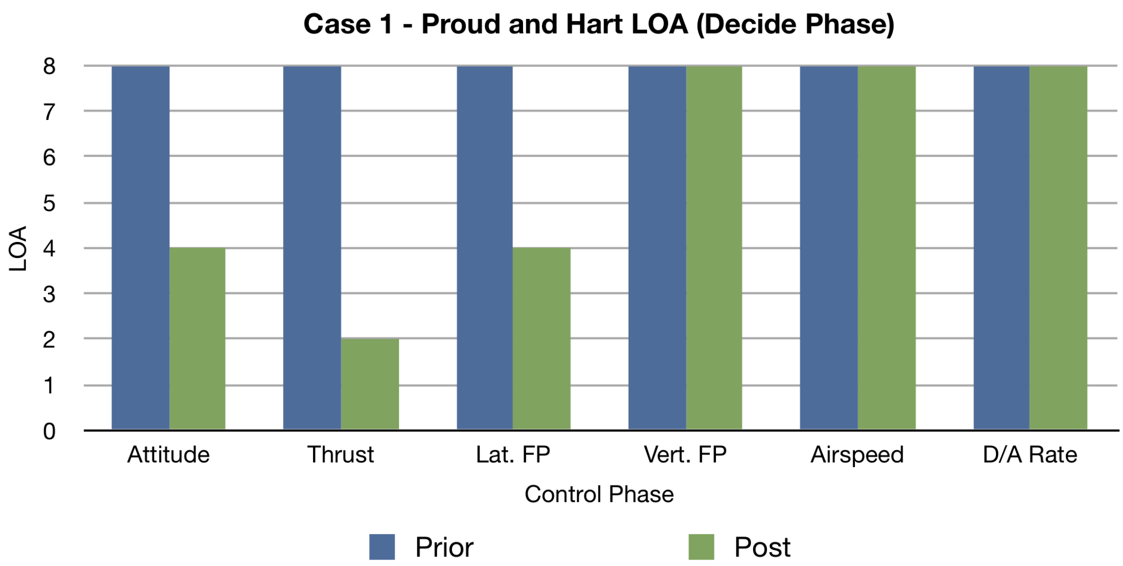


Figure D.4: Case 1 - Proud and Hart LOA (Decide Phase)

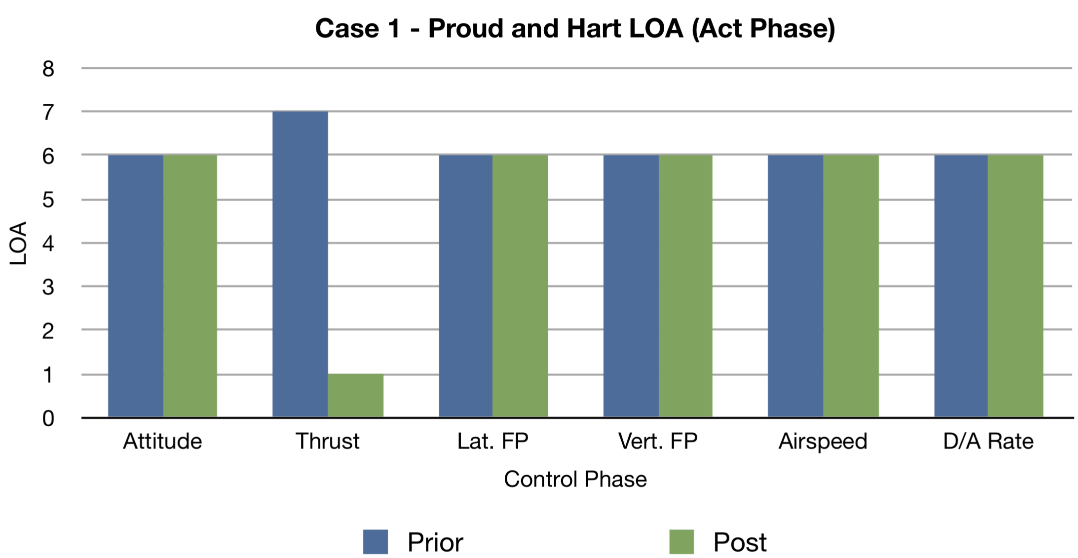


Figure D.5: Case 1 - Proud and Hart LOA (Act Phase)

Table D.2: Case 1 - Proud and Hart LOA

Case 1 - Proud and Hart								
Control Task	Observe		Orient		Decide		Act	
	Prior	Post	Prior	Post	Prior	Post	Prior	Post
Attitude	6	6	7	5	8	4	6	6
Thrust	6	6	7	2	8	2	7	1
Lat. Flight Path	6	6	7	5	8	2	7	1
Vert. Flight Path	6	6	7	7	8	8	6	6
Airspeed	6	6	7	7	8	8	6	6
Descent/Ascent Rate	6	6	7	7	8	8	6	6

- System States
- Automation Mode

System States - The automation was programmed to revert in the event that the previously mentioned vehicles states were achieved. As such, the system states were a primary factor in the triggering of this transition.

Automation Mode - The programming of the automation was the specific reason why the transition took place. If the automation had been programmed differently this transition would not have occurred in the same manner. Hence, this was a secondary factor in the triggering of the transition.

D.3.3 Factors, Mechanisms, and Design Lessons

Factors in the Transition

This mode was particularly ungraceful – after the transition took place control of the aircraft was only marginally maintained and performance suffered. While no definitive statements can be made about the situational awareness of the pilots at the time of the transition, it can be reasonably be deduced that it also suffered, as the pilots did not control the aircraft in a way that suggests an adequate knowledge of their system. This conclusion is corroborated by the following quote from the accident report:

> After analyzing the pilots' actions during a flight with thrust asymmetry, the investigation concluded that both pilots lacked basic skills for flying multiengine planes with spaced-apart engines.

Based on Endsley's updated model, the following factors were identified as applicable to this transition case:

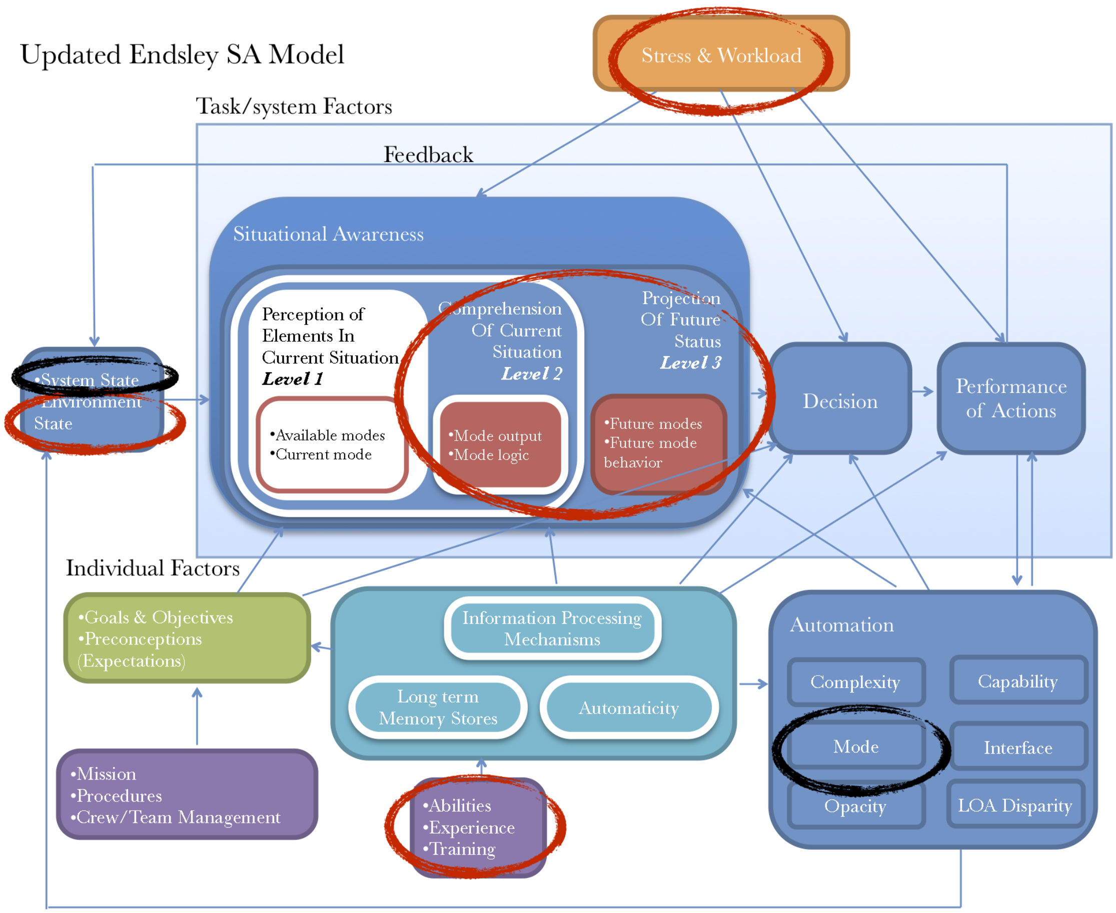


Figure D.6: Factors in Aeroflot-Nord Flight 821 Transition Case 1

- Operator abilities, training, and experience
- Stress and Workload
- System States
- General situational awareness
- Mode situational awareness (All Levels)
- Automaticity

Operator abilities, training, and experience - The operator in this transition was reported in numerous places within the accident report as having inadequate skills for operating that aircraft. As such, the abilities, training, and experience of the operator was a large factor, if not the largest, within this transition.

Stress and Workload - Throughout this transition the stress levels and workload being experienced by both pilots was quite high. This negatively affected the transition, disposing the operators to not being able to operate at peak efficiency in the particular demanding task of mode transition.

System States - The very fact that the system state was what triggered the mode transition makes it a factor in this transition; however, the system states are a factor beyond their triggering of the transition. The transition was triggered by system states that were particularly problematic; hence the pilots were being handed a dynamically changing system, increasing the demands on their ability to insert themselves into the system.

General situational awareness - As mentioned previously, little can be definitely known regarding the siutational awareness of the pilots. However, it is likely that the pilots were unaware of the issues leading up to the transition as well as the states relevant to controlling the plane following the transition.

Mode situational awareness (All Levels) - The crew's strategy of control suggests a misunderstanding of the correct ways in which to control the plane in the mode following the transition. Of particulate note is the neglecting by the crew of using rudder input to offset sideslip induced by the thrust split.

Mechanisms of Gracefulness
The following mechanisms were determined to be the sources within system leading to the ungraceful transition:

- Attention resource management
- Operator Perception
- Operator Interpretation, Comprehension, and Projection

- Operator Schema
- Machine Action Guidance

Attention resource management - Given the high amount of stress and workload, identified in the factor as present in this transition, the demand on attention resources was extremely high. As seen in many other cases, this has a flow down effect, making the cognitive processes less effective and more prone to error.

Operator Perception - It cannot be definitively ruled out whether this was, in fact, a mechanism of the ungraceful nature of this transition; however, the high demand of attentional resource and the errors in interpretation, comprehension, and projection suggest that something may have likely gone wrong in the pilot's perceptions.

Operator Interpretation, Comprehension, and Projection - Following the transition, the crew did not apply rudder as a compensation for the slip induced by the thrust split. This effect was not missed by the crew; they applied wheel inputs to compensate. Thus the interpretation and translation of this slip into a correct counteraction was not made and contributed to the ungraceful nature of this transition by compromising performance and reducing the amount of control exercised over the system.

Operator Schema - Due to the lack of training (discussed in the factors related to this transition), and what was most likely deficient perception, the wrong schema was applied to this situation, making it particularly ungraceful.

Perhaps most crucially, this transition exemplifies the necessity of training. While it may seem like only common sense, and indeed it is, operators must be trained in all of the modes which they will be operating. Additionally, they should have experience in transitioning between these modes. Had this crew been more experienced this transition would have been much more graceful and, most likely, never have been necessary.

The graphs presented in the report surrounding this particular transition paint the picture of a pilots who were attempting to gain control of a system with which they were unfamiliar. Hence, situational awareness regarding control input dynamics was being gained in the initial stages of the transition. Had this been allowed to happen prior to the transition, or had the input of the user been guided during the transition, this ungraceful action of the system might not have been observed. Hence, operator awareness of control input dynamics is a key mechanism seen in this transition.

These mechanisms are illustrated in Figure D.7

Design Principles and Lessons

Based on the major factors and mechanisms seen in this transition the following design principles and lessons can be arrived at.

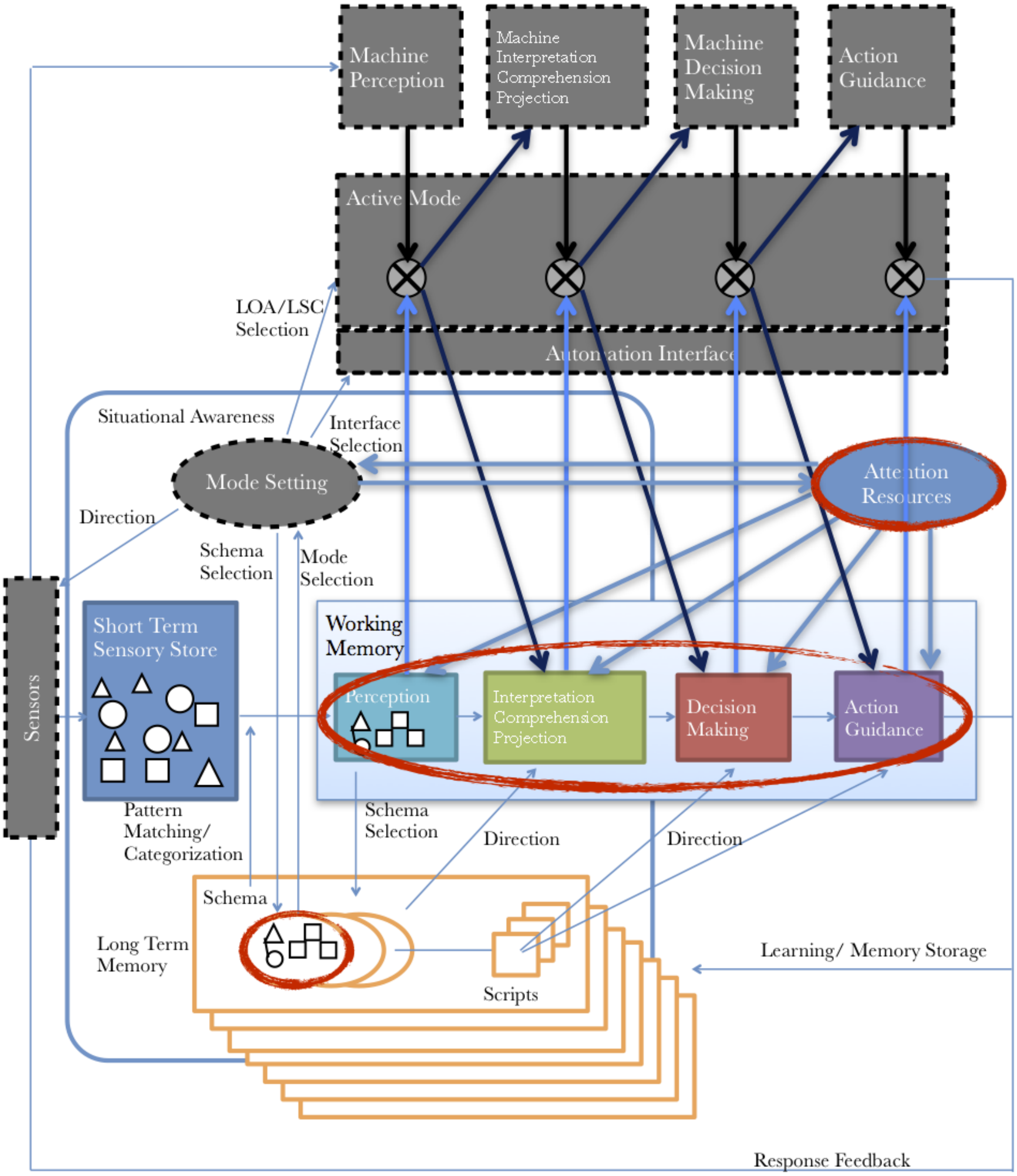


Figure D.7: Mechanism in Aeroflot-Nord Flight 821 Transition Case 2

- Mode transitions should not happen at times when the system is in a highly dynamic state. As a large amount of things were happening at the time of this transition and many different states were changing in the aircraft, the pilots were forced to act quickly and forcefully in the system during the transition. As such, the pilots were unable to be cautious as they entered the control-loop. Designing procedures and systems that preferably transition between modes when system states are stable would be a good design principle. While this may not always be achievable, it should be suggested that in the case that the human may be required to intervene in a highly dynamic system, it makes sense to have them enter the loop during the"calm-before-the-storm".
- A possible design implementation to improve operator awareness could be a flight director or control input director, in which the operator inceptor is guided either by a visual or tactile display to the most logical control input. Such a design implementation would allow for the human to gracefully learn the current gains of the inceptor system.

D.4 Transition Case 2

A switch to ALT HOLD at occurred at 23:06:20. The report can be quoted as saying:"the autopilot pitch mode changed to ALT HOLD to maintain the altitude of 600". Prior to this the plane had been functioning in LVL CHG, which calculates the best climb or descent rate to get at a selected altitude with a selected speed. At the time of this transition, the system was operating in HEADING SEL and the thrust was being controlled manually.

LVL CHG is described as a function which will calculate the best climb/descend rate to get at the selected altitude with the selected speed.

D.4.1 The Modes

Sheridan and Verplank LOA

Attitude Control - Attitude control is the inner loop of vertical flight and lateral flight control. Both of these were being controlled automatically at the time by the computer, and as such, attitude was also being controlled by the computer. Hence, prior to the transition, the system was operating at Level 7. Following the transition, the system was still operating at Level 7.

Thrust Control - Prior to the transition, thrust control was at Level 2. Following the transition, the system was still operating at Level 2.

Lateral Flight Path Control - Prior to and following the transition the system was operating in HEADING SEL mode. Hence, both preceding and following the transition, the system was operating at Level 7.

Vertical Flight Path Control - Prior to the transition, the system was operating in LEVEL CHG mode. As such prior to the transition, the system was operating at Level 7. Following the transition, the system was operating at Level 7 (ALT HOLD).

Airspeed Control - This is an inner loop of the LEVEL CHG mode, and following the transition the airspeed and it is assumed to have been maintained by the computer (this information is not provided in the report). As such, the LOA which best characterizes this situations is Level 4. Following the transition it was still operating a Level 4.

Descent/Ascent Rate Control - Prior to the transition, the system was operating at Level 7. Following the transition, the system was operating at Level 7 as well.

These levels are shown in Figure D.8 and Table D.3.

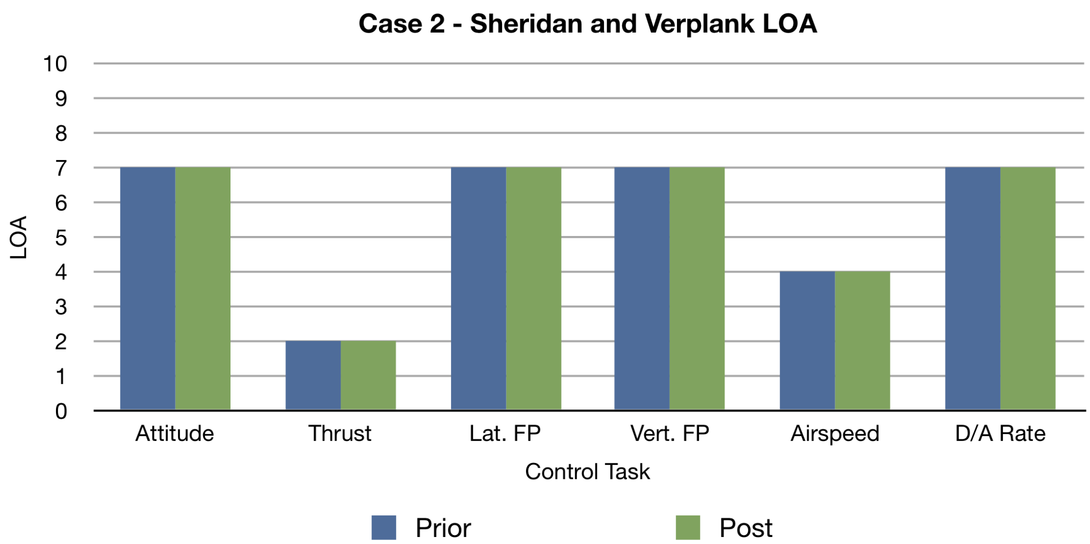


Figure D.8: Case 2 - Sheridan and Verplank LOA

Proud and Hart LOA
No changes in the LOA were found in this mode transition case.

Observe Phase - Prior to the transition, the system was operating at Level 6. Following the transition, this was still the case (the system was operating at Level 6).

Attitude Control

- Orient - Prior to the transition the system was operating in LVL CHG mode, in which the vertical flight path is controlled to the purpose of attaining certain altitude while maintain an operator specified airspeed. Attitude is controlled in order to

Table D.3: Case 2 - Sheridan and Verplank LOA

Case 2 - Sheridan and Verplank LOA		
Control Task	*Prior*	*Post*
Attitude	7	7
Thrust	2	2
Lat. Flight Path	7	7
Vert. Flight Path	7	7
Airspeed	4	4
Descent/Ascent Rate	7	7

achieved these states. As such, the system is required to orient itself to and predict system states without the human. The display of such integration, prediction, and orientation is context dependent, and thus places the system at Level 7. Following the transition, the system is operating at Level 7 as well, in that ALT HOLD essentially controls attitude towards a similar end that LVL CHG did, but instead it is tracking a stationary altitude flight path rather than a changing altitude flight path.

- Decide - The computer is responsible for all decisions made and does not involve the human in this process. As such, the system is operating at Level 8. This does not change following the transition.
- Act - The computer is responsible for all control action outputs; however, the human is placed in a position of contingent control input. Additionally, the human is necessarily informed of the action output of the system based on vestibular cues and mandatory display output on the PFD. This places the system at Level 6. This does not change following the transition.

Thrust Control

- Orient - Prior to the transition, the system is operating at Level 2, as it requires the human to orient, predict, and integrate all displayed information regarding the engine thrust. A small amount of information integration an interpretation is provided through the computer display, but the brunt of the orientation task falls on the human and ultimately rests with the human's interpretation of the data. Following the transition, the system was still operating at Level 2.
- Decide - Prior to the transition, the system is operating in a manner which requires that the human generate, evaluate, and decide all control options using the computer

as an aiding tool only. This places the system at Level 2, or full human decision making. This does not change after the transition.

- Act - Prior to the transition, the system is operating a Level 1, in which the human is responsible for all control actions regarding thrust. This does not change following the transition.

Lateral Flight Path Control

- Orient - Prior to the transition the system was operating at Level 5, in which the computer handled all orientation, integration, and prediction tasks associated with the active information handling task. However, in this case, because of the contingency of thrust management being present here, this places the system as Level 5 . Following the transition, the system is operating at Level 5 as well.

- Decide - Prior to the transition, the computer handles all enumeration, ranking, and decision making processes, with no output to the human. However, at the same time, the human is making decisions regarding thrust split levels, which impacts lateral path control. Such control is secondary to the computers decision, as it is not the primary method of lateral flight path management. As such, this places the system at Level 4. Following the transition, this did not change.

- Act - Prior to the transition, the system was operating at Level 6, in which all actions were automatically completed by the computer, with the human acting as a contingent output. In this case, the actions in the manual thrust management that were directed towards the ends of lateral flight path management are considered to be contingent control inputs (they are not the primary means of lateral flight path management). Following the transition, the system was still operating at Level 6.

Vertical Flight Path Control

- Orient - Prior to the transition the system was operating at Level 7, as the computer was in charge of all data interpretation, integration, and prediction relating to the active information processing flow. Following the transition, the system is operating at Level 7 as well.

- Decide - The computer was directly responsible for the selection of the control output, and this selection process was not displayed to the user. As such, the system was operating at Level 8 prior to the transition. This did not change following the transition.

- Act - The computer was completely in charge of all control actions, with the human acting as contingency management. As such, the system was operating at Level 6. This did not change following the transition.

Airspeed Control

- Orient - Prior to the transition the system was operating at Level 5, as the computer was directly responsible for all interpretation, integration, and state prediction tasks, with the human acting as contingency management in the case of thrust control. Following the transition, the system is operating at Level 5 as well.
- Decide - Prior to the transition, the system was operating at Level 4, in that the computer was responsible for all attitude changes which directly affected the airspeed, but the human was responsible for all thrust changes in this respect. The computers decisions are considered prime because they are implemented disregarding the output of the human decision process, whereas the human decision process is directly affected by the output of the computers current decision strategy. Following the transition, this does not change.
- Act - Prior to the transition, the computer is operating a Level 6, as the it is responsible for all system output with the human acting as contingency thrust management. Following the transition, this does not change.

Descent/Ascent Rate Control

- Orient - Prior to the transition the plane was operating in LVL CHG mode, which controls the descent/ascent rate optimally based on a desired airspeed and altitude. This mode thus requires the system to fully interpret, integrate, and predict system states without the computer; however, given the contingency of thrust operation by the human, this places the system at Level 5. Following the transition, the system is operating at Level 5, as nothing changed.
- Decide - The majority of the option enumeration and decision making was done by the computer prior to the transition, save for the thrust decision-making performed by the human. As such,the system falls under the category of Level 4, in which the computer options are deemed prime to the human. Following the transition, this is still the case.
- Act - Prior to the transition the computer is directly responsible for all actions pertaining to descent/ascent rate, save those contingent thrust inputs which are being controlled by the human. The ascent/descent rate actions of the computer are necessarily displayed to the human via the vertical speed indicator on the PFD, as well as through vestibular cues and the out-the-window view. Hence, the system is operating at Level 6. Following the transition, this is still the case.

These levels are shownn Figures D.9-D.12 and Table D.4.

D.4.2 The Trigger

The trigger for this mode switch was the reaching the goal state of 600 m from the LVL CHG function. The autopilot was programmed to make this switch upon arrival at the

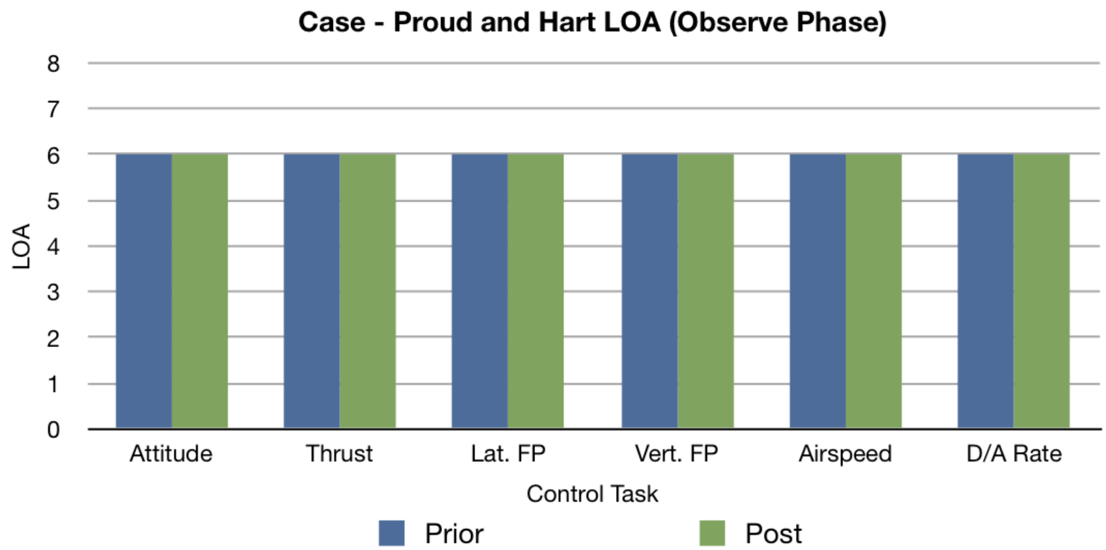


Figure D.9: Case 2 - Proud and Hart LOA (Observe Phase)

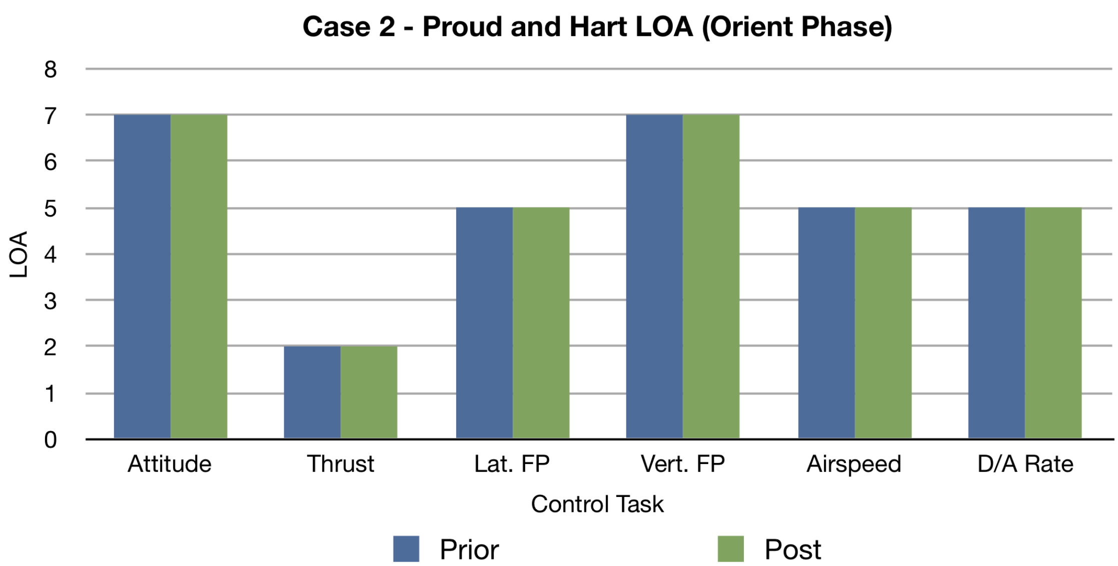


Figure D.10: Proud and Hart LOA for Aeroflot-Nord Flight 821 Transition Case 2 (Orient Phase)

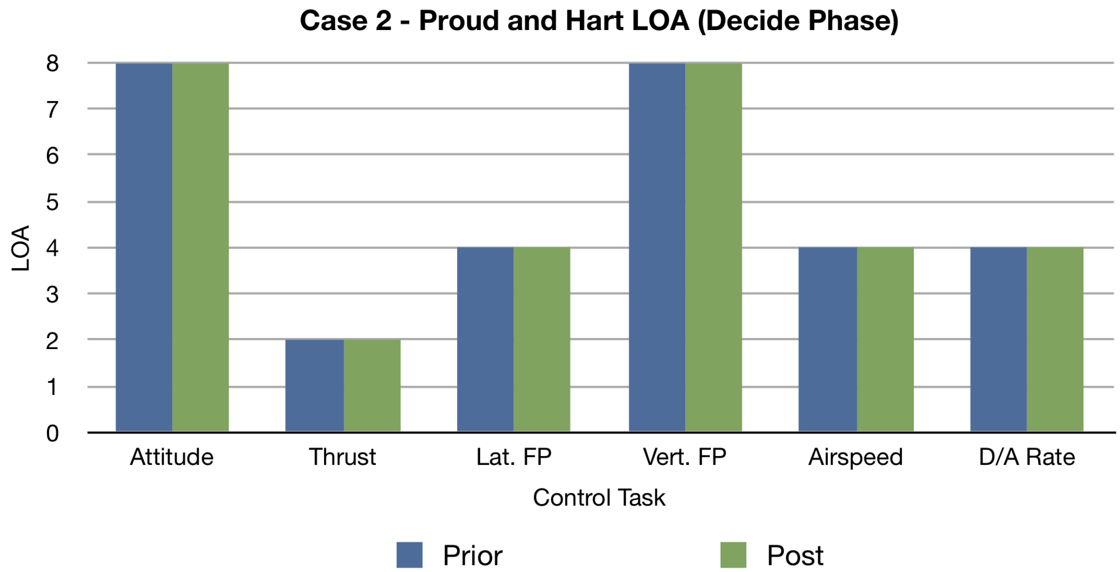


Figure D.11: Proud and Hart LOA for Aeroflot-Nord Flight 821 Transition Case 2 (Decide Phase)

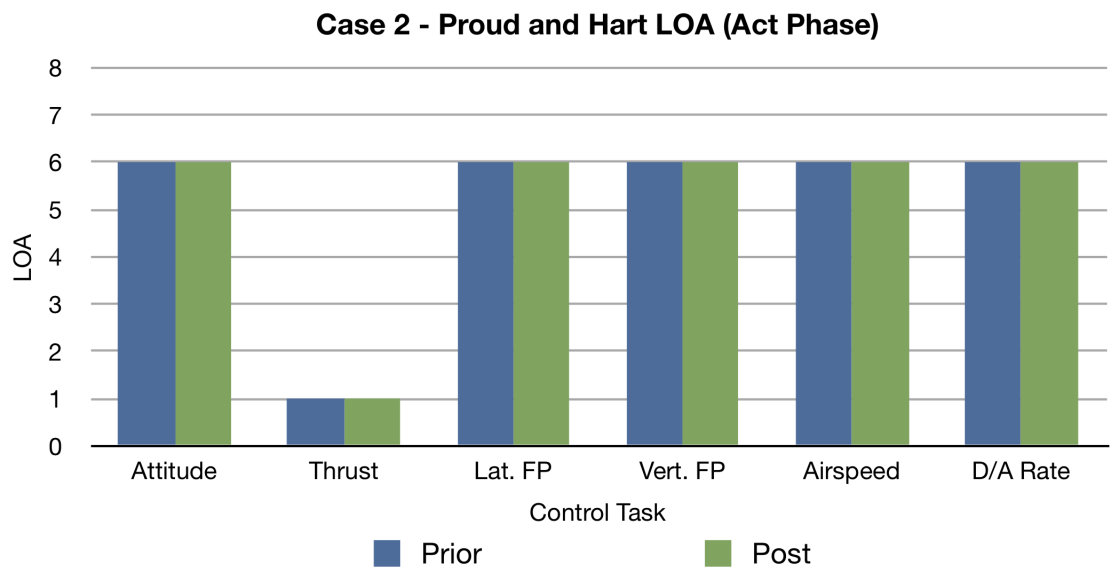


Figure D.12: Proud and Hart LOA for Aeroflot-Nord Flight 821 Transition Case 2 (Act Phase)

Table D.4: Case 2 - Proud and Hart LOA

Case 2 - Proud and Hart LOA								
Control Task	Observe		Orient		Decide		Act	
	Prior	Post	Prior	Post	Prior	Post	Prior	Post
Attitude	6	6	7	7	8	8	6	6
Thrust	6	6	2	2	2	2	1	1
Lat. Flight Path	6	6	5	5	4	4	6	6
Vert. Flight Path	6	6	7	7	8	8	6	6
Airspeed	6	6	5	5	4	4	6	6
Descent/Ascent Rate	6	6	5	5	4	4	6	6

altitude specified by LVL CHG. Hence the source of the trigger extended from the goals of the pilot and the state of the system.

The major factors affecting the trigger were as follows and are displayed in Figure D.13.

- System State
- Automation Mode

System State - The system state reaching a preprogrammed value was the precise trigger of this transition, consistent with a scripted control automation scheme.

Mode - The mode prior to the transition was was that which was designed for adaptive control. Therefore, it was this mode's own inherent programming which triggered the mode transition, making it a system triggered transition (as opposed to an operator triggered transition).

D.4.3 Factors, Mechanisms and Design Lessons

Factors in the Transition

Based on Endsley's updated model, the following factors were identified as applicable to this transition case.

- System State
- Environment State
- LOA Disparity
- Mode

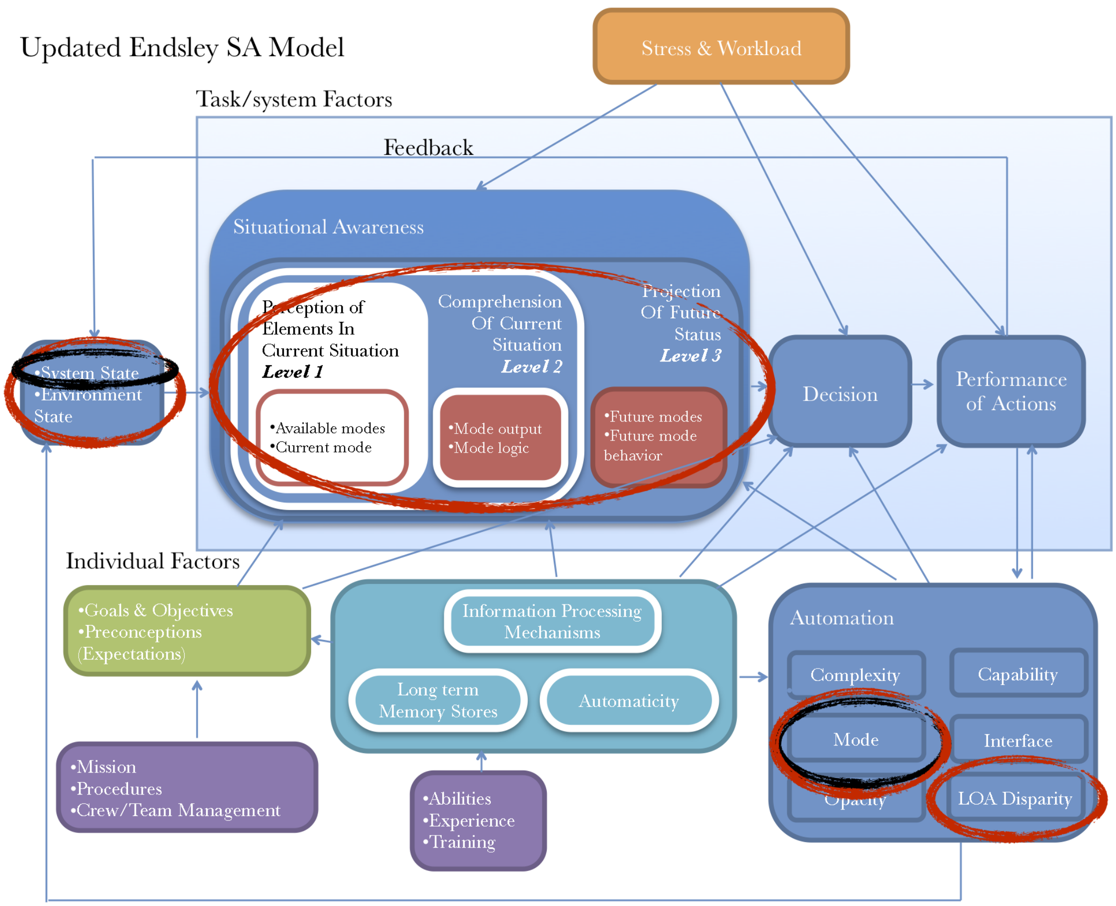


Figure D.13: Factors in the Aeroflot-Nord Flight 821 Transition Case 2

- General situational awareness (All levels)

System State - The system state was relatively stable during the transition, which reduced the overall workload of the crew during the transition allowing for it to occur more gracefully.

Environment - Along the same vein as system state, the relative absence of a large mount of dynamism form the environment kept stressors to the crew at a reasonable level, allowing for the transition to take place more gracefully.

LOA Disparity - The transition took place between to similar modes. By making a transition between two modes closely related in terms of levels of automation, the new amount of control loops requiring prior knowledge to control was reduced, allowing for an easier transition between modes.

Mode - The modes being switch between were of relatively low difficulty, making the end states on either side of the transition not particularly taxing on the operator. It is conceivable that, had these modes been significantly more difficult, the transition would not have proceeded as gracefully.

General situational awareness (All Levels) - There is no indication that the pilots' situational awareness regarding this transition was insufficient. While an insufficiency might just be masked by the automations own abilities, the relative ease and intuitiveness of the modes being considered suggests the pilots' ability to understand the actions of the automation, thereby contributing to the grace of the transition.

Mechanisms of Gracefulness
As this transition occurred in a graceful manner, it would only be beneficial to note that there were no particularly identifiable mechanisms of "ungracefull" transition, nor were there any positive mechanisms of grace. Instead, all that can be deduced from this example is that the model worked well, with the operator retaining enough attention resources throughout to successfully and accurately process information at all four stages in the cognitive process shown in Figure D.14.

Design Principles and Lessons
This particular transition was particularly graceful. Based on the factors identified, it is suggested that any procedural transition be programmed to occur when system states and environmental states are relatively calm. This reduces the overall workload of the operators, reducing stressors and increasing the amount of attention that they can devote to the transition. Additional attention provided for the transition then allows them to quickly understand the internal state variables associated with any new control loops into which they are being inserted.

Probably the most effective means of ensuring the gracefulness in this transition was the low disparity between the levels of automation between both of the modes. By keeping

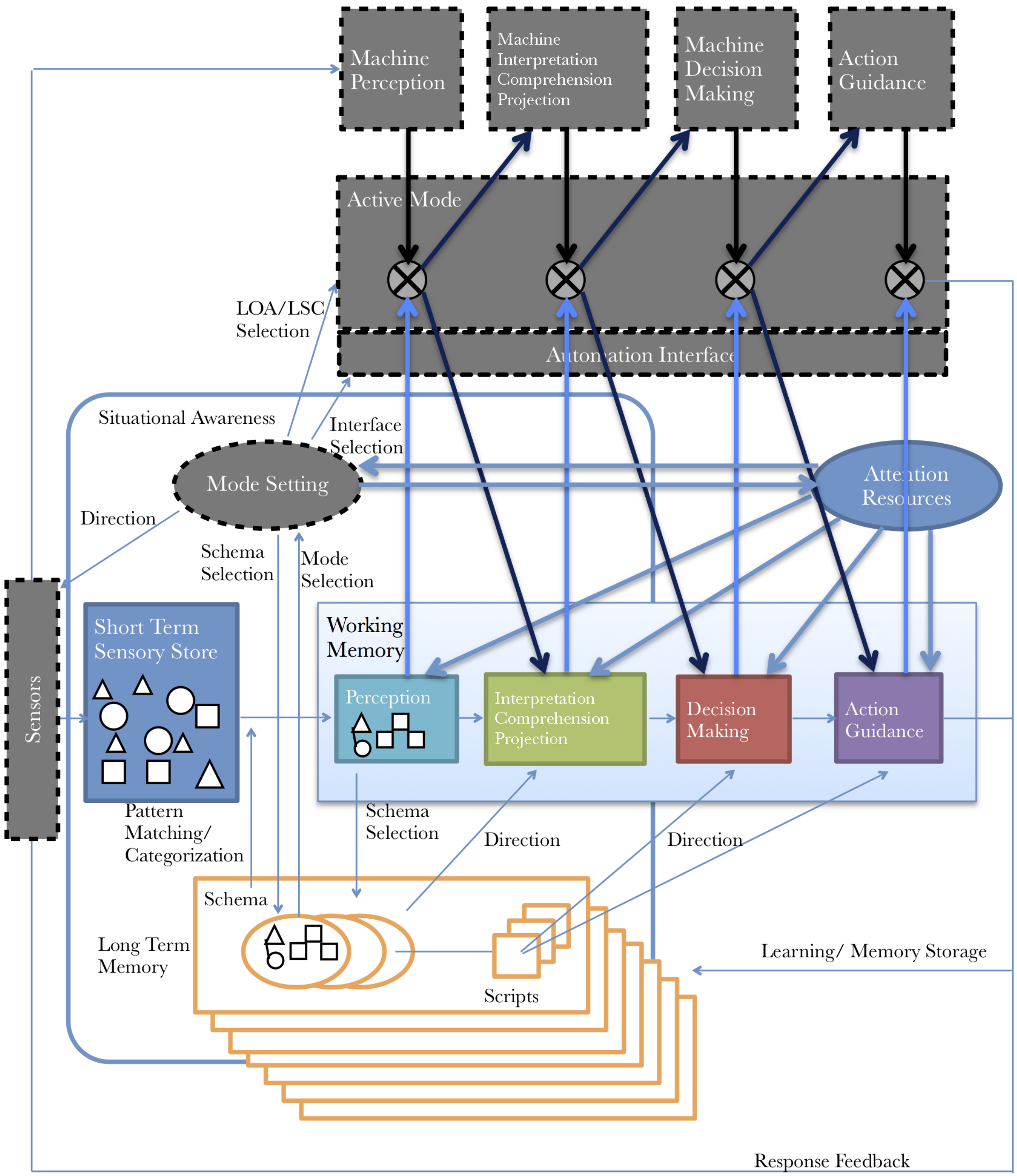


Figure D.14: Mechanisms of grace in Aeroflot-Nord Flight 821 Transition Case 1 these modes close relative to this measure, the system was able reduce the number of loops that the operator had to take on during the transition (zero in this case).

While the modes were extremely close together, it is conceivable that such a transition could become ungraceful had the pilot's not understood the logic or the actions of the system; however, as far as can be discerned from the MAK report, no situational awareness was lost during this transition, retaining the inherent gracefulness associated with such a minor mode transition.

It is thus suggested that the disparity between levels of automation be reduced to a minimum during any mode transition. Additionally, the pilot's understanding of the automation needs to be ensured by keeping them in the programming loop of the automation. For example, the "assigned altitude" here was 600 m, which suggests that the pilots had preprogrammed this and thus had knowledge of the future mode of the automation.

D.5 Transition Case 3

The transition considered here is the switching of the system into the LNAV mode at 23:06:44. The report details the transition as follows:

> At 23:06:44 one of the pilots selects the LNAV mode. Most probably it was done by mistake, when trying to select the VOR/LOC mode (the mode pushbuttons are next to each other), which was actually selected a bit later.

The LNAV mode is described as mode whose function is to fly the preprogrammed route in the FMC. It is unknown what this would have effected in the system (FMC programming unknown); however, this is not necessary to know as the next transition considered happened directly following this "inadvertent shift." Prior to this, the aircraft had been operating in ALT HOLD and HEADING SEL. Throttles were being manually controlled.

D.5.1 The Modes

Sheridan and Verplank LOA

Attitude Control - Prior to the transition, the system was operating in HEADING SEL. As discussed in prior transition cases, this mode is primarily concerned with the control of the lateral flight path. It accomplishes this control via lateral attitude control. Additionally, the use of ALT HOLD also control the vertical flight path through attitude (and thrust). Either rate, attitude is being fully controlled as the inner loop of these other control processes. As such, prior to the transition the system was operating at Level 7. Following the transition, the system was still operating at Level 7.

Thrust Control - Prior to the transition, the throttles were being controlled manually with the computer only offering assistance through display automation. As such, the system was operating at Level 2. Following the transition, the system was still operating at Level 2.

Lateral Flight Path Control - Prior to the transition, as discussed earlier, the system was operating in HEADING SEL. As such, the system was operating tat Level 7. Following the transition, the system was still operating at Level 7. The only significant different between these two modes is the method of goal input.

Vertical Flight Path Control - Prior to the transition, the system was operating in ALT HOLD, which can be considered Level 7. This did not change during the course of the transition, and so the mode following the transition was still Level 7.

Airspeed Control - The airspeed is highly coupled with thrust control, which was being operated manually and attitude control, which was highly automated. Again, the issue arises of multiple inputs into a single controlled-variable. This mode of operation can be most nearly described as Level 4. This was also the case following the transition.

Descent/Ascent Rate Control - As the vertical flight path control was being handled by the mode ALT HOLD, so was the descent/ascent rate being controlled. As such, prior to the transition the system was operating at Level 7. Following the transition the system was still operating at Level 7.

It is worth noting that in all controlled tasks, *there was not change in the LOA*. These modes of operation are virtually identical when considered in this way.

These levels are shown in Figure D.15 and Table D.5.

Table D.5: Case 3 - Sheridan and Verplank LOA

Case 3 - Sheridan and Verplank LOA		
Control Task	*Prior*	*Post*
Attitude	7	7
Thrust	2	2
Lat. Flight Path	7	7
Vert. Flight Path	7	7
Airspeed	4	4
Descent/Ascent Rate	7	7

Proud and Hart LOA

The breakdown according to the LOA suggested by Hart and Proud mirrors that described in transition Case 2. In the case of both lateral flight path control and attitude control,

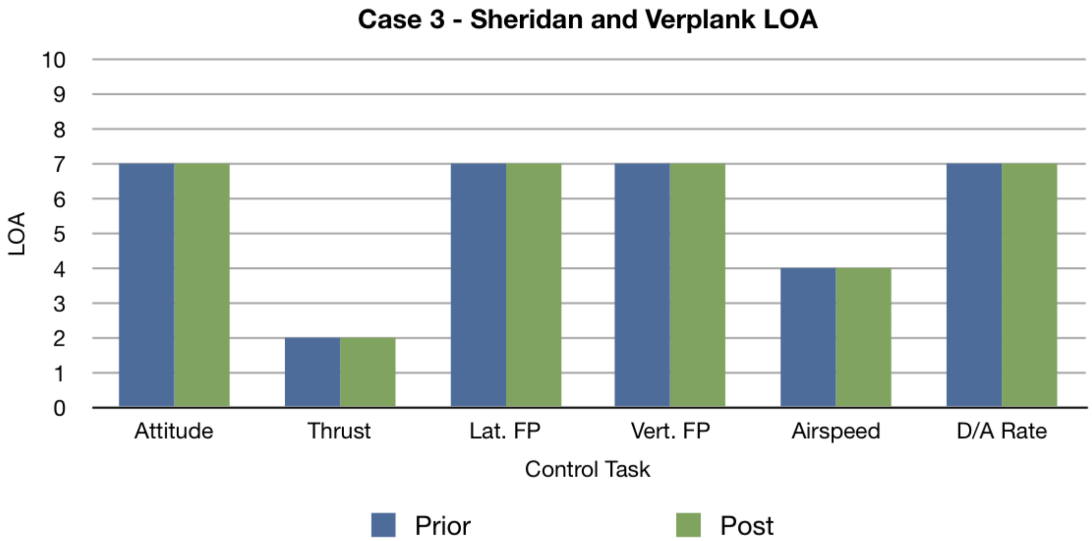


Figure D.15: Case 3 - Sheridan and Verplank LOA

the two modes most relevant to the LNAV mode change, the only change made was the source of the goal states, which falls outside the realm of the LOA classification based on the description provided earlier of the flying task. As such, no LOAs are traversed in this transition.

It should be noted that the pilots had access to an out the window view as well as unfiltered vestibular cues. As such, particularly concerning the observe phase, any filtering and highlighting specifically refers to the automation display of the environment and/or state of the vehicle.

These levels are shown in Figures D.16 - D.19.

D.5.2 The Trigger

The trigger for this mode is the most interesting facet. The report suggests the most probably reason for this mode change was a slip by the operate: they meant to press the VOR/LOC button, but instead hit the LNAV button.

As such factors involved in the mode change were the pilot's own automaticity and the interface of the autopilot which caused this slip. Additionally, these factors influenced the performance of the final action by the operator. These can then be mapped to the blocks within the updated Endsley SA Factors Model:

- Operator Automaticity

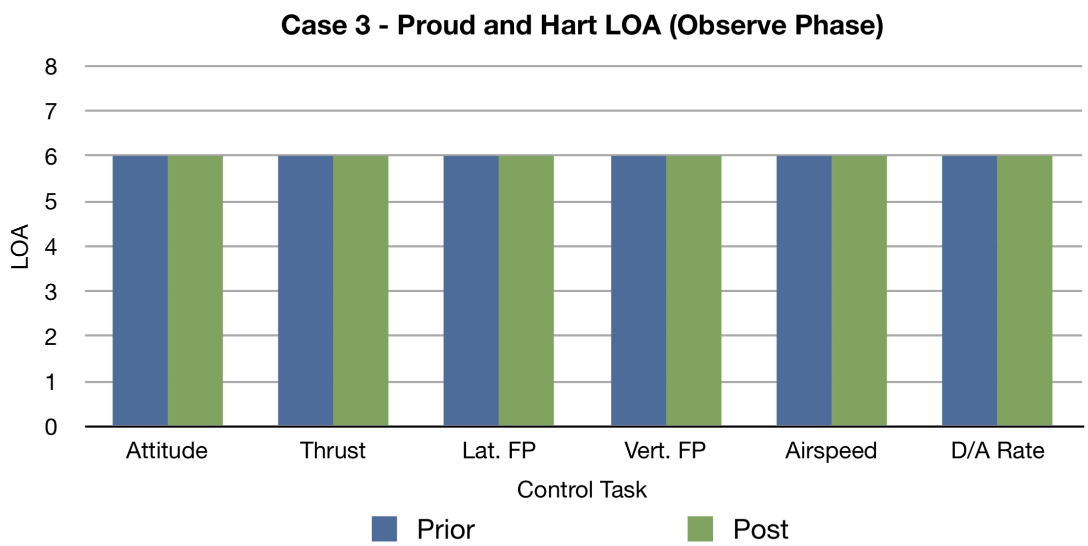


Figure D.16: Case 3 - Proud and Hart (Observe Phase)

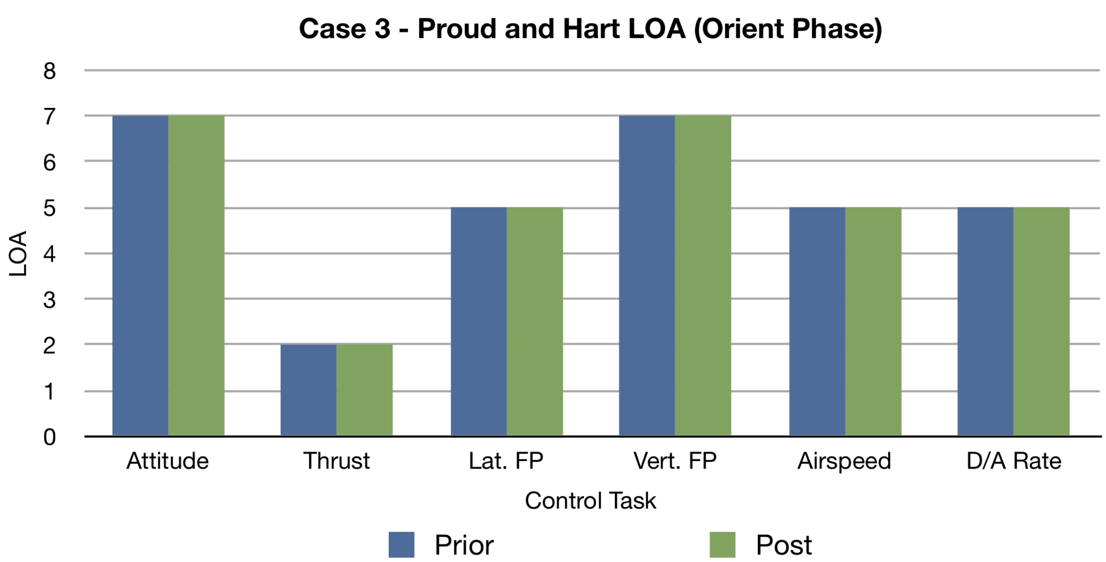


Figure D.17: Case 3 - Proud and Hart (Orient Phase)

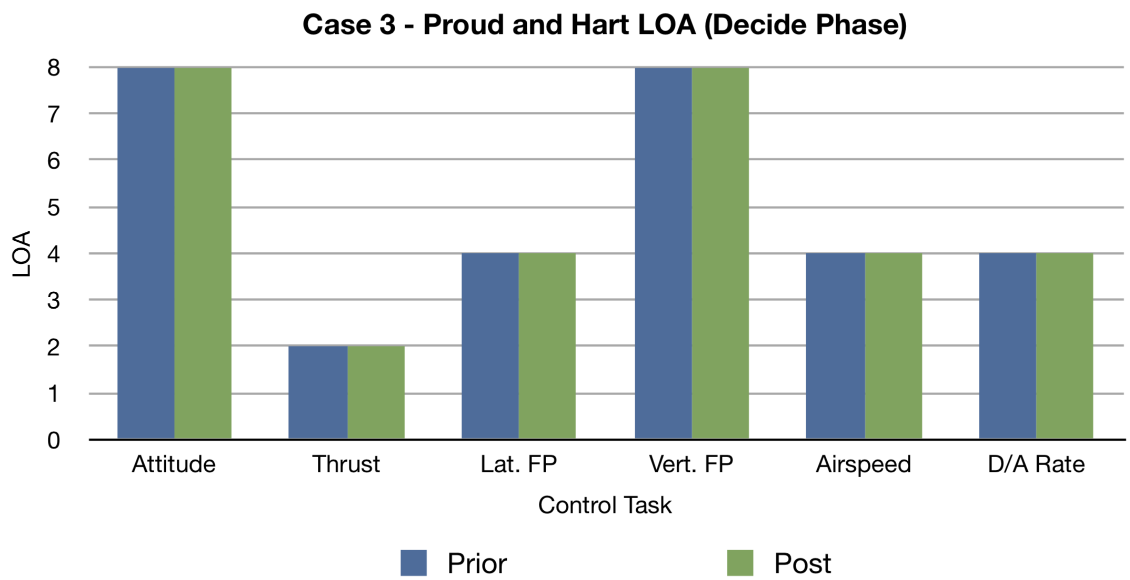


Figure D.18: Case 3 - Proud and Hart (Decide Phase)

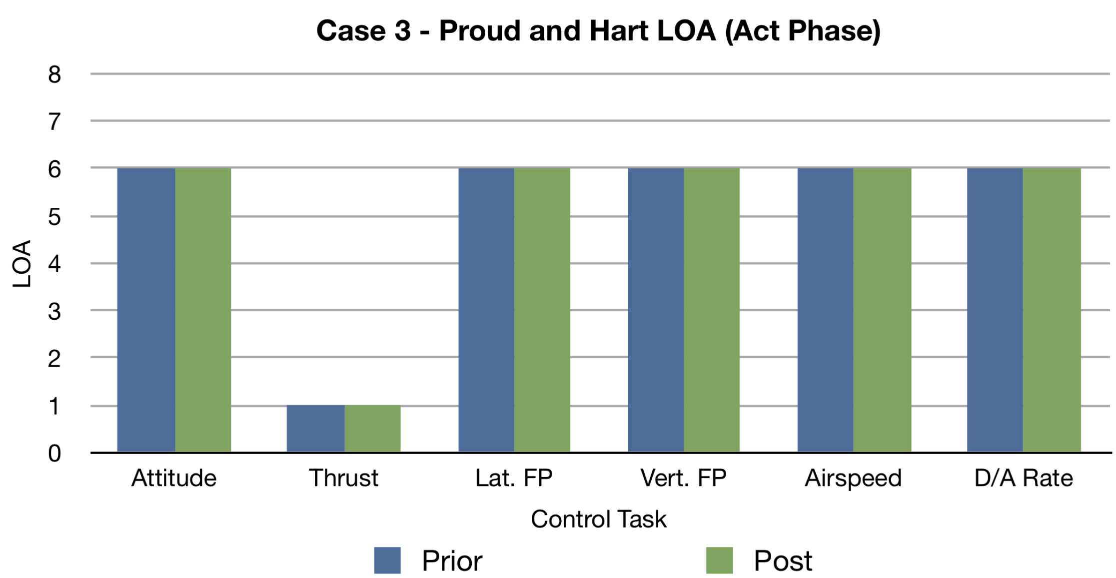


Figure D.19: Case 3 - Proud and Hart (Act Phase)

- Performance of Actions
- Decision
- Automation Interface

Operator Automaticity - The operator's automaticity in pressing that button allowed him to place less attention on that action. While this is a legitimate coping mechanism employed by operators to successfully allocate attention in a high-demand situation, in this case it led to a mistaken mode transition. Had the action not been so automatic, the mode switch never would have been triggered.

Performance of Actions - Operator automaticity, as shown in the model, feeds directly into the Performance of Actions block, which is where the failure took place. In this transition, this block serves to represent the melding of two major factors, automaticity and automation interface, which led to the supposed slip by the user.

Decision - The operator's decision to VOR/LOC was, by virtue of the other cumulative factors mentioned in this section, the root trigger of the mode transition. This is an important occurrence: the compounding effects in the operator and the automation served to alter a correct action decision into a faulty action.

Automation Interface - The automation interface was set up in a way which allowed for the operator slip to occur, and thus was a factor in the triggering of the transition.

These triggering factors are shown in Figure D.20.

D.5.3 Factors, Mechanisms and Design Lessons

Factors in the Transition

This transition took place in the midst of a large amount of activity by the crew, and due to the transition being triggered by a mistaken input, it must be classified as ungraceful. While situational awareness was maintained with respect to this particular transition (or at least as far as can be deduced from the accident report), performance was suffering due to the close proximity to other control tasks that were occurring as well as other mode transitions. Hence, the following factors were deemed as contributing to the lack of grace in this transition:

- System State
- Stress & Workload
- Operator Abilities, Experience, and Training
- Mode situaitonal awareness (Level 1)

System state - The system was actively turning at the time and ,when reviewing the report, one will see that this transition was closely followed by a transition into the CWS modes.

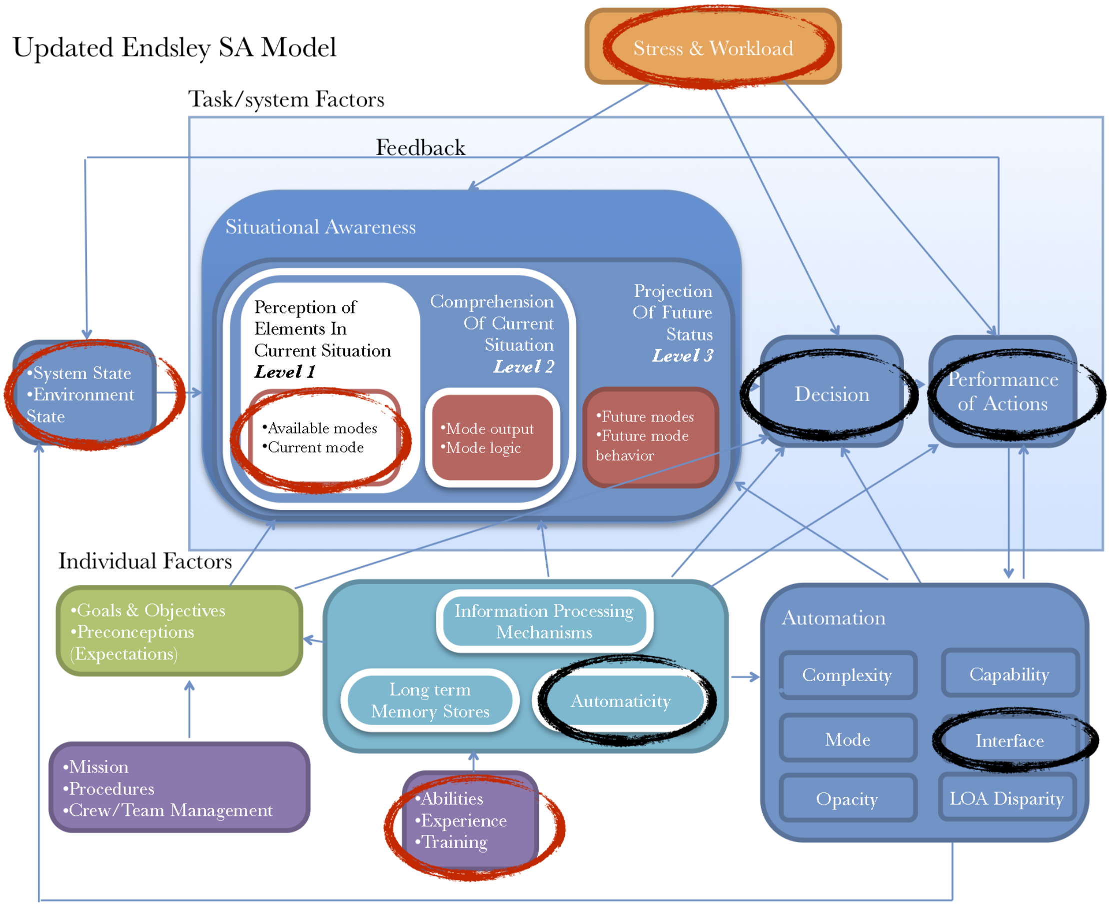


Figure D.20: Factors in Aeroflot-Nord Flight 821 Transition Case 3

This next transition was a result of the highly active state of system, which was giving rise to a high stress and workload.

Stress & Workload - These factors were key in making this transition less graceful than it ought to have been. Due to the highly dynamic state of the system, the large amount of functions which needed to be performed, and the lack of the operator abilities, experience, and training, stress and workload were extremely high. This factor has a compounding effect due to its interconnection with these other factors: as stress and workload increased the pilots became less able to deal with the situation, which led to more stress and workload, somewhat like an unstable feedback loop.

Operator Abilities, Experience, and Training - The lack of abilities, as discussed just previously, did not allow for the operators to control the system in a way which would have led to a graceful transition.

Mode siutuaitonal awareness (Level 1) - The fact that the transition happened by mistake suggests that the situational awareness of the current mode of the system was incomplete immediately following the transition. Hence, by the definition of grace this transition was ungraceful due to this lack of situational awareness.

These factors effecting the gracefulness of the transition are shown in Figure D.20.

Mechanisms of Gracefulness
Based on the update version of Endsley's SA mechanisms model, the following mechanisms were identified as relevant to this mode transition:

- Mode Setting
- Attention Resources
- Action Guidance
- Operator Schema
- Automation Interface

Mode Setting - The mode setting was faulty as not enough attention resources were able to be allocated to this process to maintain its full functionality. As such, this flowed down to the the schema temporarily selected by the pilot. While this schema didn't particularly effect the performance of the system, it does represent an ungraceful transition: a graceful transition would have seen the correct schema applied throughout the transition.

Attention Resources - Due to the large workload at the time, attention resources were scarce during the transition. As such, this directly affected the mode setting process. This also had a direct flow down to the action guidance block.

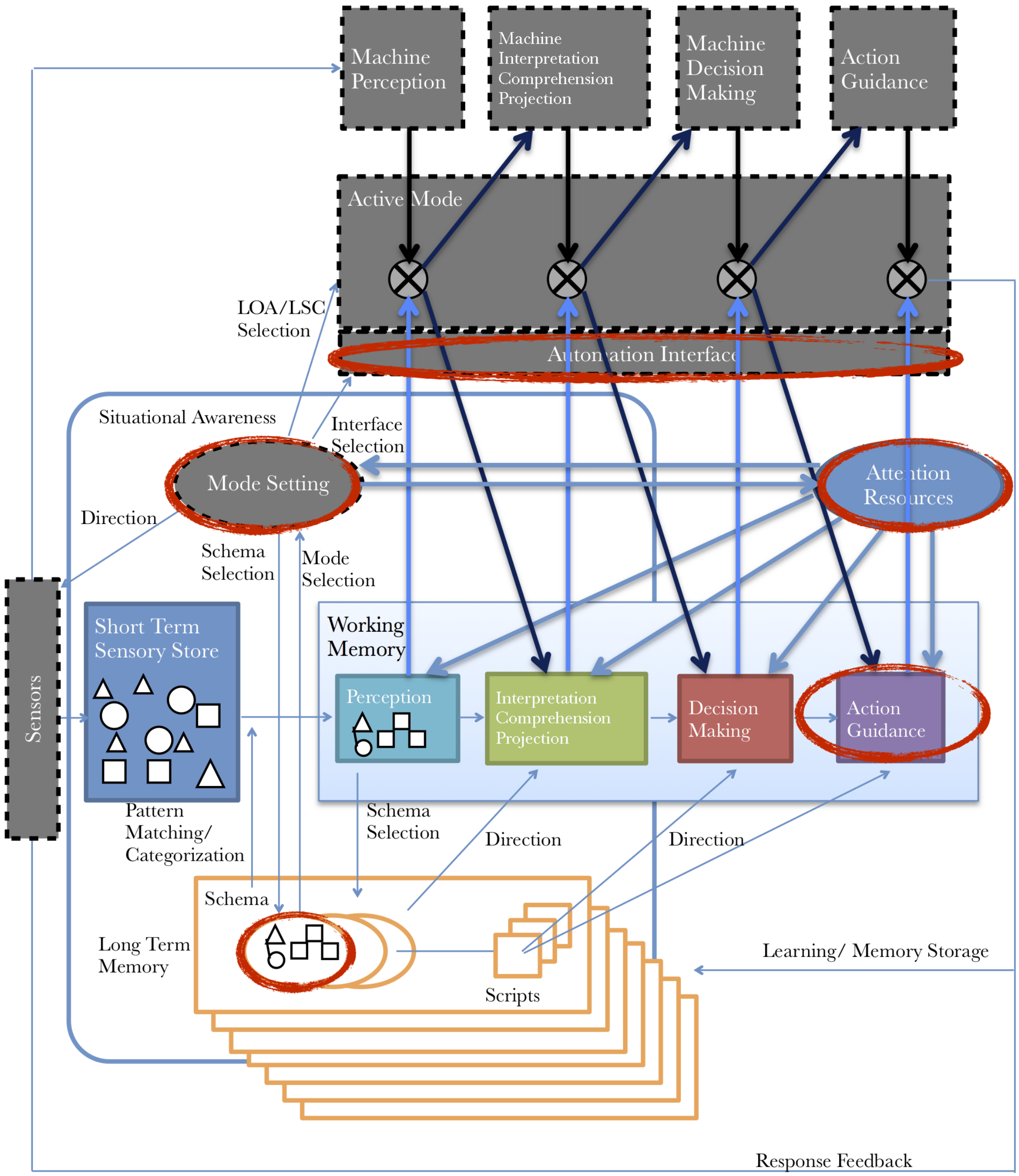


Figure D.21: Mechanisms in Aeroflot-Nord Flight 821 Transition Case 3

Action Guidance - This process was affected by the interaction of attention resources and the requirements of the automation interface. Think in terms of quotas, the automation interface was requiring that a certain amount of attention be allocated to it, attention which was not available. As such, this lack of attention resulted in the mis-application of the action guidance block, resulting in the triggering of the transition. Since the system was already in a compromised state, the transition could be anything other than ungraceful.

Operator Schema - Since the trigger of the transition was a mistake, it is impossible for this to have been perfectly applied throughout the transition. While performance was relatively maintained, given the surrounding circumstances, this schema conflict represents a loss of situational awareness, and thus a lack of transition grace.

Automation Interface - The requirements of the automation interface given its design required a certain level of attention allocation and performance from the action guidance block which could not be met. This deficiency was the root of the initial problems in the transition.

These mechanisms of gracefulness are shown in Figure D.21.

Design Principles and Lessons
The major design lesson here is to follow good display design principles: design the display to reduce the possibility of such slips occurring. A larger readout panel, more separation between buttons, following Gestalt grouping principles, and customized tactile cues for the buttons all might have prevented this mistake from occurring. All of these principles provide a means for better human-to-computer communication.

Additionally, the recurrence of attentional resources suggests this to be a major part of a graceful transition. If attentional resources are not available, this has a direct flow down for the rest of the transition. Therefore, making transitions which require less attentional resources, either by improving the circumstances in which they occur or structuring them in a way that spreads attentional demands over time should make a transition more graceful.

D.6 Transition Case 4

The transition considered here is the switching of the system from LNAV into both CWS ROLL and CWS PITCH Mode. The report details the transition as follows:

> Only at 23:06:48, when the left bank reached 32°, the Co-pilot applied more right wheel, switching the autopilot to the CWS ROLL mode....

Probably the Co-pilot was not familiar with the CWS mode, as he also inadvertently applied force in the pitch channel, switching the autopilot also to the CWS PITCH mode.

D.6.1 The Modes

Sheridan and Verplank LOA

Attitude Control - Prior to this transition, the system was operating at Level 7 (see previous transition Cases for further explanation). Following the transition, the system had switched to CWS ROLL and CWS PITCH mode.

The CWS modes do not fit particularly well into the Sheridan and Verplank Levels of Automation. The CWS modes, CWS standing for Control Wheel Steering, work by holding a particular aircraft attitude upon the release of the control wheel, provided that it outside a specified dead zone (6 degrees bank in the 737). The attitude can be changed in this mode if the pilot provides a specific amount of force with his or her input. This mode of operation best fits in the"execution by approval" LOA described by Sheridan. Hence, following this transition, the system is operating in at Level 5.

Thrust Control - Prior to the transition, the human had been was fully in charge of thrust management, and the system was operating at Level 2 (see previous transition cases). Following the transition this did not change.

Lateral Flight Path Control - Prior to the transition, the system had been operating in the LNAV mode, and in HDG SEL mode just prior to that. Both of these modes seek to control, primarily, the lateral flight path by affecting the attitude of the aircraft. Hence, before the transition the system was operating at Level 7. Following the transition, the system was operating in the CWS modes, which are only concerned with vehicle attitude and do not consider lateral (or vertical) flight path. Hence, the system was now operating at Level 2, as only minor trend holding is provided in this mode.

Vertical Flight Path Control - Prior to the transition, the system had been operating in ALT HOLD mode (see the previous transition case). This placed the system at Level 7. Following the transition, the system had switched into CWS PITCH mode, which disregards the vertical flight path (although it will eventually attain some form of a constant path) and only seeks to control pitch by holding constant unless the human intervenes. As such, the system was operating at Level 2.

Airspeed Control - Airspeed prior to the transition, was being managed (see previous transition cases regarding this assumption) by the computer partially, as attitude control effects on the airspeed were being mediated by the computer, but the human was in direct control of thrust. As As such, the system was operating in a regime that most closely resembles Level 4. Following the transition into the CWS ROLL and CWS PITCH modes, this control was not present, and the system was now operating at Level 2 with respect to airspeed control. The transition is not to Level 1 because the computer still offers assistance through display automation.

Descent/Ascent Rate Control - Prior to the transition, descent/ascent rate control was being handled by the ALT HOLD function, which placed the system at Level 7. Following the transition to CWS PITCH mode, this was no longer the case, and descent/ascent rate was being set by the user via the commanded pitch. The holding of pitch still did provide some descent/ascent rate control, in that it would hold constant if left alone. Hence, the system was operating at Level 2.

These levels are shown in Figure D.22 and Table D.6.

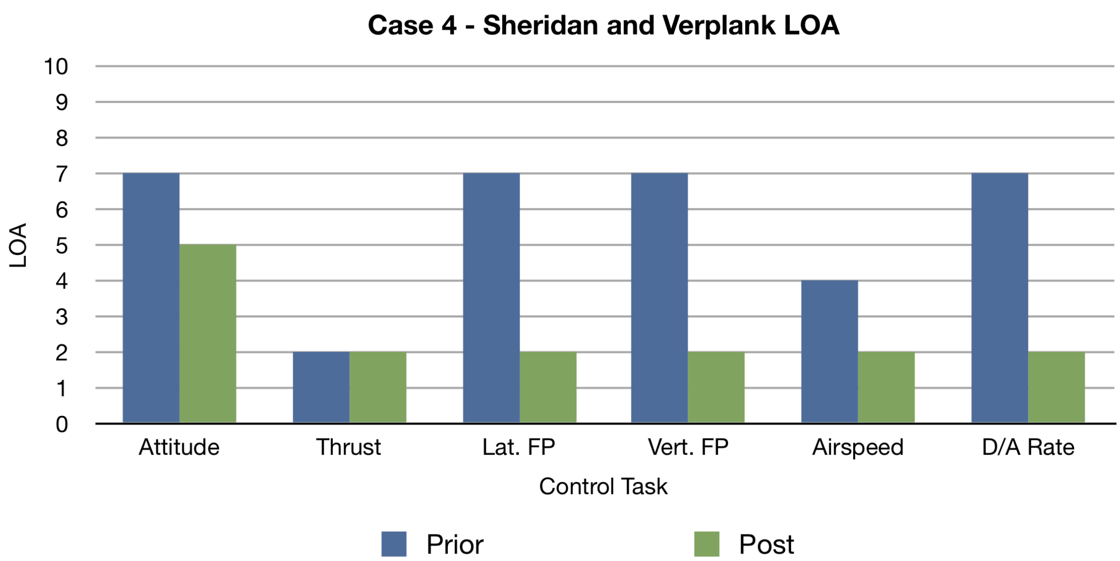


Figure D.22: Case 4 - Sheridan and Verplank LOA

Proud and Hart LOA
Observe Phase - Prior to this transition, the system was in charge of all data that was presented to the human. The inherent limits of electronic displays means that this displayed data was filtered, and the multilayer nature of the PFD and the other displays in the cockpit describe this information as being both prioritized and highlighted. As such, the system was operating at Level 6. Following the transition, this was still the case.

It is worth noting that there were vestibular cues as well as an out-the-window view available to the pilot. In some was this can be considered either as a parallel data gathering system, or as an effective way to reduce the Level of Automation.

Attitude Control

Table D.6: Case 4 - Sheridan and Verplank LOA

Case 4 - Sheridan & Verplank LOA		
Control Task	*Prior*	*Post*
Attitude	7	5
Thrust	2	2
Lat. Flight Path	7	2
Vert. Flight Path	7	2
Airspeed	4	2
Descent/Ascent Rate	7	2

- Orient - Prior to the transition the system was operating in LNAV mode and as such was operating at Level 5 (see previous transition cases). Following the mode transition, the system was now operating at in CWS ROLL and CWS PITCH modes. These modes still directly control the attitude of the aircraft and require that the computer interpret, integrate, and project sensor data in order to control the system; however, the human is placed in a position contingency operation still. As such, the system is still operating at Level 5.
- Decide - Prior to the transition, the system was operating at Level 4 (see previous transition studies). Following the transition, the human decision making process was now considered to be of higher priority, and as such the system was now operating at Level 3.
- Act - Prior to the transition the system was operating at Level 6 (see previous transition cases). Following the transition, the system was operating in a regime that closely resembles an authority to proceed (the human sets the roll or pitch angle and the computer holds this command). As such, the system is now operating at Level 3.

Thrust Control

- Orient - Prior to the transition, the system was operating at Level 2 (see previous transition cases). This did not change following the transition.
- Decide - Prior to the transition, the system was operating at Level 2 (see previous transition cases). This did not change following the transition.
- Act - Prior to the transition the system was operating at Level 1 (see previous transition cases). This did not change following the transition.

Lateral Flight Path Control

- Orient - Prior to the transition the system was operating at Level 5 (see previous transition cases). When the system switched to CWS ROLL, the human was now placed in charge of a majority of the integration tasks, placing the system at Level 2 following the transition.
- Decide - Prior to the transition, the system was operating at Level 4 (see previous transition cases). Following the switch to CWS ROLL, the system began to operate in at Level 2, with the computer only being used as an assistant in the control decision process.
- Act - Prior to the transition, the system was operating at Level 6 (see previous transition cases). With the switch to CWS ROLL, the system was now operating at Level 2 with respect to lateral flight path control. It is important to note that while the computer was only handling attitude and only handled lateral flight path management to the point that a held bank angle controls this.

Vertical Flight Path Control

- Orient - Prior to the transition the system operating at Level 7 (see previous transition cases). Following the transition, the system was operating in CWS PITCH mode. This places the human in charge of most interpretation, integration, and prediction tasks related to vertical flight path control. The computer still acts as an assistant in this respect. Hence, the system was operating at Level 2.
- Decide - Prior to the transition, the system was operating at Level 8 (see previous transition cases). Following the transition, the system was operating at Level 2. This is because the computer now began to only be used as an assistant in the pilot's decision process.
- Act - Prior to the transition, the system was operating at operating at Level 6 (see previous transition cases). Following the transition, the system began operating at Level 2, in which the human was responsible for major task executions, but used the computer as a backup control system.

Airspeed Control

- Orient - Prior to the transition the system was operating at Level 5 (see previous transition cases). Following the transition, the system was operating at Level 2, in which the human is responsible for all interpretation and prediction of data. The display still helps with integration as an assistant.
- Decide - Prior to the transition, the system was operating at Level 4 (see previous transition cases). Following the transition the human is now primarily in charge of

all major control inputs, with the computer being used as an assistant in this respect. As such, the system is operating at Level 2.

- Act - Prior to the transition, the system is operating at Level 6 (see previous transition cases). Following the transition, the system is now operating in a way that has the human executing all major control actions and the computer acting as back up by maintaining the inner loops of attitude control. Hence, the system is operating at Level 2.

Descent/Ascent Rate Control

- Orient - Prior to the transition, the system is operating at Level 5 (see previous transition cases). Following the transition, the system is now operating at Level 2, in which the computer only acts as an assistant in the integration of the data from the Observe phase.
- Decide - Prior to the transition, the system is operating at Level 4 (see previous transition cases). Following the transition, the system shifted to Level 2, in which the computer is now only being used a tool to assist in the enumeration and selection of control options.
- Act - Prior to the transition the system was operating at Level 6 (see previous transition cases). Following the transition, the system shifted to Level 2, with human handling major control inputs regarding ascent/descent rate. The computer, through the handling of attitude played the role of a backup system in the control of this parameter.

Table D.7: Case 4 - Proud and Hart LOA

Case 4 - Proud and Hart LOA								
Control Task	Observe		Orient		Decide		Action	
	Prior	Post	Prior	Post	Prior	Post	Prior	Post
Attitude	6	6	5	5	4	3	6	3
Thrust	6	6	2	2	2	2	1	1
Lat. Flight Path	6	6	5	2	4	2	6	2
Vert. Flight Path	6	6	7	2	8	2	6	2
Airspeed	6	6	5	2	4	2	6	2
Descent/Ascent Rate	6	6	5	2	4	2	6	2

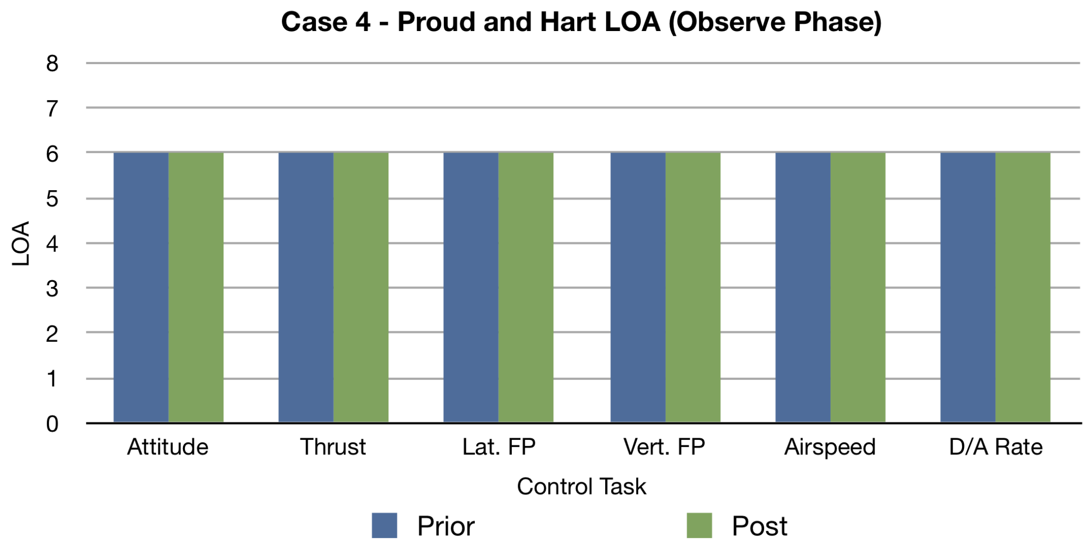


Figure D.23: Case 4 - Proud and Hart (Observe Phase)

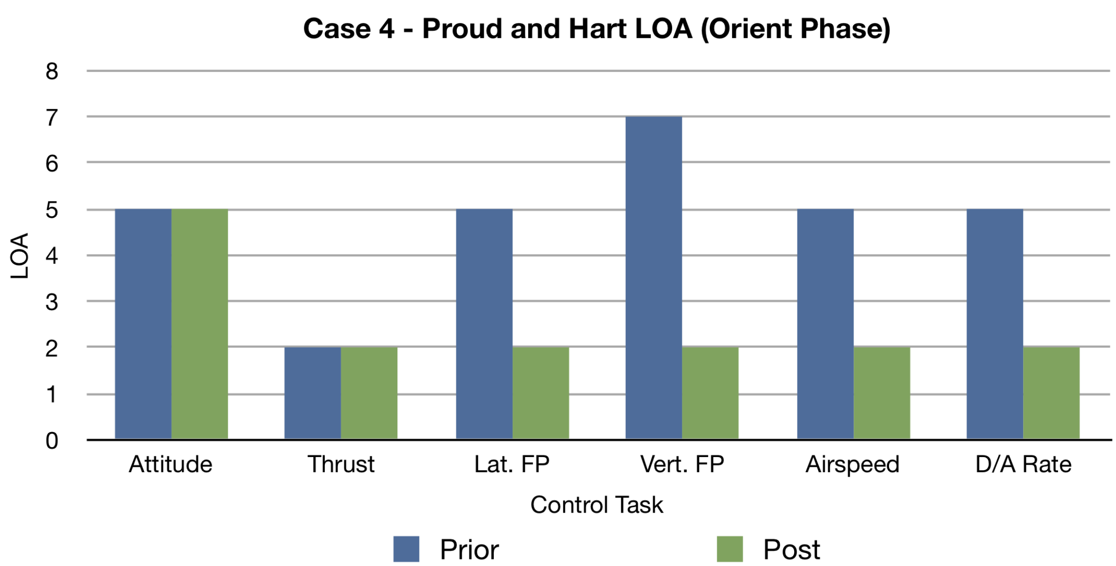


Figure D.24: Case 4 - Proud and Hart (Orient Phase)

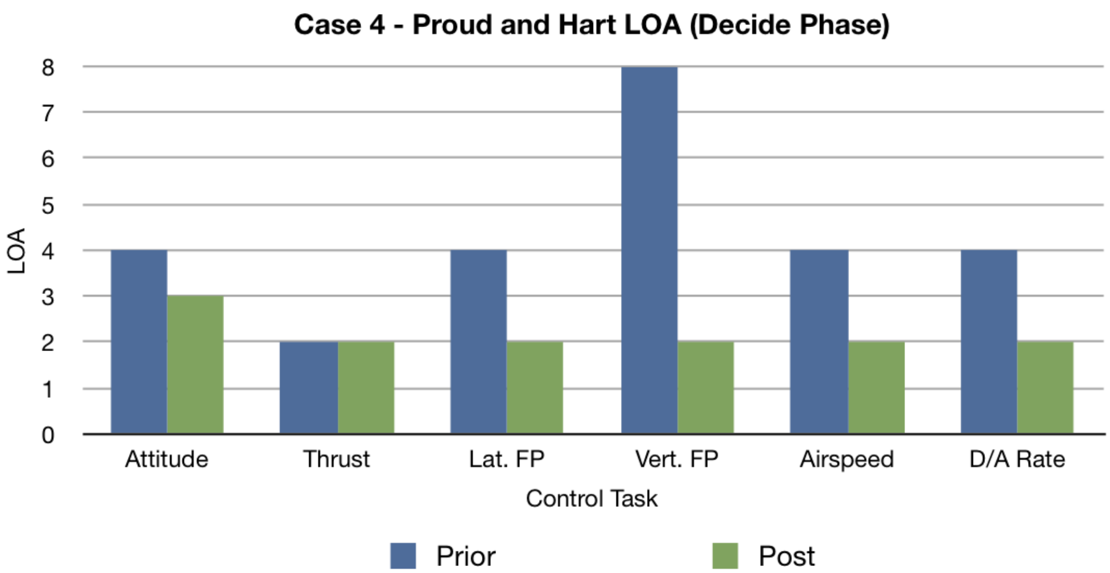


Figure D.25: Case 4 - Proud and Hart (Decide Phase)

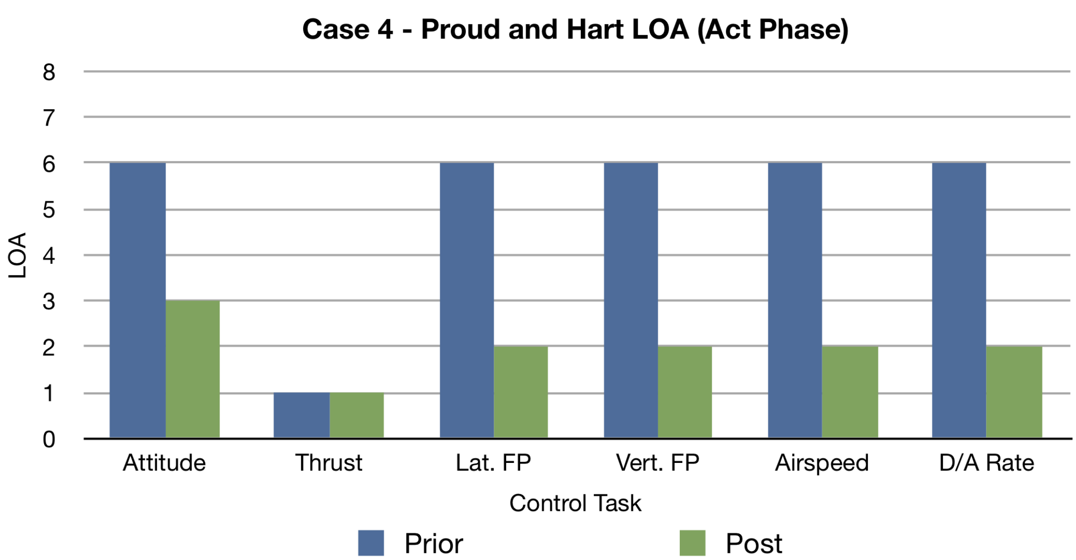


Figure D.26: Case 4 - Proud and Hart (Act Phase)

D.6.2 The Trigger

The trigger for this transition was the input of the human into the system which exceeded a preset threshold; any control wheel inputs beyond the said threshold would automatically transition the plane into these modes.

The surrounding circumstances describe the plane as entering into a bank at a steady 2 deg/sec rate. The pilot input into the control wheel was an attempt at arresting this motion. Hence, the trigger source was the pilot's detection of an off nominal state in the system. Additionally, the transition into CWS PITCH was most likely inadvertent, as the the threshold was exceeded while the pilot was manipulating the control wheel in the CWS ROLL mode.

Hence the following factors in the trigger were as follows:

- System State
- General SA (All Levels)
- Automaticity
- Performance of Actions
- Interface

System State - As described earlier, the system reached a state which triggered the operator to make an action input into the system. In this case, that particular system state was one which the operator perceived to be sufficiently out of control that it warranted intervention.

General SA (All Levels) - The general SA of the operator describes his comprehension, perception, and prediction of the system. In this case, a full understanding of the system states in this fashion was the trigger for his action.

Automaticity - In perceiving the motion of the system and in attempting to arrest that motion, the operator's first and automatic reaction was to move the wheel in a direction opposite this motion. Had the operator fully understood what this action would accomplish (namely the transition to CWS modes), a different set of actions would have taken place. Hence, the automaticity of the operator in response to his understanding of the situation was a direct contributor to the triggering of this transition.

Performance of Actions - This was, again, the culmination of all the other trigger factors and was the final triggering mechanism of the transition. The movement of the control stick (an action that can be interpreted in separate ways based on context) was the direct trigger of this transition.

Interface - The user interface mechanism, as just mentioned, was the control stick which has different effects based on context. In normal flight operations its deflection would result effectively in the manual control of the rate of attitude change; however, in this case, the switch triggered the activation of the CWS mode, which controlled the system similarly but also in a subtly different way.

These factors in trigger the transition are shown in Figure D.27.

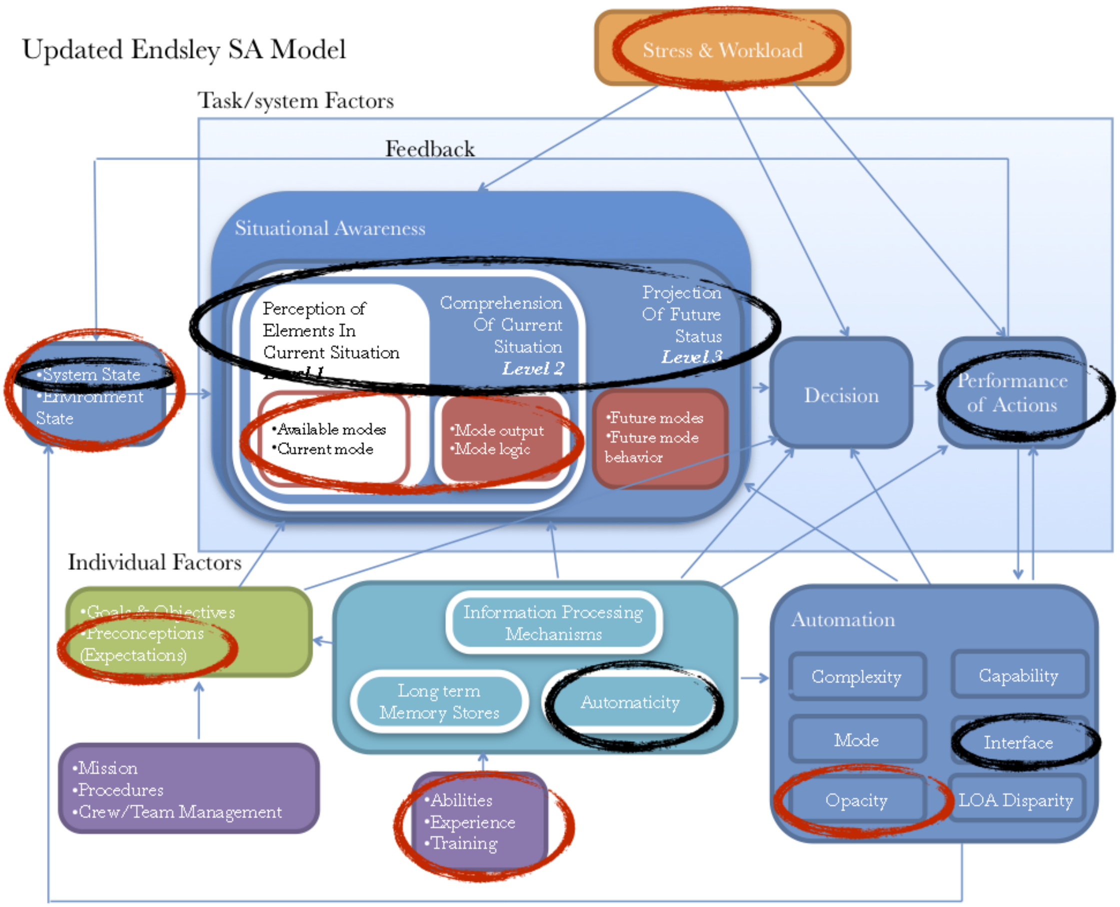


Figure D.27: Factors in Aeroflot-Nord Flight 821 Transition Case 4

D.6.3 Factors, Mechanisms, and Design Lessons

Factors in the Transition

This transition was ungraceful in multiple ways: the high workload involved at the time (not necessarily all of this was because of the mode transition), the lack of mode awareness, and the loss of performance in the system. Based on the updated Endsley model, the following factors were identified as affecting the gracefulness of the transition:

- Operator Preconceptions & Expectations
- Operator Abilities, Experience, and Training
- Opacity
- System State
- Environment State
- Mode Situational Awareness
- Stress & Workload

Operator Preconceptions & Expectations - The operator's preconceptions of the control stick effects was condition based on the context of normal flight operations. Hence, these masked the subtle differences of the new mode and allowed for the operator to remain ignorant of these changes. Only if the operator had been looking or expecting these changes would they have been picked up.

Operator Abilities, Experience, and Training - The lack of training in the CWS mode allowed enabled the operator's preconceptions and expectation to play such a detrimental role. Had experience and training existed in the CWS modes, it is possible that these subtle differences between normal operations and CWS may have been noticed by the operator even though the transition was unintentional.

Opacity - The subtle difference between the modes is a type of opacity in the system, in which the operation of one mode masks the understanding of another mode. In this case, normal operation is so often experienced and so similar in many operations to CWS mode that the use of CWS modes is not directly obvious. Hence, with little experience and a preconception of how the aircraft would fly, this transition was doomed to be ungraceful.

System State - The system states were in quite a dynamic state, splitting the operator's attention. Hence, when the transition took place, the operator relied on his preconceptions of the new flying mode and was not looking for his mode confusion but was instead attending to other matters.

Environment State - The environment of operation was quite hectic at the time, creating an additional drain on the operators attention resources.

Mode Situational Awareness - The lack of understanding of the new mode's control strategy was a key element in the lack of grace in this transition.

Stress & Workload - Both of these were high during the time that the transition took place. The presence of this factor fits the observed trend that this quantity has a significant effect on the gracefulness of the transtion.

These factors in the graceulfness of the transition are shown in Figure D.27.

Mechanisms of Grace
Looking again at the mechanisms model, the deficient mechanisms in this transition leading to a lack of grace can be summarized as follows:

- Attention Resources
- Mode Setting
- Operator Schema
- Operator Scripts
- Interpretation, Comprehension, and Projection
- Automation Interface

Attention Resources - Due to the large workload, associated mostly with tasks secondary to the transition, attention resources were scarce for focusing on the transition. This had a flow down effect on the Mode Setting block, as well as the Interpretation, Comprehension, and Project Block.

Mode Setting - The correct processing of the mode setting block did not occur due to the lack of attention resources. While a transition was triggered, it was not completely understood by the operator. This flowed directly into the Schema Selection.

Operator Schema - By applying the improper schema to the new mode, the operator controlled the system in a way that was not appropriate for the new mode. This effect is subtle because much of the strategies between full manual and CWS Pitch/Roll can be used; however, this is *not completely* the case as was apparent here. In addition to having flow down effect to the applied script, this effected the Interpretation, Comprehension, and Projection Block, which were already operating at suboptimal levels due to the lack of attentional resources.

Operator Scripts - Because the improper schema was applied, this allowed for improper decisions to be made and thus incorrect actions. Nothing suggests that these blocks not functioning properly; there feeding processes were faulty.

Interpretation, Comprehension, and Projection - In applying the wrong schema to the situation, any information passed to this block by the perception block was misinterpreted. As such, this would result in wrong decisions and actions in context of the true system state but in correct actions in context of the interpreted system.

Automation Interface - The difficulty in delineating modes as an artifact of the automation interface was a major mechanism is making this transition not graceful. Additionally, the subtle way in which this mode was activated did also did not provide adequate feedback to

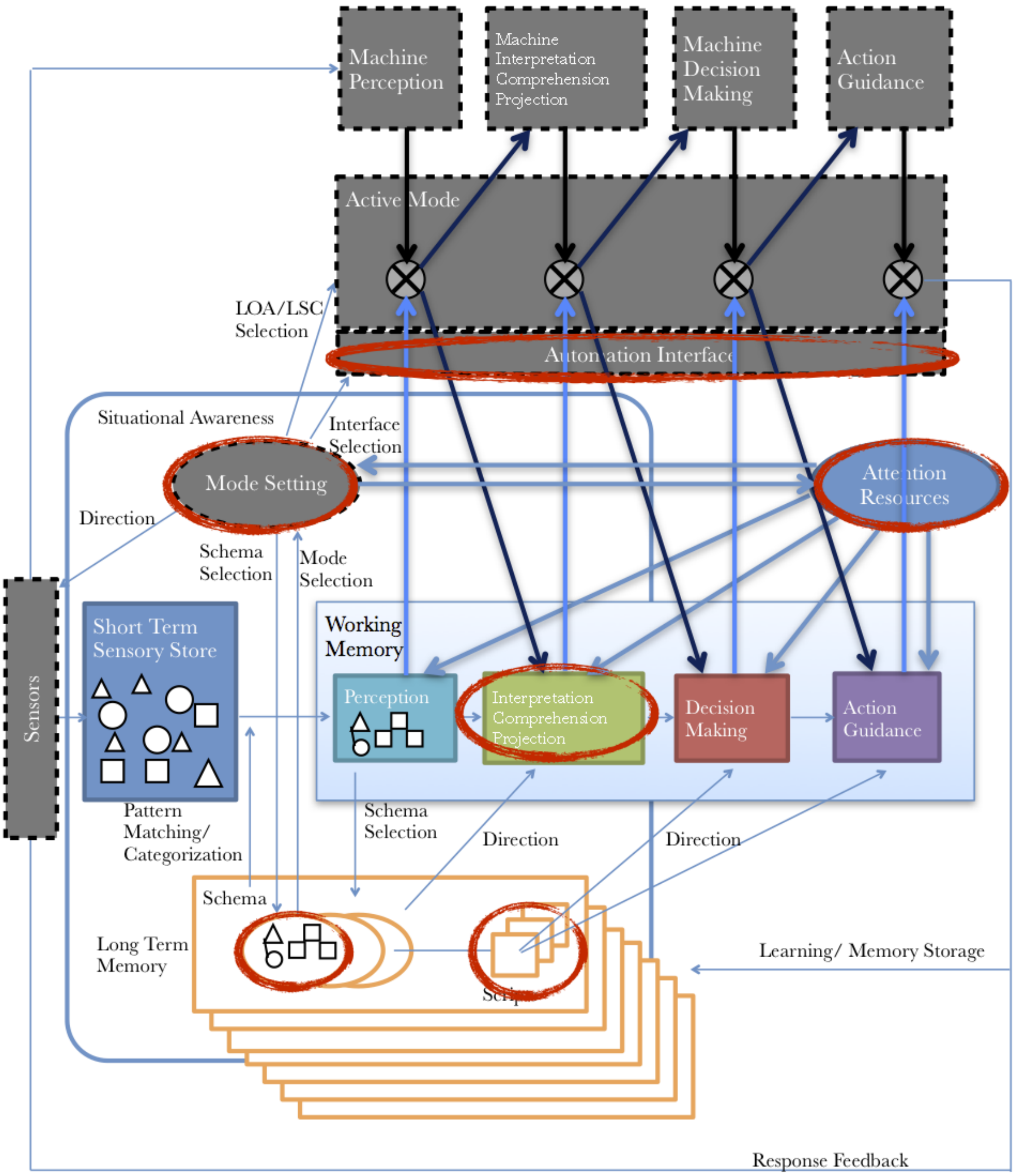


Figure D.28: Mechanisms in Aeroflot-Nord Flight 821 Transition Case 4

the operator for them to understand that they were operating in a mode which they were not expecting.

Design Principles and Lessons

The coupled nature of the modes via the control wheel made was the main cause of the full transition into both CWS modes. Hence, the design of the interface is yet another major mechanism seen in a transition.

The trigger in this transition effected more transitions that it bargained for. In attempting to arrest the banking movement of the plane, the pilot transition to a new level of automation in not only attitude control, but also in vertical and lateral flight path control. The pilot had only been interested in making sure that the plane did not bank any further than it was already banking, but in doing so was burdened with the tasks of navigating as well. Designing the automation to react to the pilots input only in a way that would affect attitude control would have lessened the workload associated with this transition.

The following design features might be considered useful in light of this transition:

- In the case of a modes that are very similar, make sure that any trigger is not a subtle switch but requires a conscious switch by the user. If this is not possible or undesirable, both modes should be thoroughly trained by operators so that an understanding of the subtle difference is second nature.
- Decoupling of mode change triggers by using only buttons for mode switching.
- If the previous suggestion is rejected based on the desire for quick and intuitive mode switching, make sure there is a salient alert to the mode switch and allow for a quick “undo” feature that will return the aircraft to the previous mode. For example, an “undo” button here would have allowed the pilot to have reverted back to ALT HOLD mode instead of remaining in CWS PITCH.
- Allow outer loop modes that deal with such functions as navigation, to dynamically interact with user inputs into the lower order modes. For example, in the case of this transition such a design feature would have updated the LNAV mode to modify the lateral path of the vehicle so that, while the rate of turn was reduced, the programmed waypoint was still the goal state of the computer. Essentially, the user would have been modifying in an indirect way the flight path, but the total navigation task would have still been handled by the computer. Such a design feature would have significantly reduced the workload of the pilot in this case.

D.7 Transition Case 5

The transition considered here is the disengagement of the autopilot to manual control which happened at 23:07:08. The report gives the following explanation:

> As the Co-pilot was controlling the flight in the CWS ROLL and PITCH modes, concentrating on the roll control (by 23:07:21 he had managed to recover from the bank) and the increasing speed (up to 160 knots by 23:07:08), the aircraft started climbing (which was assisted by a significant nose-up moment from the engines operating at 85-90% N1) and 20 seconds after switching to the CWS mode (at 23:07:08), the Co-pilot applying manual stabilizer trim (most likely inadvertently) disengages the autopilot. Neither of the pilots made a relevant callout though one of them switched off the alert that was activated.

D.7.1 The Modes

Sheridan and Verplank LOA

Attitude Control - Prior to transition, the system was operating at Level 5 (see previous transition cases). Following the transition, the system was operating at Level 2, in which the pilot was manually controlling the flight.

Thrust Control - Prior to the transition, the system was operating at Level 2 (see previous transition cases). Following the transition, this did not change.

Lateral Flight Path Control - Prior to the transition the system was operating at Level 2 (see previous transition cases). Following the transition this did not change.

Vertical Flight Path Control - Prior to the transition the system was operating at Level 2 (see previous transition cases). Following the transition this did not change.

Airspeed Control - Prior to the transition the system was operating at Level 2 (see previous transition cases). Following the transition this did not change.

Descent/Ascent Rate Control - Prior to the transition the system was operating at Level 2 (see previous transition cases). Following the transition this did not change.

These levels are shown in Figure D.29 and Table D.8

Proud and Hart LOA

Observe Phase - Prior to the transition, the system was operating at Level 4 (see previous transition cases). Following the transition this is still the case.

Attitude Control

- Orient - Prior to the transition the system was operating at Level 5 (see previous transition cases). Following the transition, the system reverted to a Level 2, in which the human was not solely responsible for interpretation and prediction of attitude

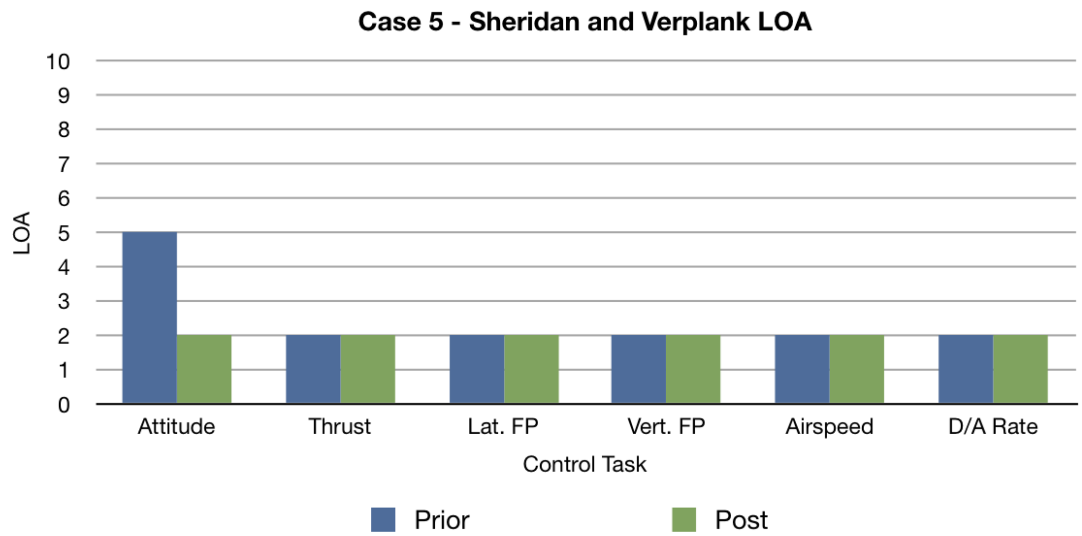


Figure D.29: Case 5 - Sheridan and Verplank LOA

Table D.8: Case 4 - Sheridan and Verplank LOA

Case 4 - Sheridan and Verplank LOA		
Control Task	*Prior*	*Post*
Attitude	5	2
Thrust	2	2
Lat. Flight Path	2	2
Vert. Flight Path	2	2
Airspeed	2	2
Descent/Ascent Rate	2	2

states. The computer was used as a integration tool to the extent that the PFD provides.

- Decide - Prior to the transition the system was operating at Level 3 (see previous transition cases). Following the transition, the system was operating at Level 2, with human providing all the decisions using the computer as an aiding tool.
- Act - Prior to the transition the system was operating at Level 3 (see previous transition cases). Following the transition, the system was operating at Level 1, in which the human was responsible for all control inputs.

Thrust Control

- Orient - Prior to the transition the system was operating at Level 2 (see previous transition cases). Following the transition, this did not change.
- Decide - Prior to the transition the system was operating at Level 2 (see previous transition cases). Following the transition, this did not change.
- Act - Prior to the transition the system was operating at Level 1 (see previous cases). Following the version, this did not change.

Lateral Flight Path Control

- Orient - Prior to the transition the system was operating at Level 2 (see previous transition cases). Following the transition this did not change.
- Decide - Prior to the transition the system was operating at Level 2 (see previous transition cases). Following the transition this did not change.
- Act - Prior to the transition the system was operating at Level 2 (see previous transition cases). Following the transition the system was operating a Level 1, as there was no computer assistance in the implementation of action (this is neglecting computer mediated control inputs to the hydraulic system, ie. control gains).

Vertical Flight Path Control

- Orient - Prior to the transition the system was operating at Level 2 (see previous transition cases). Following the transition this did not change.
- Decide - Prior to the transition the system was operating at Level 2 (see previous transition cases). Following the transition this did not change.
- Act - Prior to the transition the system was operating at Level 2 (see previous transition cases). Following the transition the system was operating a Level 1, as there was no computer assistance in the implementation of action (this is neglecting computer mediated control inputs to the hydraulic system, ie. control gains).

Table D.9: Case 5 - Proud and Hart LOA

Case 5 - Proud and Hart LOA								
Control Task	Observe		Orient		Decide		Act	
	Prior	Post	Prior	Post	Prior	Post	Prior	Post
Attitude	6	6	5	2	3	2	3	1
Thrust	6	6	2	2	2	2	1	1
Lat. Flight Path	6	6	2	2	2	2	2	1
Vert. Flight Path	6	6	2	2	2	2	1	1
Airspeed	6	6	2	2	2	2	2	1
Descent/Ascent Rate	6	6	2	2	2	2	2	1

Airspeed Control

- Orient - Prior to the transition the system was operating at Level 2 (see previous transition cases). Following the transition this did not change.
- Decide - Prior to the transition the system was operating at Level 2 (see previous transition cases). Following the transition this did not change.
- Act - Prior to the transition the system was operating at Level 2 (see previous transition cases). Following the transition the system was operating a Level 1, as there was no computer assistance in the implementation of action (this is neglecting computer mediated control inputs to the hydraulic system, ie. control gains).

Descent/Ascent Rate Control

- Orient - Prior to the transition the system was operating at Level 2 (see previous transition cases). Following the transition this did not change.
- Decide - Prior to the transition the system was operating at Level 2 (see previous transition cases). Following the transition this did not change.
- Act - Prior to the transition the system was operating at Level 2 (see previous transition cases). Following the transition the system was operating a Level 1, as there was no computer assistance in the implementation of action (this is neglecting computer mediated control inputs to the hydraulic system, ie. control gains).

These levels are shown in Figures D.30-D.33 and Table D.9.

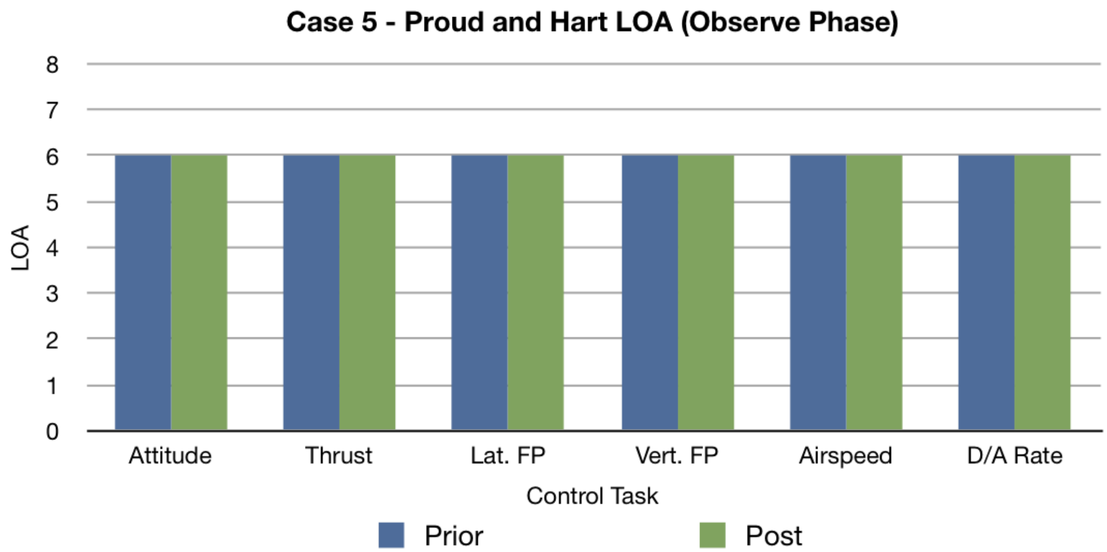


Figure D.30: Case 5 - Proud and Hart (Observe Phase)

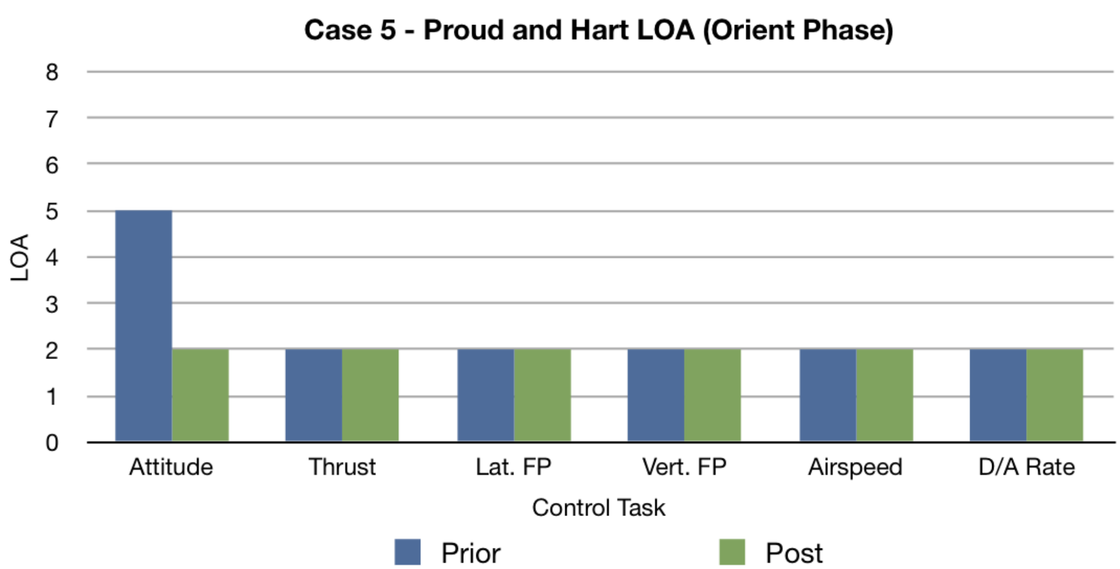


Figure D.31: Case 5 - Proud and Hart (Orient Phase)

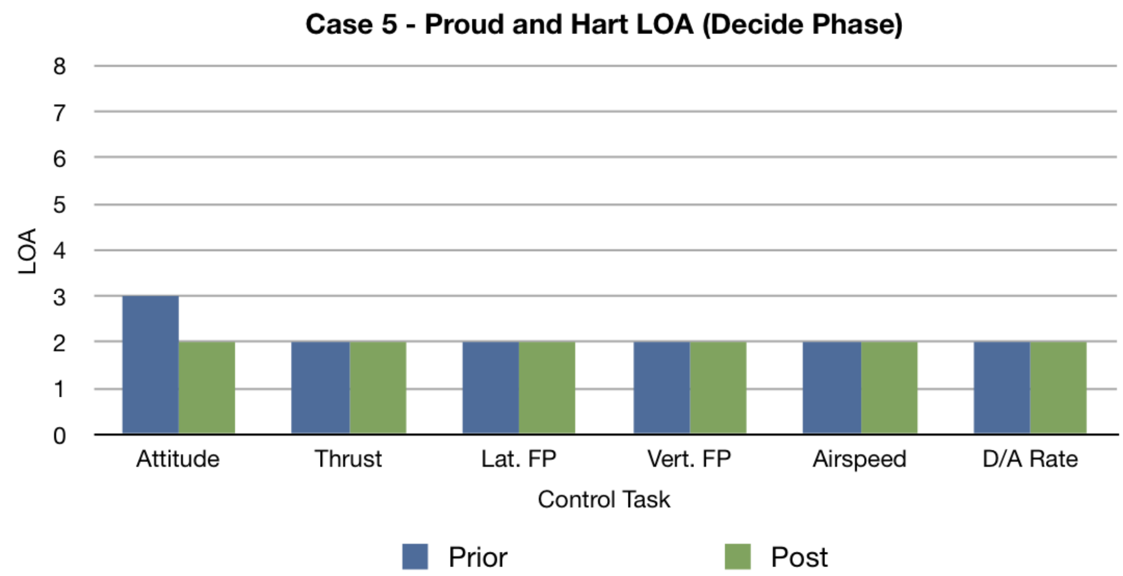


Figure D.32: Case 5 - Proud and Hart (Decide Phase)

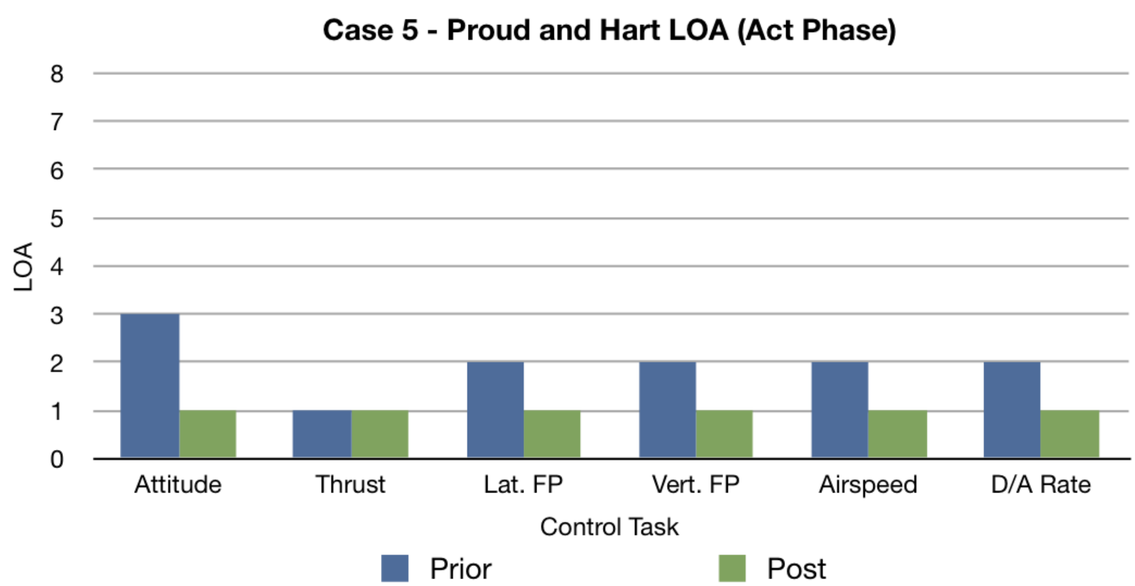


Figure D.33: Case 5 - Proud and Hart (Act Phase)

D.7.2 The Trigger

This transition was triggered by the manual input of the pilot into the system in a way which was automatically programmed to turn off the autopilot.

These factors are then summarized as:

- System States
- Automaticity
- General SA (All Levels)
- Performance of Actions
- Interface

System States - The state of the system was what prompted the operator to make the control action which triggered the mode transition.

Automaticity - The control action which the user took is a very common one for pilots, who all learn how to trim a plane as a basic skill the first time they fly a plane). As in the previous transition case, this was an automatic reaction by the pilot and was not a rigorously thought out control action; there was not enough attention to warrant such caution.

General SA - The operator was aware enough of the state of the system to make this control input. Hence, this partial SA (partial as his mode awareness and comprehension was insufficient to prevent the mistaken mode change) was a direct factor in making this transition.

Performance of Actions - This was the direct factor in the triggering of the transition: the operator triggered the transition by trimming the airplane.

Interface - The automation interface was setup to make this transition based on a user input. This was not a directly commanded transition, it was an implied transition (i.e. the operator made an input so the computer should switch to a mode that can handle that input).

These triggering factors are shown in Figure D.34.

D.7.3 Factors, Mechanisms, and Design Lessons

Factors in the Transition

The following factors, based on the updated Endsley SA model, were identified as active during this transition:

- Opacity
- Mode

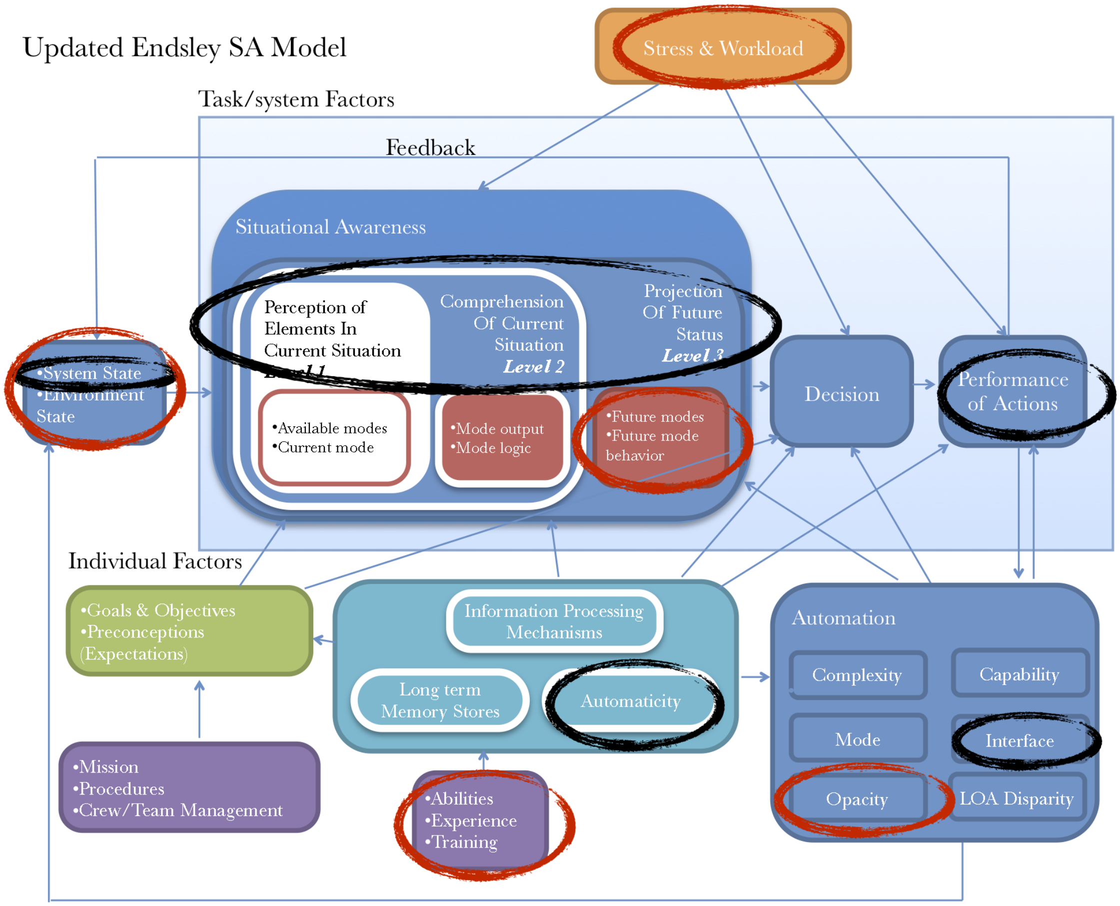


Figure D.34: Factors in Aeroflot-Nord Flight 821 Transition Case 5

- Stress & Workload
- Abilities, Experience, and Training
- System States
- Environment State
- Mode situational awareness (Level 3)

Opacity - The operator did not realize that his control action in the previous mode would cause that particular transition. Hence, this opacity in the automation architecture led to an unintentional mode transition, which compromised the immediate situational awareness of the pilot (he was not able to predict future mode activation).

Mode - The mode into which was transition was fully automatic. Additionally, the prior mode was also a fairly taxing mode to be operating in. These most likely had an effect on the operator's ability to transition gracefully.

Stress & Workload - At the time of the transition, the operator stress & workload was high, creating a drain on the attention resources (discussed in the Mechanisms section) and also reduced his capacity in other regard. Hence, this had an effect on the grace seen in the transition.

Abilities, Experience, and Training - Both operators were lacking in this area, hence making this transition less graceful.

System State - The system was in a highly dynamic state at the time of the transition, making it all the more difficult to achieve by demanding quick action on part of the operators. The operators, who, at the time did not have enough knowledge of the system states, were forced to make inputs into the system with incomplete information.

Environment State - The dynamism of the environment was a major source of the high workload and stress that the operators were experiencing.

Mode situational awareness (Level 3) - As the mode change was unintentional, it follows that the operator did not maintain Level 3 Mode situational awareness at the time. This is direct loss in the gracefulness of the transition.

These factors affectingv the gracefulness of the transition are shown in Figure D.34.

Mechanisms of Gracefulness
This particular transition did not traverse across LOAs in a majority of the major tasks. The only traverse was seen in attitude control. This is particularly because the prior transition to CWS had already placed the other tasks at low levels of automation. At this time in the report the performance of the system can be seen to be deviating form what would be optimal. Additionally, the description of the Co-pilots activity at this

time suggests an inordinate amount of work, creating a very high task load which in turn was increasing his workload. All of these describe a system that was not gracefully reverting.

Because very few LOAs were actually traversed in this particular transition, it is important to look at the context. In looking at this context, a very important mechanism can be seen: prior transition activity. The amount of mode transitions that took place prior to this transition were significant and in quick succession. Additionally, a few of these mode transitions were inadvertent, meaning that the pilot had not necessarily desired or planned to have entered that mode.

Hence, the following mechanisms from the update Endsley situational awareness mechanisms model were identified:

- Attention Resources
- Mode Setting
- Automation Interface

Attention Resources - As in the past transition cases, these were in short supply which had a flow down effect.

Mode Setting - This again was affected by the lack of the attention resources. Fortunately, the transition was hard-coded with an annunciation which helped the operator to adopt the correct schema, eliminating the domino effect seen in previous transition cases. The problems seen in the mode setting process were not only affected by the lack of attention resources: the previous mode schema having been incorrectly applied (a previously ungraceful transition) led to a faulty setting for the next mode. All of this suggests that a high amount of prior transition activity reduces the gracefulness of subsequent mode transitions. This is probably due to a number of mechanisms within these prior transitions, chief among which would be the reduction of situational awareness of the current system mode, as well as high workload carry over from each previous transition.

Automation Interface - The interface yet again did not sufficiently facilitate proper user interaction at the outset. It did function well in announcing the new mode to the operator, thereby forcing a certain amount of gracefulness into the system which would have otherwise been lost by the subtle triggering mechanism observed here.

These mechanisms are shown in Figure D.35.

Design Principles and Lessons
The following design implementations could have helped improve the gracefulness in this mode transition:

- Reducing the number of modes available is one way to reduce the amount of prior

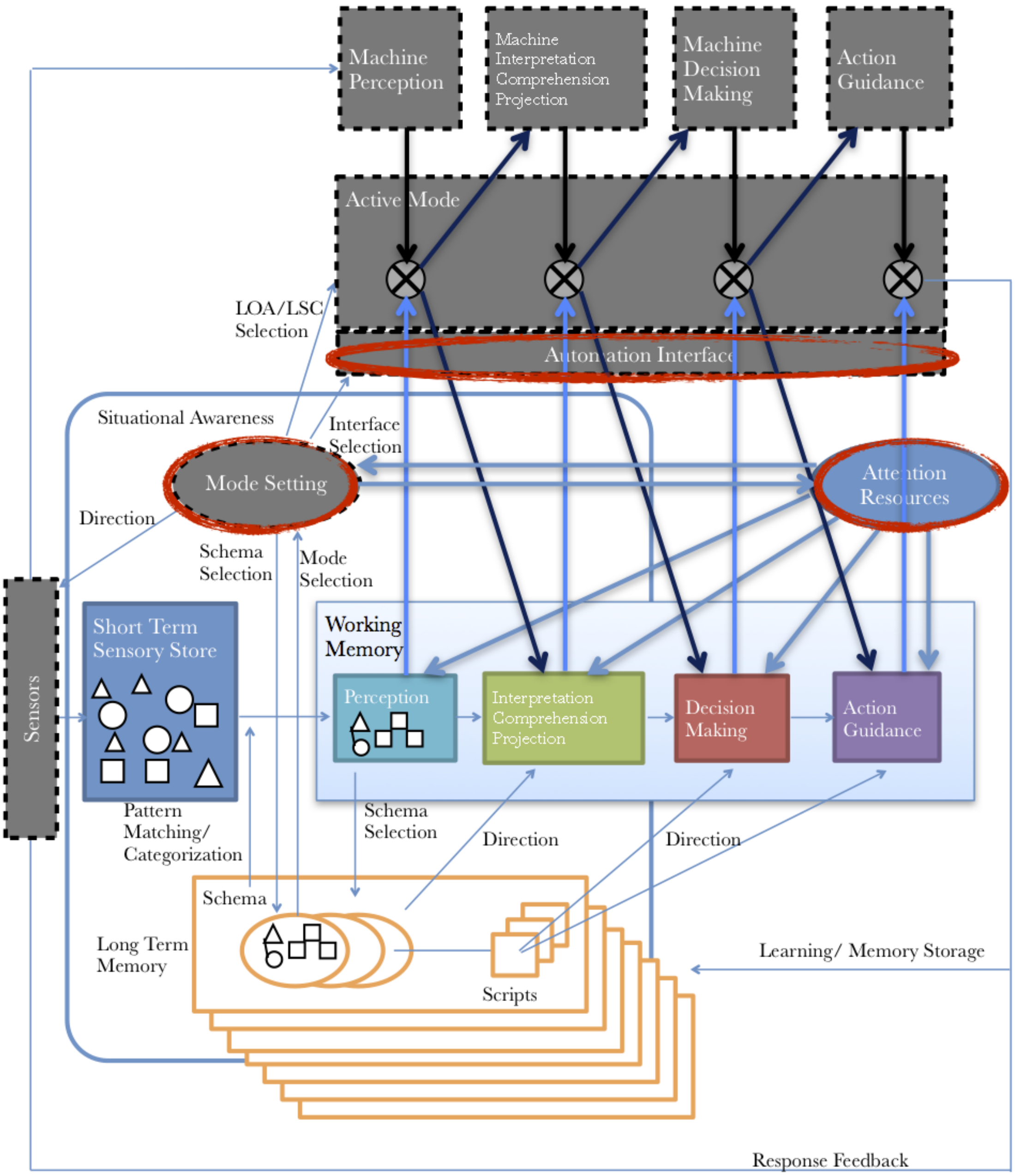


Figure D.35: Mechanisms in Aeroflot-Nord Flight 821 Transition Case 5

mode activity. This would reduce the number of changes necessary to perform a particular function and would also reduce the changes of inadvertent mode switches or mode confusion.

- Having "implied" mode transitions, such as the switch to manual based on a trimming action, are a double edged sword and should be treated accordingly. While they do allow for quick access to certain modes, the probability that the computer will misinterpret the human's intent to transition dramatically increases.
- The addition of an "undo" function onto any autopilot which will revert to the last system configuration would allow for the user to escape from any inadvertent mode switches.
- Preview displays showing the immediate effects of a transition prior to implementation.

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Appendix E

Case Study: TNT Airways Limited Cargo Flight 325N

E.1 General Description

On June 15th, 2006, a cargo flight (Boeing 737-300) run by TNT Airways limited attempted a CAT IIIA approach at the East Midlands airport. On approach the aircraft autopilot was disengaged by mistake. In attempted to reengage the autopilot the pilot failed to accurately judge his proximity to the ground and execute the TOGA procedure before the airplane landing gear impacted the ground, nor did he ever successfully re-engage the autopilot. In the impact the nose gear was broken off. After regaining altitude, the crew made an emergency landing at Birmingham Airport (BHX).

The following transitions were identified in the case study:

1. The accidental transition to manual when the pilot attempted to respond to ATC.
2. The attempted transition by the commander to re-engage both autopilots immediately following the first transition case.
3. The last minute re-engagement of the autopilot in approach mode.
4. The final transition into TOGA mode just before ground impact.

E.2 Transition Case 1

The first transition being considered is described in the report [43] as follows:

> Meanwhile, the co-pilot had been monitoring the instrument annunciations. He heard the aircraft automatic call of "Five Hundred' and made the SOP "five hundred feet" call to the commander, but he did no register the call from ATC. With no response from the co-pilot, the commander was not sure whether the ATC message was for his aircraft and, if so, what it meant. He attempted to respond to ATC himself but he inadvertently pressed the autopilot disconnect button as he started to speak so that both autopilots disconnected and the autopilot disconnect warning sounded.

Given the description in the report, the aircraft had been configured for a CAT IIIA landing, which is a method of all weather, ILS landing. The report [43] explains (emphasis added by this report):

> For a CAT IIIA automatic approach and landing, dual autopilot operating in APP (Approach) mode is required. Both VHF NAV receivers must be tuned to the ILS frequency and both autopilot channels must be selected to the CMD position, prior to 800 ft RA height. After localiser and glideslope capture, APP mode may only be disengaged by sing an autopilot disengage switch, by pushing a TOGA switch, or by returning a VHF/NAV receiver. If disengaged, the paddle switches will drop back rom the CMD position to the OFF position, a flashing red warning light on the FMA panel will activate and a warning tone will sound. If below approximately 800 ft RA, it is not possible to re-engage both autopilots; one may be re-engaged, but the automatic land function is disabled.

Hence, prior to the transition, the system is operating in APP mode using a glideslope and a localizer.

E.2.1 The Modes

Sheridan and Verplank LOA

Attitude Control - Prior to the transition, attitude was being controlled as the inner loop of the lateral flight path control. This was fully automated, with a mandatory readout from the pilot's attitude indicator. As such, the system was operating at Level 7. Following the transition, the system had disengaged the autopilot completely, and so the system revert to Level 2, in which the human was in complete control of the attitude with only analog display aids.

Thrust Control - Prior to the transition, the thrust was being controlled in APP mode by the autothrust SPEED mode. This was fully automated, with a manual readout of the engine status to the pilot. As such, the system was operating at Level 7. Following the transition, the system was still operating in SPEED mode with analog display aids. Hence, the system was operating at Level 7.

Lateral Flight Path Control - Prior to the transition, the system was operating in APP mode, which controls the lateral flight path of the plane using a localizer. This is highly automated, and is only displayed to the user in the contextual basis of a heading indicator (there is no flight path trend display or future path display. Hence, this mode can be considered Level 8. Following the transition, the human was in complete control of this with only the heading display as an aid, hence this can be considered to be at Level 2.

Vertical Flight Path Control - Prior to the transition, the system was operating in APP mode, which controls the vertical flight path of the plane using a glideslope track. This is highly automated and is only displayed to the user in the contextual basis of the altitude indicator as well as the vertical speed indicator (VSI) in the main panel. Hence, this mode of operation can be considered to be at Level 8. Following the transition the plane was operating at Level 2, as these same indicators were aiding the pilot, but the pilot was in complete charge of the control inputs.

Airspeed Control - Prior to the transition, the system was operating in APP mode, which was used alongside the autothrust SPEED mode to control airspeed. Airspeed is directly displayed to the user, and as such, this can be considered to be Level 7. Airspeed is both a function of engine thrust as well as attitude. Since the plane was still in SPEED mode it was able to compensate for any attitude changes made by the human and maintain the desired airspeed. Hence, while number of ways in which the computer could affect the airspeed changed, the LOA didn't, and the system was at Level 7 following the transition.

Descent/Ascent Rate Control - Prior to the transition, the system was operating in APP mode, which used a glideslope lock to set the vertical flight path of the plane and, as follows, the descent/ascent rate. The controlled process was directly displayed to the user through the the VSI, which places the system operating at Level. Following the transition the pilot was in direct control of this variable with these same readouts, placing the system at Level 2.

These levels are shown in Figure E.1 and Table E.1

Proud and Hart LOA

The system can be analyzed based on Proud and Hart in the following manner. A breakdown into the individual tasks becomes necessary for the Orient, Decide, and Act phase. Such a breakdown is unnecessary for the Observe phase because this phase is concerned with raw data which had not yet been sorted by task relevance.

The display within the cockpit is particularly static, making the phase of Observation stationary when considered with respect to LOA. While an out the window view is always available to the pilot, to include this option would make the analysis overly complex and impossible by requiring that every shift of attention by the user be a mode change. In fact, this is precisely what is happening when the pilot switches his or her gaze to the out-the-window view and away from the analog display dials (at least in consideration of the OODA breakdown). Instead of analyzing such "mode" changes, this ability will only

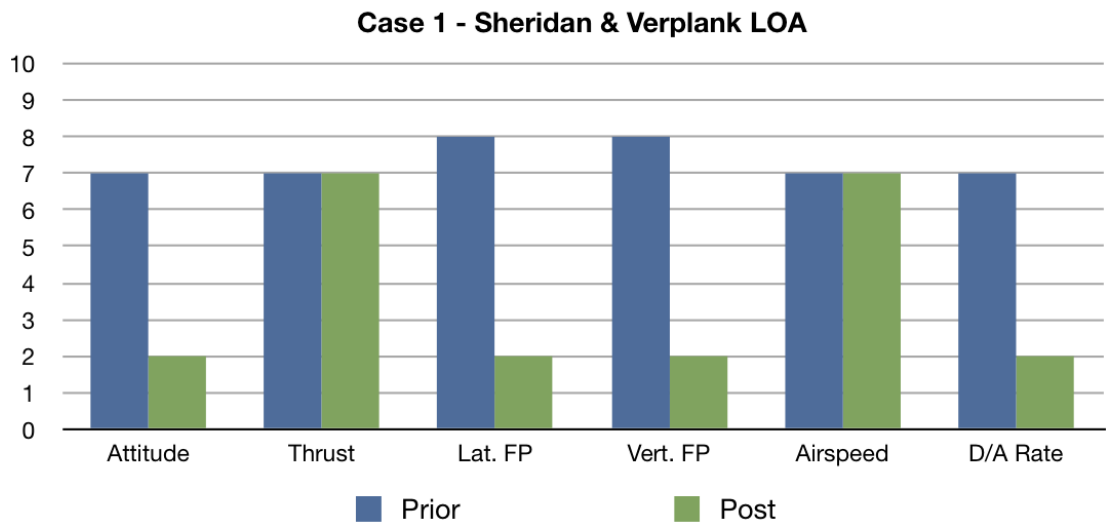

Figure E.1: Case 1 - Sheridan & Verplank LOA

Table E.1: Case 1 - Sheridan & Verplank LOA

Case 1 - Sheridan and Verplank LOA		
Control Task	*Prior*	*Post*
Attitude	7	2
Thrust	7	7
Lat. Flight Path	8	2
Vert. Flight Path	8	2
Airspeed	7	7
Descent/Ascent Rate	7	2

be considered a dynamic process that can for the most part be considered in the realm of Level 6, in which the computer is responsible for gathering, filtering, and prioritizing all data.

Filtering of data is inherent to any automated sensory system other than perhaps a realtime video and sound display, as such displays do not filter our a negligible amount of information. Prioritization, while not directly apparent, is inherent to the display layout, in which displays such as the attitude indicator take priority over other display readouts (e.g. coolant levels, turn coordinator, etc.)

Attitude Control

- Orient - Prior to the transition, the computer was in charge of all interpretation, integration, and prediction in order to control the plane. Any data from this process is then necessarily submitted to the human for review in the movement of the displays; however, no prediction of states is provided. Still, this places the system at Level 6. Following the transition, the system was operating at Level 2, with the computer only providing aid through display integration of data.
- Decide - Prior to the transition the system was operating at Level 8, with no decisions or action options being displayed to the human. Following the transition, the system began operating at Level 2, with the computer providing aid through the display of data. No computational assistance was being given.
- Act - Prior to the transition, the system was operating at Level 6, in which the computer acted automatically, informed the human necessarily (displays, visual, and vestibular cues), and allowed for human override in the form of a mode transition. Following the exercise of this override ability, the system began operating at Level 1.

With these levels classified, the following understanding of the active mode prior to and following the transition can be mapped on an updated version of Endsley's model of situational awareness which includes the implementation of automation:

Thrust Control

- Orient - Prior to the transition, the computer was in charge of all interpretation, integration, and prediction regarding thrust control. Any data was necessarily shown to the pilot through the engine output dial. As such, the system was operating a Level 6. Following the transition, the system remained at this level.
- Decide - Prior to the transition, all decision options and selections were done completely independent of the human. The pilot was only made aware of such decisions in the act phase. Hence, the system was operating at Level 8. Following the transition this remained true.

- Act - Prior to the transition, all actions were handled by the autothrust system and necessarily displayed to the human through displays, visual cues, and vestibular cues. Hence, the system was operating at Level 6. Following the transition, the system remained at Level 6..

Lateral Flight Path Control

- Orient - Prior to the transition the computer was in charge of all integration, interpretation, and prediction directly involved with the controlling process. This data was displayed contextually with the mechanical compass (analog heading readout), which places the system at Level 7. Following the transition the pilot was replaced the computer completely, using the dials only as a aiding tool. This placed the system at Level 2.
- Decide - Prior to the transition, the system was operating at Level 8, with the computer determining all control options and data selection. Following the transition, these processes were turned over to the human, with the displays serving as tools in this process. Hence, the system was operating at Level 2.
- Act - Prior to the transition, the system was operating at Level 7, with the actions being automatically executed by the computer and then contextually informing the human of this action through the mechanical compass (as well as the magnetic compass, but this isn't used by pilots nearly as regularly as the mechanical version). Following the transition, all control in this process was turned over to the human, placing the system at Level 1.

Vertical Flight Path Control

- Orient - Prior to the transition the system was operating in APP mode, which requires the computer to completely orient itself. The human is informed of a portion of this data integration, interpretation, and prediction through the displays, but is only being informed of this process in a contextual way. Hence, the system is operating at Level 7. Following the transition the system is operating at Level 2, where these same displays are being used by the human to perform the active orientation task.
- Decide - Prior to the transition the system was operating in at Level 8, where the computer was in charge of all option enumeration and selection and ignored the human. Following the transition, this process was completely turned over to the human, with the displays acting as tools in the selection process. This placed the system at Level 2.
- Act - Prior to the transition to the system was operating at Level 7, with the pilot being contextually informed of the output of the system using the altimeter and VSI. Following the transition, the human was responsible for all control outputs, placing the system at Level 1.

Airspeed Control

- Orient - Prior to the transition the computer is charge of all interpretation, integration, and predictions of vehicle states. The human is necessarily informed via the airspeed indicator, hence placing the system at Level 6. Following the transition, the system turned over attitude control, which is coupled to airspeed control. Hence, the human became partially involved in the orientation process regarding airspeed, placing the system at Level 5 (the human handling orientation regarding contingencies: in this case the attitude management).

- Decide - Prior to the transition, the computer handles all option enumeration and decision processes related to airspeed control and ignores the human in this processes, placing the system at Level 8. Following the transition, the system reverts to Level 4, placing the attitude decision making in regards to thrust in the hands of the human. However, the SPEED mode still attempted to obtain the desired airspeed regardless of human decisions or input, so the computer decisions are considered prime.

- Act - Prior to the transition, the computer handles all actions, with the human being directly informed of the action through the airspeed indicator. This places the system at Level 6. Following the transition the system continues to operate at Level 6, with the human handling the contingency of attitude management and control.

Descent/Ascent Rate Control

- Orient - Prior to the transition, the computer is in charge of the active orientation process, with the human being necessarily informed of this process through the VSI. This places the system at Level 6. Following the transition, the system was operating at Level 2.

- Decide - Prior to the transition, the computer was in charge of the enumeration of all options and decisions pertaining to the descent/ascent rate of the plane. The computer ignored the human in fulfilling this role, placing the system at Level 8. Following the transition, the system was operating a Level 2.

- Act - Prior to the transition, the system was operating at Level 6, with the human being informed of all actions of the system via the VSI. Following the transition, the human was placed in complete control of all descent/ascent rate control, setting the system at Level 1.

These levels are shown in Figures E.2-E.5 and Table E.2.

E.2.2 The Trigger

Using an updated model developed for describing Situational Awareness and its mechanisms, the courses and mechanisms involved in this transition can be identified. Mecha-

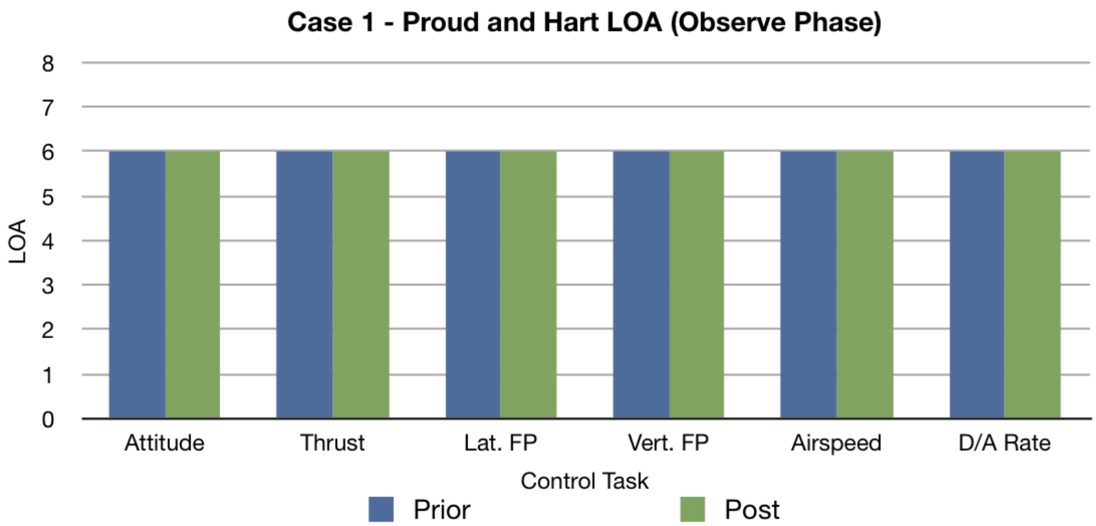

Figure E.2: Case 1 - Proud and Hart (Observe Phase)

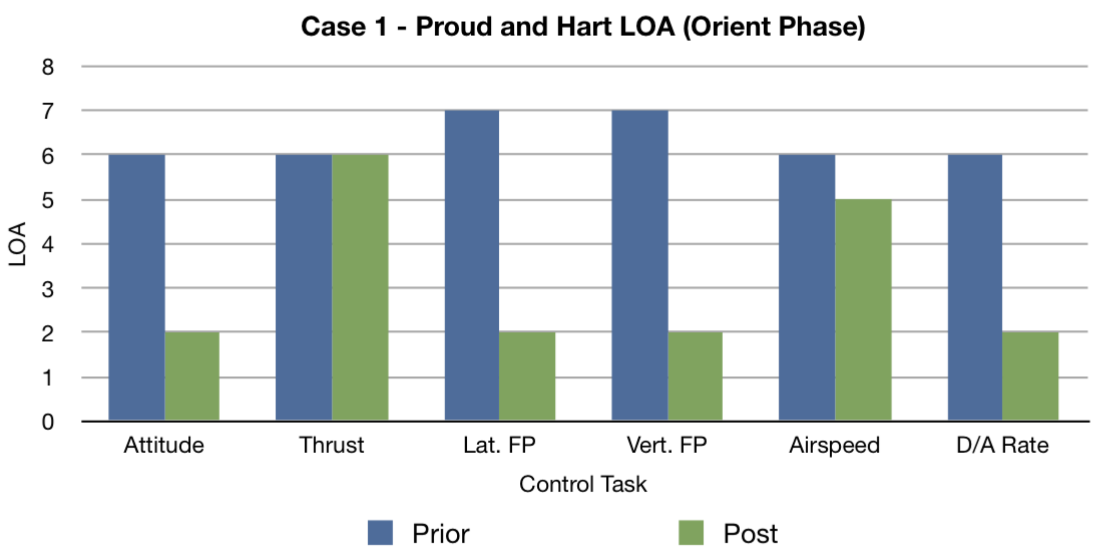

Figure E.3: Case 1 - Proud and Hart (Orient Phase)

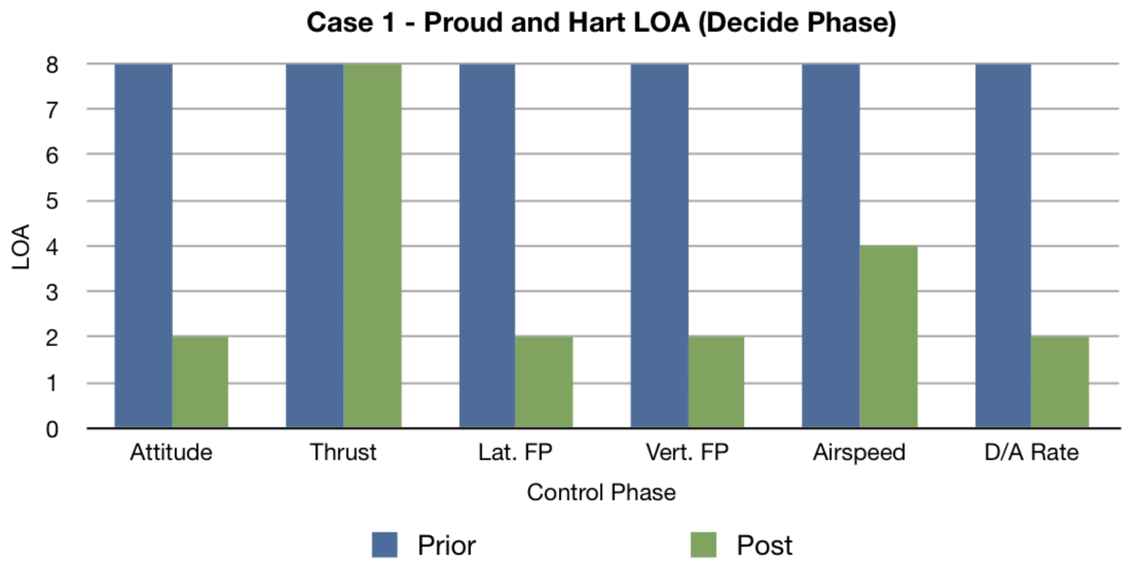

Figure E.4: Case 1 - Proud and Hart (Decide Phase)

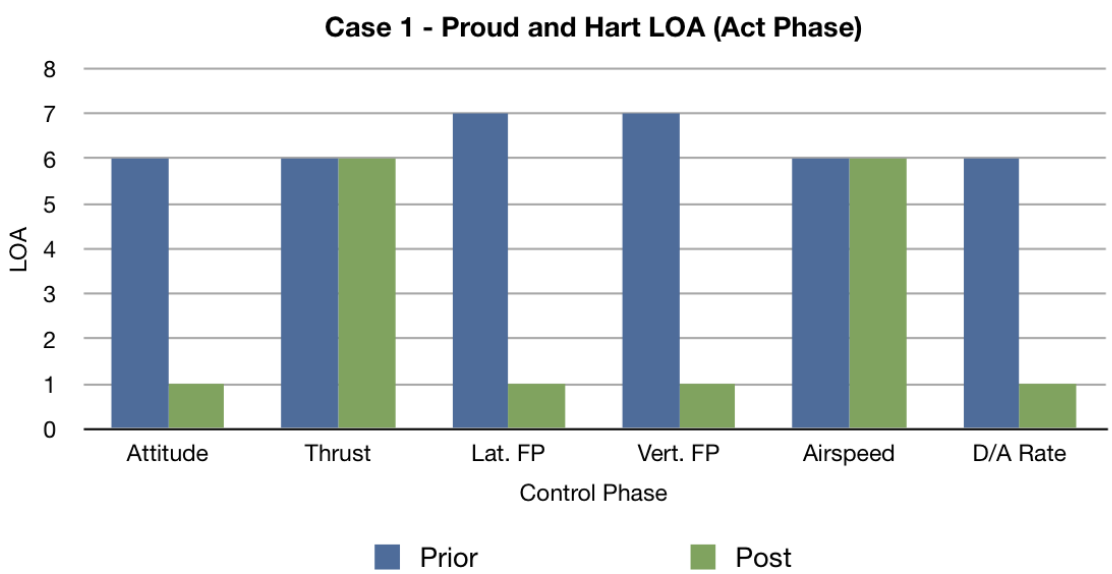

Figure E.5: Case 1 - Proud and Hart (Act Phase)

Table E.2: Case 1 - Proud and Hart LOA

Case 1 - Proud and Hart LOA								
Control Task	Observe		Orient		Decide		Act	
	Prior	Post	Prior	Post	Prior	Post	Prior	Post
Attitude	6	6	6	2	8	2	6	2
Thrust	6	6	6	6	8	8	6	6
Lat. Flight Path	6	6	7	2	8	2	7	1
Vert. Flight Path	6	6	7	2	8	2	7	1
Airspeed	6	6	6	5	8	4	6	6
Descent/Ascent Rate	6	6	6	2	8	2	6	1

nisms boxed in red refer to those which caused the system to revert ungracefully. Mechanisms boxed in black refer to those which triggered the transition.

The trigger for the mode change in this case was a pilot slip which occurred while the pilot was performing communications operations. This slip could be sourced to faulty information processing mechanisms (the pilot just didn't see where he was putting his finger) and/or automaticity (he just wasn't thinking about what he was doing because he'd done it so often).

The trigger mechanisms are mapped using an updated model of SA from Endsley. As these transition studies continue this model is being updated to map more mechanisms seen in transition. As can be seen in this model, the following mechanisms were identified as sources of the trigger of the transition:

- Operator Automaticity
- Stress & Workload
- Automation Interface

Operator Automaticity - The presence of a slip suggests that the operator was just not thinking about the action which was being performed. This is exactly what automaticity refers to.

Stress & Workload - At the time of the transition, the pilot was engaged in communication with ATC, which is part of the reason why automaticity was so likely here. The high stress, but mostly the high workload, of the system caused had shifted the attention of the user so input into the computer was not as precise. Reduction of the workload very well may have prevented this trigger from occurring.

Automation Interface - The design of the interface allowed for this slip to occur by placing the controls for communications and the autopilot in a configuration that could be confused by the operator.

These triggering factors are shown in Figure E.6.

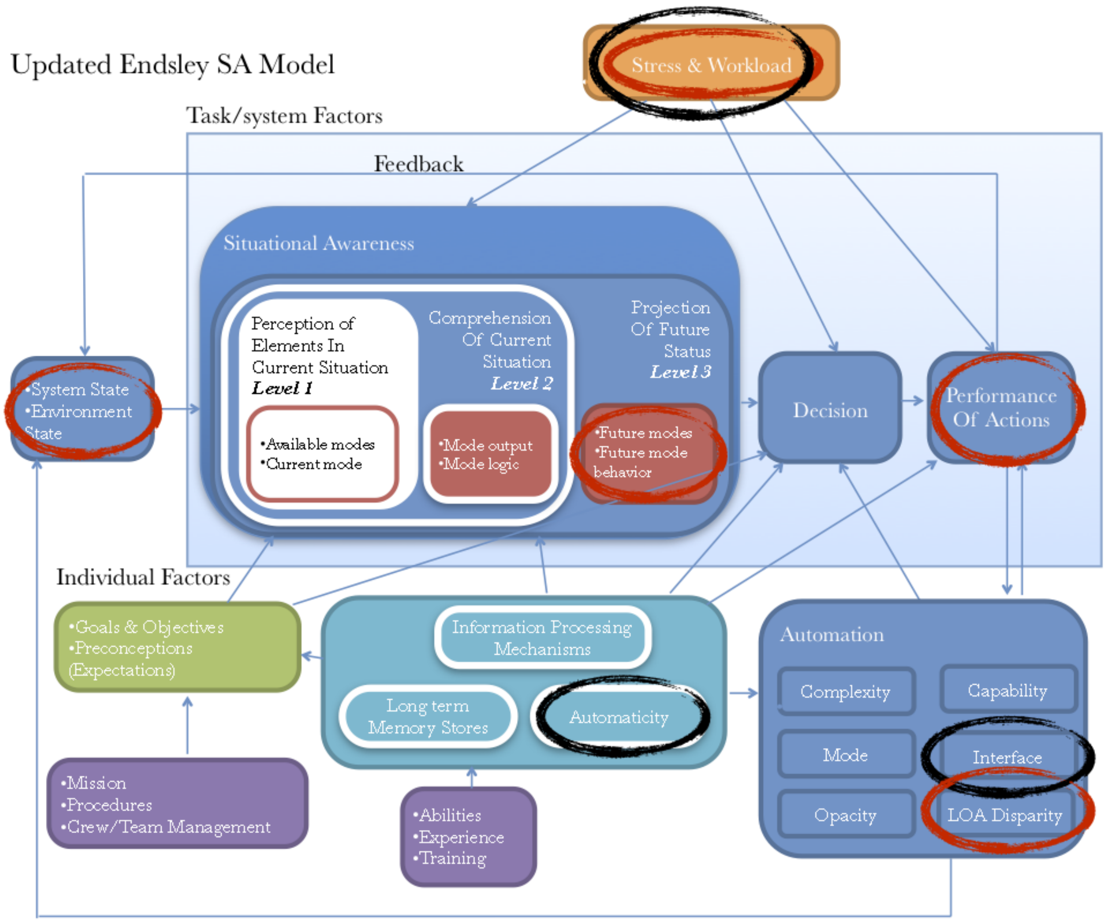

Figure E.6: Factors in TNT Airways Cargo Flight 325N Transition Case 1

E.2.3 Factors, Mechanisms, and Design Lessons

Factors in the Transition

Regarding the factors which made this transition particularly ungraceful, these mechanisms have been mapped using the same updated Endlsey model (Figure E.6). These factors are as follows:

- Environment State
- System State
- Performance of Actions
- Mode situational awareness (Level 3)
- Stress & Workload
- LOA Disparity

Environment State - The environment required a CAT IIIA landing due to bad weather. These less than ideal conditions made the error tolerance of the system much less. Additionally, this made the monitoring job of the pilot much higher, leading to a high workload.

System State - This transition occurred when the system was operating in a very specialized regime, namely landing (CAT IIIA). Aside from just the difficulty of the environment in which it was operating, the system was in a particular regime of states which did not allow for any large amount deviation.

Performance of Actions - The transition trigger was ultimately a mistake. There is no reason to believe that there as an error in any of the pilots processing of the information outside of the mistaken action (definition of a slip). The very fact that this mode was unexpected because of the mistake in the human's performance of a control action was a large part of the subsequent ungraceful transition.

Slips have been the trigger and cause of other transition in some of the other case studies that have been looked at; however, the major difference between this transition and the others is the dramatic change caused here. Previous studies which contained slips as triggers only resulted in minor mode changes, this slip caused the complete (an irreversible) switch to full manual. The fact that such a drastic change could be triggered by a slip input should raise a red flag.

Mode situational awareness (Level 3) - Because the mode transition was a slip, there was a deficiency in the pilot's Level 3 situational awareness, namely his expectations of future mode actions. He was not projecting that such a transition would occur, and as such he was not ready to insert himself into the control, nor did he want to.

Stress & Workload - The high workload and stress placed upon the pilot in this transition directly impacted his ability to maintain control of the system. Prior to the transition the pilot had been engaged in communication with ATC, now with the system reverted he was also in charge of the entire flying task of the plane, a significant increase in his taskload.

LOA Disparity - A major characteristic of this transition was the disparity between the modes that were switched between. The pilot reverted from a mode at a very high LOA to a mode at a very low LOA. Additionally, the LSC were very different, causing an appreciable change not only in the magnitude of the taskload on the pilot, but also the major difference in the types of tasks being handled by the pilot.

These factors in the gracefulness of the transition are shown in Figure E.6.

Mechanism of Gracefulness
By using Endsley's 1988 model of mechanisms in situational awareness augmented with a 4-stage model of automation, the mechanisms which led to the lack of graceful transition can be better understood. This model is shown in Figure E.7, with the mechanisms of interest circled in red.

As can be seen in Figure E.7, the mechanisms of interest regarding the gracefulness of this transition are:

- Attention Resources
- Mode Setting
- Operator Perception
- Operator Interpretation, Comprehension, and Projection
- Operator Schema

Attention Resources - As suggested by the factors related to this transition, there was a significant attention drain on the operator at the time, give the environment, system state, stress, and workload associated with the tasks at hand. In particular, this reduced the amount of attention that the operator had to devote to the particular processes of perception, interpretation, comprehensions, and projection.

Mode Setting - Additionally, the attention deficiency had a cascade affect to the mode selection process, particularly in reference to the operators proper selection of a new operating schema. While the operator was aware of the mode change and the new active mode of the automation, the lack of attention resources caused the operator to select a particular schema which was not capable of maintaining nominal vehicle states.

Operator Schema - The operator's adopted schema following this transition is seen in the next transition case as attempting to revert back to the mode prior to this current transition. This schema was affected both by the current mode setting of the plane as well as the pilot's perception of the states. These two influences on the schema selection are discussed in the following paragraphs. What should be noted is that the schema helps to determine the users own perception, a loop describing a phenomenon known as continuation bias. Interestingly with the introduction of automation as shown in Figure E.7, this closed loop becomes easier to break out of because of the outside influence of automation on schema selection.

Operator Perception - The lack of attention resources also affected the first two phases of the operator's information processing, but it is difficult to determine which of these was most at fault. As the plane began to drift from centerline and deviate from the glideslope it is apparent that the pilot was not fully aware of the states of the plane. Had he been fully aware, as the model in Figure E.7 suggests, this would have positively affected his schema selection, which would have then positively affected his interpretation, comprehension, and projection of the current states of the system. Had this ideal flow been accomplished, it is conceivable that the pilot would have reverted to a state in which he was maintaining more of the planes states than trying to revert again (see the next case).

Operator Interpretation, Comprehension, and Projection - It could be argued that the pilot did in fact perceive the states of the system and the environment to the point where it positively affected the selection of his schema for the situation; however, the mode setting was enough of an influence to offset this positive influence. Regardless, the lack of attention can be seen affecting particularly the projection abilities of the pilot, as had this mechanism been functioning correctly the pilot would have taking preventative actions at once, of which would have included regaining control of the aircraft instead of neglecting that control while trying to revert (see next the next case).

Design Principles and Lessons

The following possible designs could have been implemented to provide a more graceful transition:

- Concerning the effect that the extreme environmental conditions at the time of the transition, it is suggested that systems be designed to require as few transitions as possible when operating under extreme conditions.
- Placing safeguards on such transition would be advisable. This would effectively (1) reduce the possibility of a slip resulting in such a drastic mode transition and (2) increase the chances that the pilot will be aware of future mode behavior.
- Reduce the disparity between levels of automation in between modes.
- Develop the cockpit interface to remove the autopilot panel from any proximity to a frequently used panel in order to remove the chances of a slip.
- Require an more interactive mode change to remove the possibility of automaticity setting in. Additionally, this interaction can help affect the correct selection of schema by the operator through the learning/storing loop.
- Place a default time delay (one which can be overridden by the pilots in case of emergency) with a count down before a transition and a salient warning to minimize

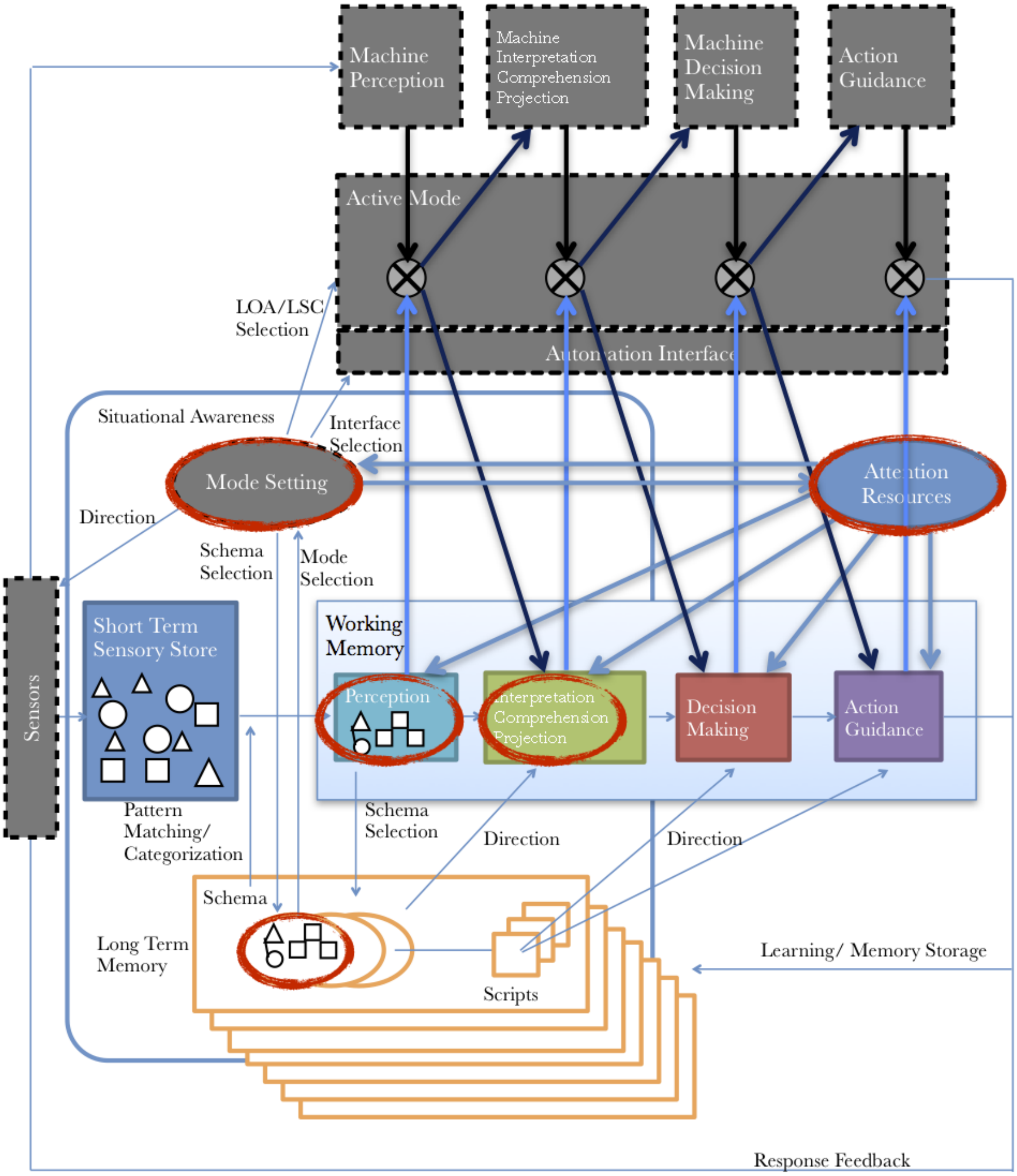

Figure E.7: Mechanisms in TNT Airways Cargo Flight 325N Transition Case 1

unexpected transitions. For example, in this particular case a warning would have sounded indicating that in 3 seconds the plane would be reverting to manual control.

- In the event that the previous design suggestion is implemented, provide a transition cancel button.
- Do not allow such a large transition unless absolutely necessary. Such a large change in level of automation necessarily brings with it a large change in the operator's schema. The less change required for the operator the better. Additionally, such large changes, as shown by the model, place a significant demand on the operator's attention resources in a very limited amount time, reducing the operators overall performance. A flight director would provide an intermediate level of automation which could reduce the attention demand on the pilot and reduce workload.
- Including a preview display and/or trend display could improve the operator's prediction of the future states of the vehicle, regardless of his or her own schema selection, improving decision and action performance.

E.3 Transition Case 2

The second transition being considered is the attempt of the commander to re-engage the autopilots following the transition described in Case 1. The report describes this transition as follows:

> A short time later, Channel B was re-engaged in Command mode. Channel A was then re-engaged, but this resulted in Channel B dropping out. When Channel B was re-engaged, Channel A dropped out. For most of the remainder of the approach, the autopilot was left with Channel B engaged and CWS P (pitch) and CWS R (roll) mods were active. At this point, the aircraft pitch trim had been adjusted by the autopilot and the aircraft's pitch attitude had become slightly more nose high than during the earlier part of the approach. The aircraft also adopted a slight left wing down roll attitude, with its heading diverging slowly to the left, towards the runway extended centreline.

Channel A and Channel B refer to the two autopilot computers. In all cases other than APP mode, there is only one active. It is required that both be active for the plane to enter APP mode, hence, the switching back and for shows the pilots intention of moving back to APP mode. The report offers the following description of the autopilot as well:

> Whenever an autopilot engage paddle switch is selected, but without a pitch or roll mode begin selected, then the switch will latch in the CMD position. In this circumstance, the autopilot mode will default to CWS and the CWS R

and CWS P legends will illuminate on the status panel. When the autopilot is operating in CWS mode with the paddle switch in the CMD position, and the APP mode is armed, the autopilot can intercept a localiser. As the localiser course is intercepted, the autopilot status annunciation CWS ROLL disappears and VOR/LOC appears.

E.3.1 The Modes

Sheridan and Verplank LOA

While there were multiple phases in this transition, there is no discernible difference in the operation of the system when operating in Channel A or Channel B. The main purpose of activating both autopilot channels was to allow for the transition back into APP mode, which was theoretically not allowed below 800 ft.

Attitude Control - Prior to the transition the system was operating at Level 2 (see the previous transition case). Following the transition, the system was operating with CWS ROLL and CWS PITCH active. In this case, this particular mode holds the current attitude of the aircraft unless the human inputs a control wheel input larger than a preset threshold. While this doesn't map particularly easy to Sheridan and Verplank's Levels, the most applicable is the execution on approval, placing the system at Level 5.

Thrust Control - Prior to the transition the system was operating at Level 7 (see the previous transition case), with the SPEED mode handling all thrust related control. Following the transition this was still case.

Lateral Flight Path Control - Prior to the transition the system was operating at Level 2 (see the previous transition case). Following the transition the system was operating in CWS ROLL mode which, while it partially handles the attitude (roll) control of the aircraft, it only partially aids the human in the management of the lateral flight path. As such, the system can still be considered as operating at Level 2.

Vertical Flight Path Control - Prior to the transition the system was operating at Level 2 (see the previous transition case). Following the transition the system was operating at Level 2 for similar reasons as discussed in for lateral flight path management.

Airspeed Control - Prior to the transition the system was operating at Level 7 (see the previous transition case). Following the transition this did not change.

Descent/Ascent Rate Control - Prior to the transition the system was operating at Level 2 (see the previous transition case). Following the transition, while CWS PITCH was helping in the management of the vehicle attitude, in consideration of descent/ascent rate control the human was in charge of the main control task. As such, the system can still be considered as operating at Level 2.

These levels of automation are shown in Figure E.8 and Table E.3.

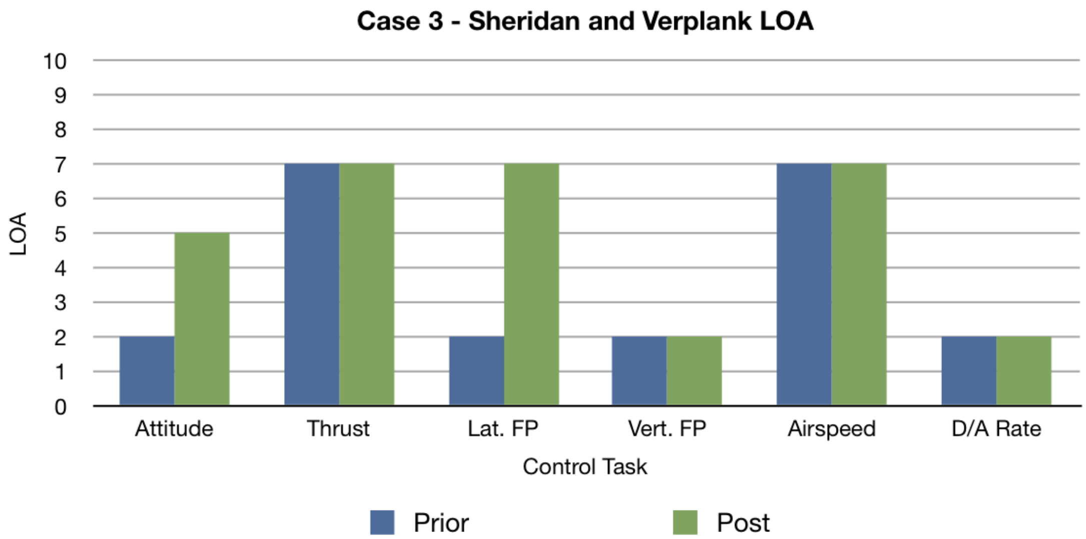

Figure E.8: Case 2 - Sheridan and Verplank LOA

Table E.3: Case 2 - Sheridan and Verplank LOA

Case 2 - Sheridan and Verplank LOA		
Control Task	*Prior*	*Post*
Attitude	2	5
Thrust	7	7
Lat. Flight Path	2	2
Vert. Flight Path	2	2
Airspeed	2	2
Descent/Ascent Rate	2	2

Proud and Hart LOA
The system can be analyzed based on Proud and Hart in the following manner. A breakdown into the individual tasks becomes necessary for the Orient, Decide, and Act phase. Such a breakdown is unnecessary for the Observe phase because this phase is concerned with raw data which had not yet been sorted by task relevance.

Attitude Control

- Orient - Prior to the transition the system was operating at Level 2 (see the previous transition case). Following the transition, the system was operating in both CWS ROLL and CWS PITCH modes, which places human in the position of constantly checking the computers own orientation, acting as contingency control in the case that the current action of the system is not satisfactory. Hence, the system is operating at Level 5.
- Decide - Prior to the transition the system was operating at Level 2 (see the previous transition case). Following the transition the system left the computer making control decisions for the most part; however, if the human decided on a control action, this was considered the prime to the computer's decision. As such, the system was now operating at Level 3.
- Act - Prior to the transition the system was operating at Level 1 (see the previous transition case). Following the transition the system left the computer making a majority of the control inputs; however, the fact that the human is constantly able to make control inputs with based on a fairly tight control loop with the computer, the system resembles an authority-to-proceed structure. This places the system at Level 3.

Thrust Control

- Orient - Prior to the transition the system was operating at Level 6 (see the previous transition case). Following this transition, since the system was still operating in SPEED mode, there was not shift in LOA.
- Decide - Prior to the transition the system was operating at Level 8 (see the previous transition case). This did not change following the transition.
- Act - Prior to the transition the system was operating at Level 6 (see the previous transition case). This did not change following the transition.

Lateral Flight Path Control

- Orient - Prior to the transition the system was operating at Level 2 (see the previous transition case). Following this transition, the system remained at this level, as the human was still in charge of all orientation tasks using the computer as an aid.

- Decide - Prior to the transition the system was operating at Level 2 (see the previous transition case). Following the transition this did not change.
- Act - Prior to the transition the system was operating at Level 1. With CWS ROLL mode engaged, the computer began to aid the human in the action task, but only slightly (hold the current attitude). Hence, the system can be considered as operating at Level 2.

Vertical Flight Path Control

- Orient - Prior to the transition the system was operating at Level 2 (see the previous transition case). Following this transition the system remained at this level.
- Decide - Prior to the transition the system was operating at Level 2 (see the previous transition case). Following this transition there was not change.
- Act - Prior to the transition the system was operating at Level 1 (see the previous transition case). Following the transition the CWS PITCH mode provided some aid in the Act phase; however, this was very small amount of aid, with the human primarily in charge controlling the system with respect to the vertical flight path. Hence, the system can be considered as operating at Level 2.

Airspeed Control

- Orient - Prior to the transition the system was operating at Level 5 (see the previous transition case). This did not change following the transition.
- Decide - Prior to the transition the system was operating at Level 4 (see the previous transition case). This did not change following the transition.
- Act - Prior to the transition the system was operating at Level 6 (see the previous transition case). This did not change following the transition.

Descent/Ascent Rate Control

- Orient - Prior to the transition the system was operating at Level 2 (see the previous transition case). This did not change following the transition.
- Decide - Prior to the transition the system was operating at Level 2 (see the previous transition case). This did not change following the transition.
- Act - Prior to the transition the system was operating at Level 1 (see the previous transition case). Following the transition, the CWS PITCH mode provide a very small amount of aid in the action phase of this control task, placing the system at Level 2.

These levels are shown in Figures E.9-E.12 and Table E.4.

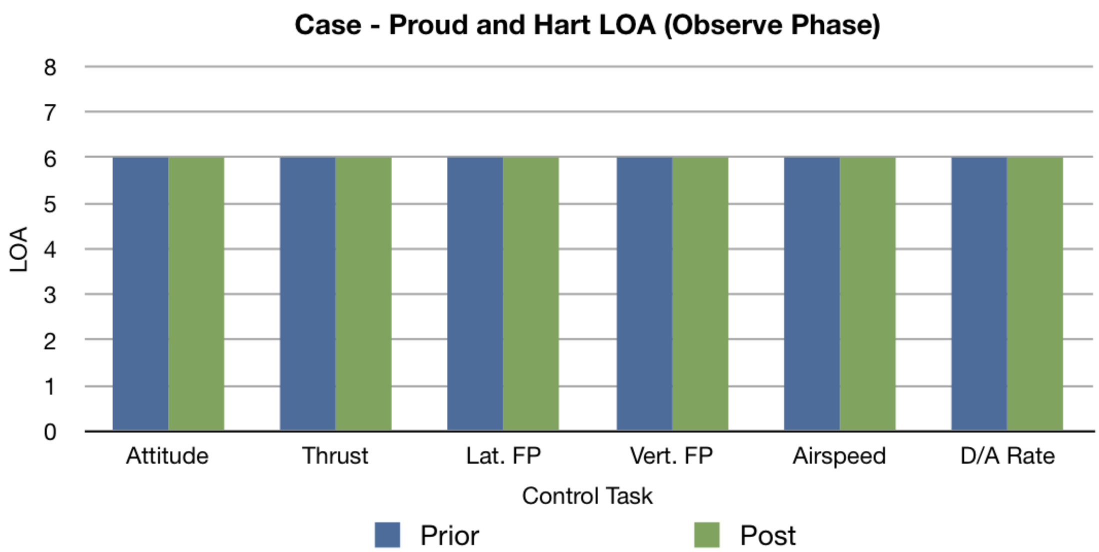

Figure E.9: Case 2 - Proud and Hart (Observe Phase)

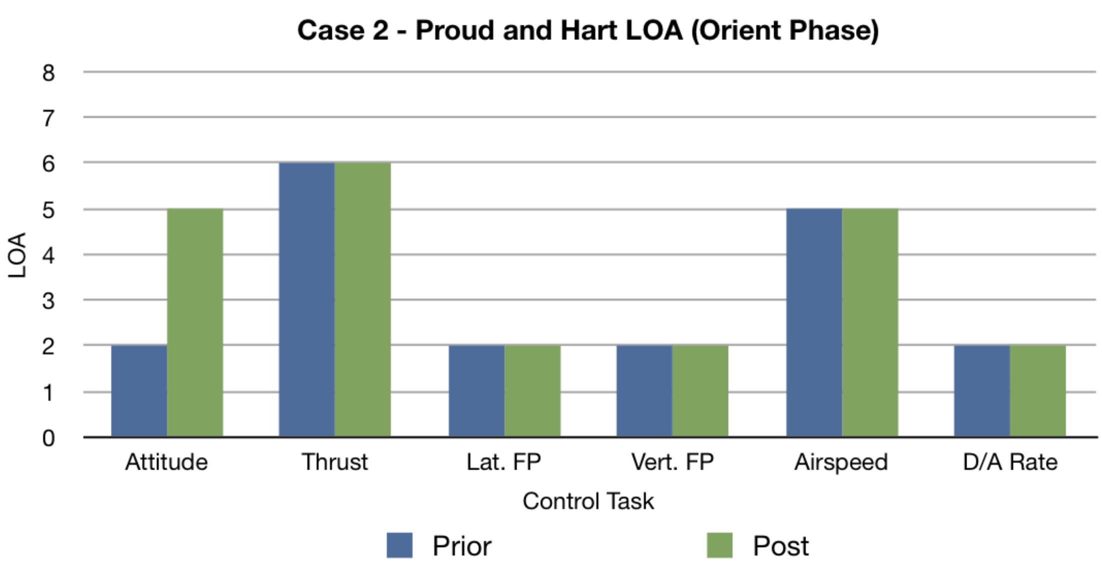

Figure E.10: Case 2 - Proud and Hart (Orient Phase)

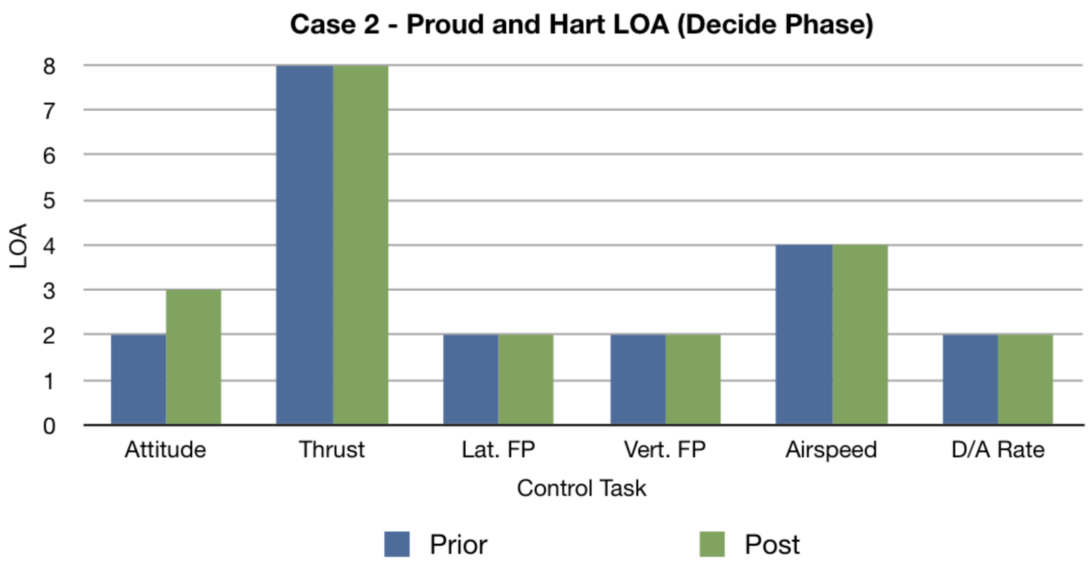

Figure E.11: Case 2 - Proud and Hart (Decide Phase)

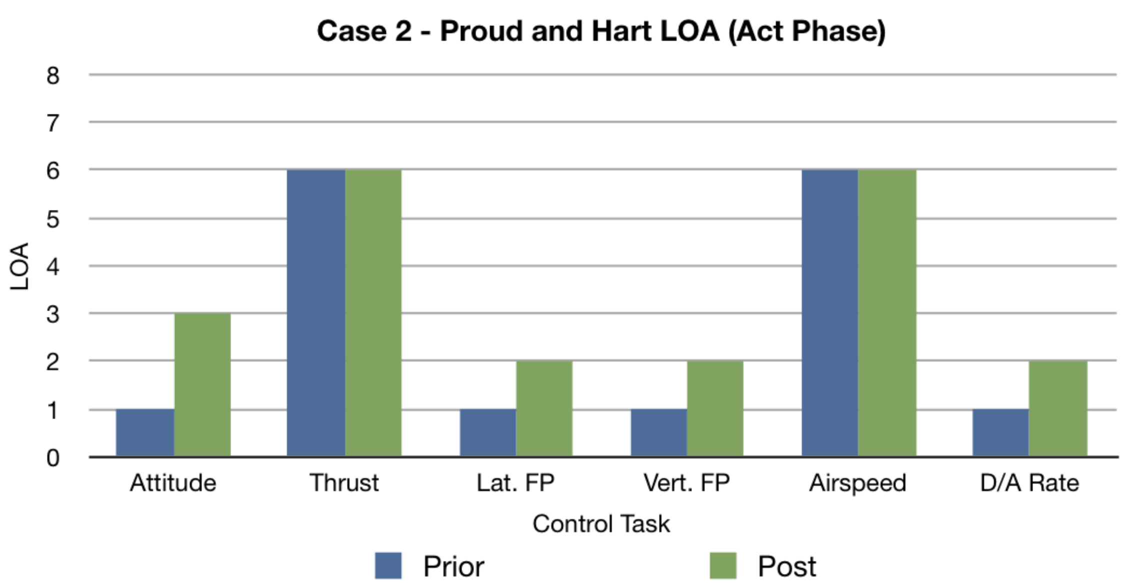

Figure E.12: Case 2 - Proud and Hart (Act Phase)

Table E.4: Case 2 - Proud and Hart LOA

Case 2 - Proud and Hart LOA								
Control Task	Observe		Orient		Decide		Act	
	Prior	Post	Prior	Post	Prior	Post	Prior	Post
Attitude	6	6	2	5	2	3	1	3
Thrust	6	6	6	6	8	8	6	6
Lat. Flight Path	6	6	2	2	2	2	1	2
Vert. Flight Path	6	6	2	2	2	2	1	2
Airspeed	6	6	5	5	4	4	6	6
Descent/Ascent Rate	6	6	2	2	2	2	1	2

E.3.2 The Trigger

The report suggests the following in regards to these mode transitions:

> During his short period of distraction, while he was responding to ATC, he attempted to reinstate the autopilot. A natural and automatic human response to a problem, particularly when under stress, is to reverse actions associated with an unwanted effect, in an attempt to re-establish a status-quo. Thus, the commanders action of re-engaging the autopilot was probably an (inappropriate) automatic rather than a considered action.

Hence, the main source for this transition was the automaticity of the user. Additionally, we can suggest that the trigger for the user was his desire to revert back to the previous mode.

Mapping the trigger sources to the updated Endsley mode suggests the following factors were involved in the triggering:

- Individual Goals & Objectives
- Operator Preconceptions
- Operator Automaticity

Individual Goals & Objectives - The operator's goal at the time of the transition was to continue to the descent and land. Instead, given the operating constraints suggested by a CAT IIIA landing, this goal should have turned towards regaining control and executing a go-around. Hence, by the goal of landing remaining active, the trigger towards reverting modes was enabled. This trigger would not have been considered had the goal changed correctly.

Operator Preconceptions - Operator knowledge concerning the structure and restrictions in the autopilot system were another factor. Had the pilot known that this transition was impossible, the transition would not have been attempted in the first place, most likely.

Operator Automaticity - The major factor seen here is the automaticity the pilot in attempting to affect a mode change. As the prior transition was obviously not intended by the user, the natural "gut reaction" of the pilot was to try and regain the control of the system by reverting back to the previous mode. As such, prior mode transition success and intentions were factors affecting this mode transition.

These triggering factors are shown in Figure E.13.

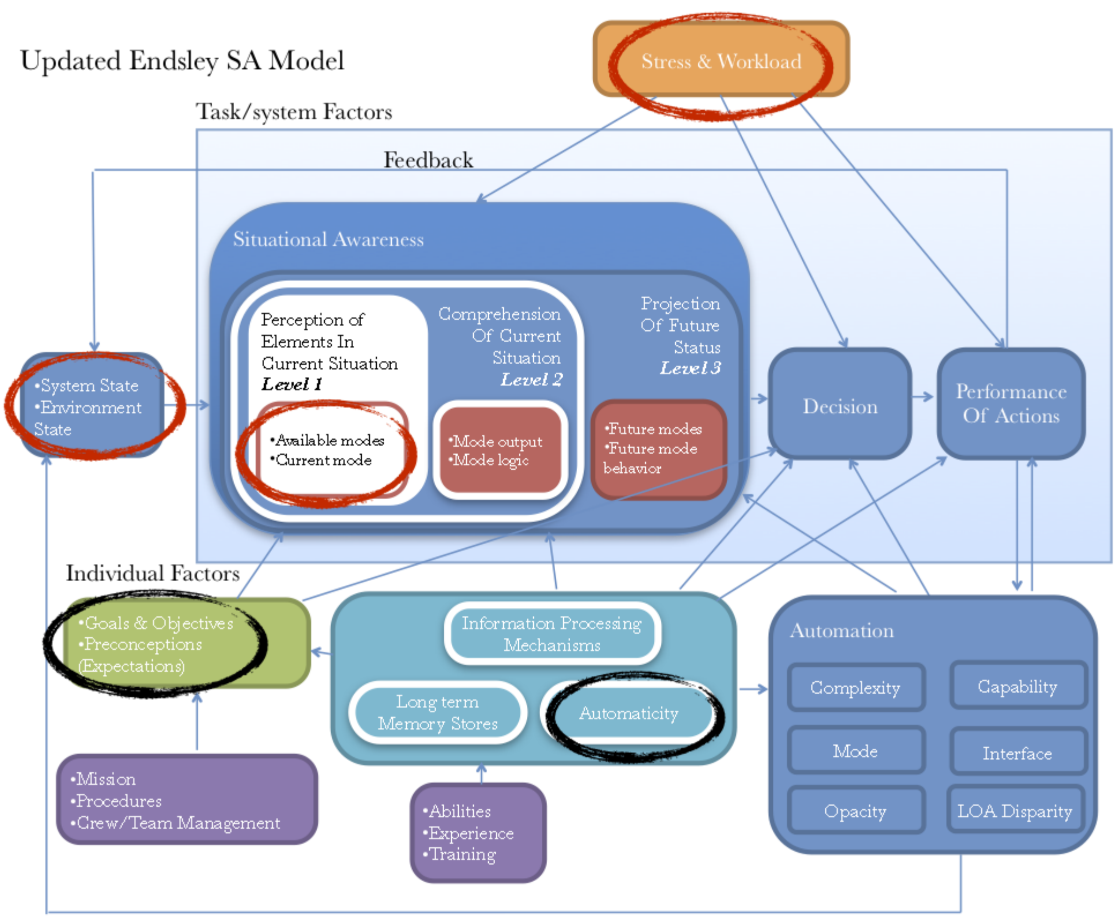

Figure E.13: Factors in TNT Airways Cargo Flight 325N Transition Case 2

E.3.3 Factors, Mechanisms, and Design Lessons

Factors in the Transition

Regarding the ungraceful nature of this transition, the following factors were deemed significant at the time of the transition:

- System State
- Environment State
- Mode SA (Level 1)
- Stress & Workload
- Automation Capability

System State - The states of the system were operating in the context of landing, placing a super-normal amount of performance requirements on the system and the operator. This contributed to the high workload and stress seen during the transition.

Environment State - As discussed in prior transition, the operating environment consisted of severe weather conditions. This environmental state contributed directly to the workload placed on the pilot, but it was also responsible for reducing the boundary of safe operation for the pilot.

Mode SA (Level 1) - The pilot was unaware of the 800 ft aal. APP mode activation restriction, hence he continued to try and gain control of a system through an impossible means. This lack of awareness enabled a significant attention drain as he attempted to undo his mistake instead of directing these efforts towards controlling the system.

Stress & Workload - With the previous mode being almost fully manual the workload on the pilot was considerable. Additionally, the CWS modes still required a large amount of pilot interaction. These conditions elevated the stress and workload of the pilot, decreasing the efficiency with which the operator was able to allocate attention resources.

Automation Capability - The automation was unable to make the intended transition to APP mode due to the programmed 800 ft aal. limit to the implementation of that mode.

These factors concerning the gracefulness of the transition are shown in Figure E.13.

Mechanisms of Gracefulness

As this transition case happened in such quick succession with the previous transition case, it is not surprising to see that the same mechanisms of gracefulness are at work here as well. As can be seen in Figure 2.6, the mechanisms identified as active in inhibiting the gracefulness were:

- Attention Resources

- Mode Setting
- Operator Perception
- Operator Interpretation, Comprehension, and Prediction
- Operator Schema

Attention Resources - Given the factors discussed previously, attentional resources were scarce for the operator while this transition was taking place, as well as following the transition. This scarcity of resources impacted the other mechanisms within the operator's information processing, in general leading to ungraceful nature of the transition.

Mode Setting - The way in which the mode setting process was occurring was particularly problematic in this transition. In some senses, this transition was ungraceful because this process was never able to accomplish the intent of the pilot, which was to revert back to the previous mode of operation. As such, the difficulties in the mode setting process allowed the pilot to retain an inappropriate schema for the given circumstances.

Operator Perception - This process was affected in a similar way as it was in the previous transition. The scarcity of attention resources interfered with the ability of the pilot to perceive the environment around him, which in turn affected the correct application of schema to the current situation.

Operator Interpretation, Comprehension, and Prediction - As the correct application of schema was impacted by deficient perception phase, this in turn affected the operator's interpretation, comprehension, and prediction of the current situation. This is seen in the operator's determination that the system could recover back to the previous mode (while this may have been theoretically possible the architecture of the automation made this infeasible, a fact which should have been recognized by a correctly perceiving pilot). This interpretation of a system still operating within acceptable parameters led to the incorrect (objectively incorrect; subjectively, based on the interpretation, correct) decision of attempting re-engage the autopilot on APP mode.

Operator Schema - The incorrect schema was applied to the current situation based on a faulty perception of the system and environment, as well as an incorrect understanding of the available modes with the mode setting process.

These mechanisms of gracefulness are shown in Figure E.14.

Design Principles and Lessons
The major design lessons from this transition are as follows:

- The obvious implementation that would have affected a more graceful transition here would have been the "undo" design option mentioned in the previous transition case. The pilot's intention was to re-engage this mode, but this effort was hampered by

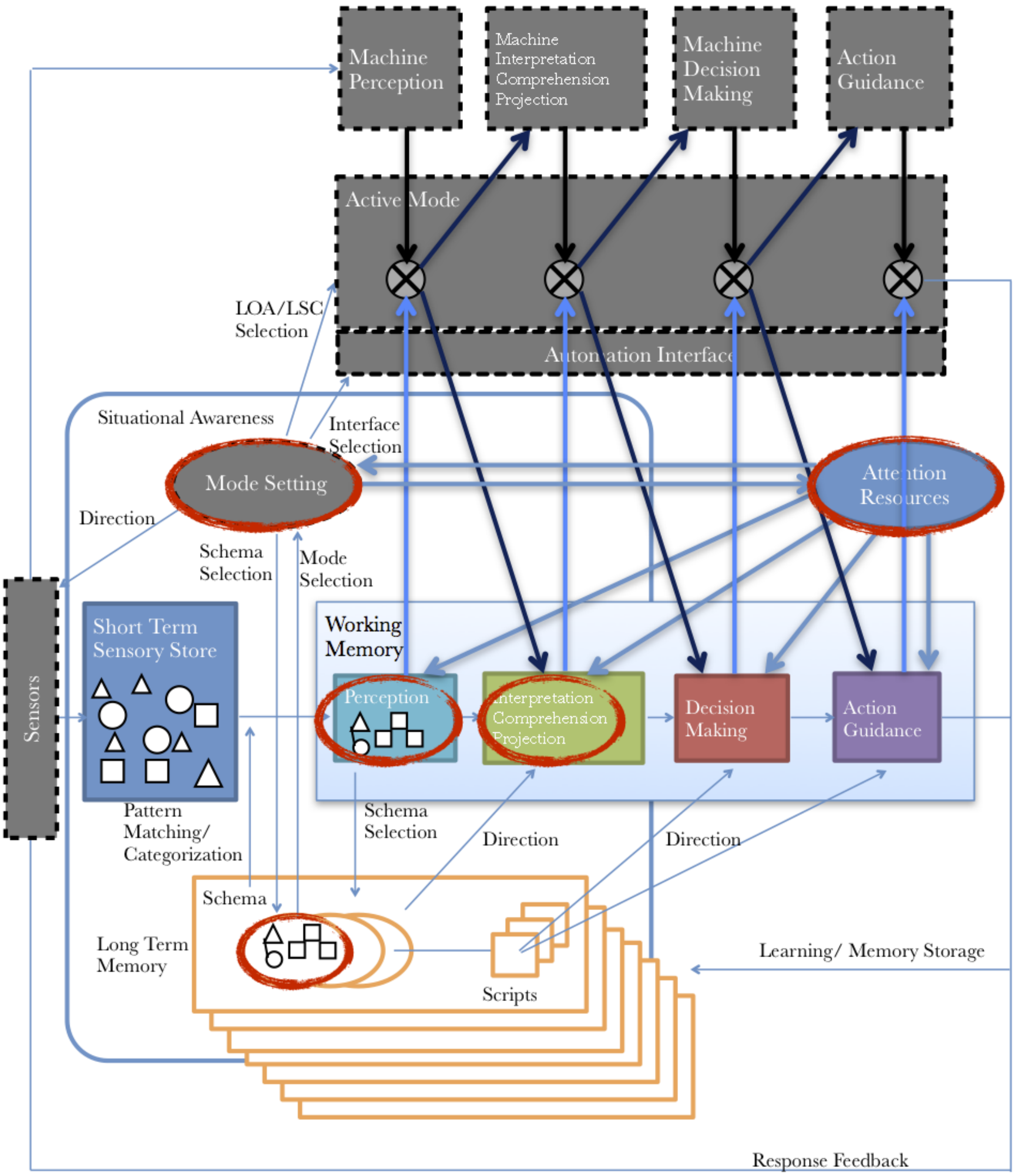

Figure E.14: Mechanism in TNT Airways Cargo Flight 325N Transition Case 2 the inability of the system to complete his wishes. Such a desire is not by any stretch unreasonable and represents an intuitive design function for the user.

- Intuitive mode design is crucial. While the "undo" function is the obvious answer in this case, there may arise other cases in which a very simple end state is desired by the pilot but is unattainable because a complex and unworkable procedure must be followed to access it. Prior to automation design, a simple user desire survey would help identify those modes of operation which the user just wants to be able to "switch on"; however, at the same time it cannot be disregarded how one mode will switch to another. Gross changes in goal states with little regard to how the system will switch to these goal states can leave some states uncontrolled and prone to unsatisfactorily high deviations.

- Indication of what modes are available and which are unattainable should be displayed to the user in some way, especially in the case of modes demonstrating the same unique qualities as the APP mode being analyzed here. The pilot's repeated attempts re-engaging the APP mode show a fundamental lack of knowledge concerning the 800 ft aal limit on this re-engagement. In colloquial terms: don't dangle a carrot in front of the operator's face if they can never reach it.

- Set apart modes which aren't used in everyday flight, such as APP (this is theoretically only used once throughout the entire flight), with mode transition procedures. Such procedures would then allow for the further informing of the pilot of such mode limits, like the 800 ft aal one observed here.

E.4 Transition Case 3

The third transition to be considered is the last minute reengagement of the autopilot into APP (Approach) mode. The report describes the transition as follows:

> AT 250 ft aal, the co-pilot state that they were "ONE DOT HIGH". The control column then went slightly forward and the pitch attitude of the aircraft started to decrease. Shortly afterwards, the approach mode was re-armed; this was done as the co-pilot expressed in French "we need to descend". The control column then moved further forward pitching the aircraft nose down at a rate of 2 degrees/sec. It was then brought back, such that the aircraft's pitch attitude stopped at 4° nose-down. The co-pilot then gave the "APPROACHING MINIMUMS" callout but, by this time, the aircraft was 130 ft aal, 1.5 dots above the glideslope slope and descending at an increasing rate of descent of more than 1,500 fpm.

At the time the localizer was reacquired:

After the APP mode became active, the aircraft re-acquired the localiser and began a gentle roll to the right.

At not time did the FDR record that the glideslope was re-captured by the autopilot or that there was any attempt by the aircraft to reduce its rate of descent as it approached the glideslope from above. It passed through the glideslope, at approximately 45 ft aal and with a rate of descent in excess of 1,500 fpm.

The recorded pitch and roll inputs made during the final stages were almost certainly made by the commander as the PF.

It is unknown how the APP mode was re-engaged below the 800 ft minimum described earlier.

E.4.1 The Modes

Sheridan and Verplank LOA

Attitude Control - Prior to the transition the system was operating at Level 5 (see the previous transition case). Following the transition, the system was still operating at Level 5; however, the method by which this was happening was operationally different. Lateral attitude (roll) was being handled completely by the computer, which were attitude not being considered as all three axes, would be considered to be operating at Level 7. Pitch is still operating in CWS PITCH mode, and as such is still at Level 5.

These levels can be seen in Figure E.15 and Table E.5

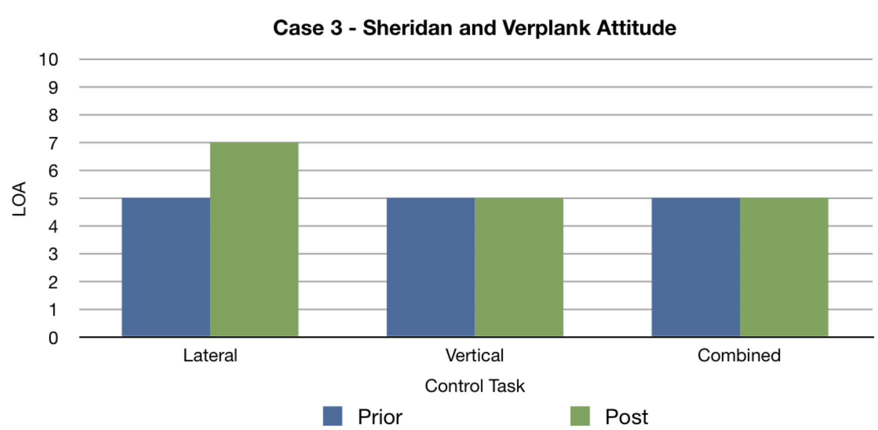

Figure E.15: Case 3 - Sheridan and Verplank Attitude LOA

Thrust Control - Prior to the version the system was operating at Level 7 (see the previous transition case). Following the transition this did not change.

Table E.5: Case 3 - Sheridan and Verplank Attitude

Case 3 - Sheridan and Verplank Attitude		
Control Task	*Prior*	*Post*
Lateral	5	7
Vertical	5	5
Combined	5	5

Lateral Flight Path Control - Prior to the transition the system was operating at Level 2 (see the previous transition case). Following the transition the localiser was reacquired, placing the lateral path control loop under the jurisdiction of the computer again. Hence the system was now operating at Level 7.

Vertical Flight Path Control - Prior to the transition the system was operating at Level 2 (see the previous transition case). Following the transition the system was still operating in CWS PITCH mode as the glideslope was never reacquired. Hence the system remained (although technically in APP mode) at Level 2.

Airspeed Control - Prior to the transition the system was operating at Level 7 (see the previous transition case). Following the transition this did not change, as the two modes of influencing airspeed had not changed (vertical attitude and thrust control).

Descent/Ascent Rate Control - Prior to the transition the system was operating at Level 2 (see the previous transition case). Following the transition this did not change.

These levels are shown in Figure E.16 and Table E.6.

Table E.6: Case 3 - Sheridan and Verplank LOA

Case 3 - Sheridan and Verplank LOA		
Control Task	*Prior*	*Post*
Attitude	2	5
Thrust	7	7
Lat. Flight Path	2	7
Vert. Flight Path	2	2
Airspeed	7	7
Descent/Ascent Rate	2	2

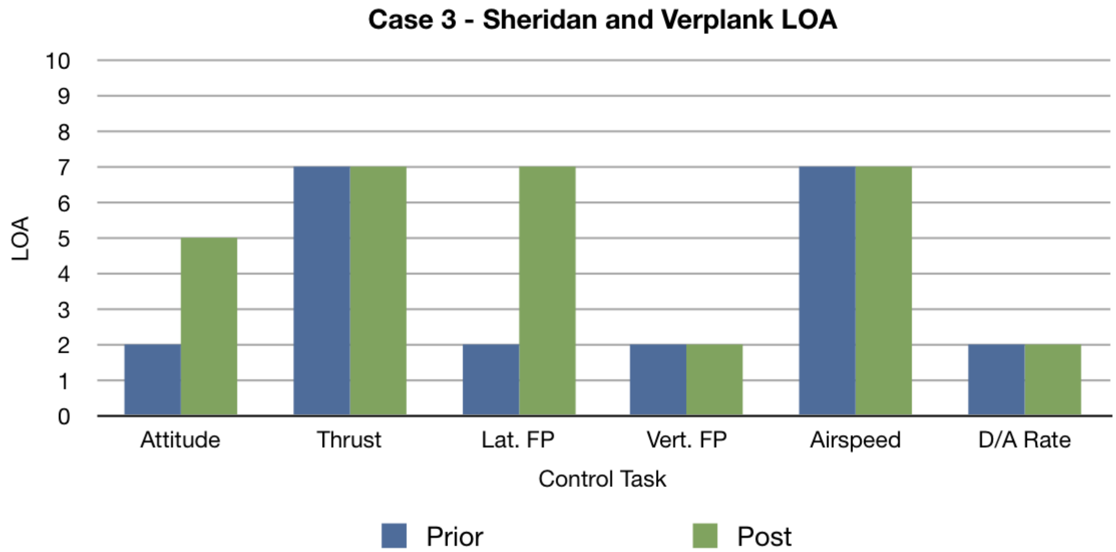

Figure E.16: Case 3 - Sheridan and Verplank LOA

Proud and Hart LOA

The system can be analyzed based on Proud and Hart in the following manner. A breakdown into the individual tasks becomes necessary for the Orient, Decide, and Act phase. Such a breakdown is unnecessary for the Observe phase because this phase is concerned with raw data which had not yet been sorted by task relevance.

Attitude Control (Roll)

As seen in the LOA breakdown based on Sheridan and Verplank's LOA, this particular transition benefits from the analysis of attitude split into two components: lateral (roll) and longitudinal (pitch). Hence, this breakdown is continued here, with attitude being considered in both the pitch and roll components, as well as a combined analysis for continuity in analysis.

- Orient - Prior to the transition the system was operating at Level 5 (see the previous transition case). Following the transition the system was operating at Level 6, as the computer now was in charge of all active lateral data integration, interpretation, and prediction. The human, while able to perform this process himself, was only in a position to override the system base on the mandatory display of the roll information via the attitude indicator.
- Decide - Prior to the transition the system was operating at Level 3 (see the previous transition case). Following the transition the system was operating at Level 8, in

which the computer was in charge of all option enumeration and decision making regarding lateral attitude control.

- Act - Prior to the version the system was operating at Level 3 (see the previous transition case). Following the transition the system was operating at Level 6.

Attitude Control (Pitch)

- Orient - Prior to the transition the system was operating at Level 5 (see the previous transition case). This did not change following the transition.
- Decide - Prior to the transition the system was operating at Level 3 (see the previous transition case). This did not change following the transition.
- Act - Prior to the transition the system was operating at Level 3 (see the previous transition case). This did not change following the transition.

Attitude Control (Combined)

- Orient - Prior to the transition the system was operating at Level 5 (see the previous transition case). This did not change following the transition.
- Decide - Prior to the transition the system was operating at Level 3 (see the previous transition case). This did not change following the transition.
- Act - Prior to the transition the system was operating at Level 3 (see the previous transition case). This did not change following the transition.

Thrust Control

- Orient - Prior to the transition the system was operating at Level 6 (see the previous transition case). This did not change following the transition.
- Decide - Prior to the transition the system was operating at Level 8 (see the previous transition case). This did not change following the transition.
- Act - Prior to the transition the system was operating at Level 6 (see the previous transition case). This did not change following the transition.

Lateral Flight Path Control

- Orient - Prior to the transition the system was operating at Level 2 (see the previous transition case). Following the transition the computer had reacquired the localiser, placing it control of the later flight path. Hence, the system was operating at Level 7, with the computer handling all data integration, interpretation, and prediction related to control of the lateral flight path.

- Decide - Prior to the transition the system was operating at Level 2 (see the previous transition case). Following the transition the system was operating at Level 8, with the computer responsible for the enumeration and selection of all control actions.
- Act - Prior to the transition the system was operating at Level 2 (see the previous transition case). Following the transition the system was operating at Level 7, in which the computer was responsible for the implementation of all control decisions. Human interaction is through control override.

Vertical Flight Path Control

- Orient - Prior to the transition the system was operating at Level 2 (see the previous transition case). Following the transition this did not change.
- Decide - Prior to the transition the system was operating at Level 2 (see the previous transition case). Following the transition this did not change.
- Act - Prior to the transition the system was operating at Level 2 (see the previous transition case). Following the transition this did not change.

Airspeed Control

- Orient - Prior to the transition the system was operating at Level 5 (see the previous transition case). Following the transition this did not change.
- Decide - Prior to the transition the system was operating at Level 4 (see the previous transition case). Following the transition this did not change.
- Act - Prior to the transition the system was operating at Level 6 (see the previous transition case). Following the transition this did not change.

Descent/Ascent Rate Control

- Orient - Prior to the transition the system was operating at Level 2 (see the previous transition case). Following the transition this did not change.
- Decide - Prior to the transition the system was operating at Level 2 (see the previous transition case). Following the transition this did not change.
- Act - Prior to the transition the system was operating at Level 2 (see the previous transition case). Following the transition this did not change.

These levels are shown in Figures E.17-E.20 and Table E.7.

E.4.2 The Trigger

The reacquiring of the localiser by the computer which cause the switch back into APP mode (albeit partial). This search for the localiser was a left-over of the previous transition, in which the pilot had been attempting to return to APP mode. Thus, the source of this

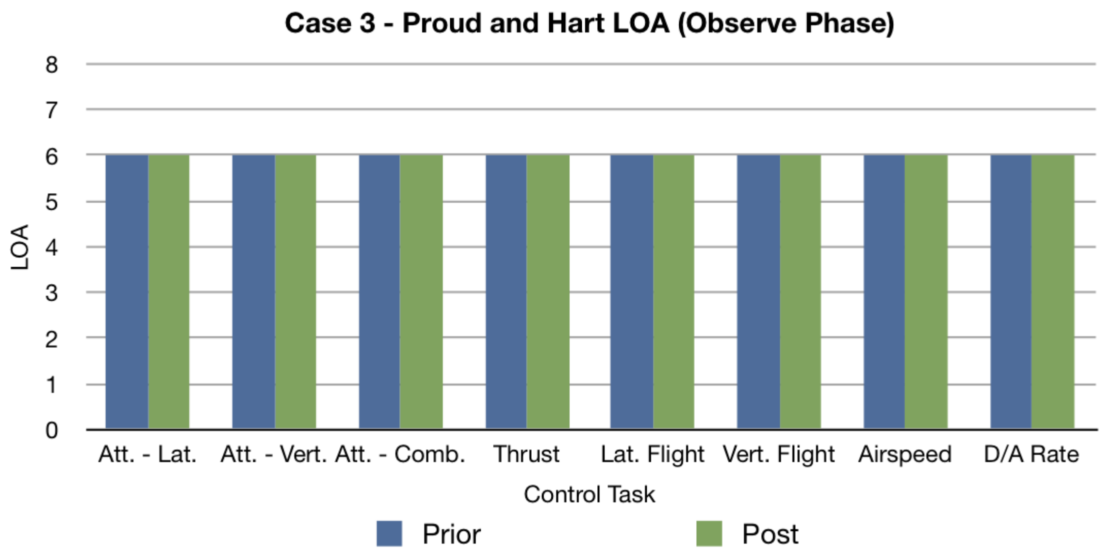

Figure E.17: Case 3 - Proud and Hart (Observe Phase)

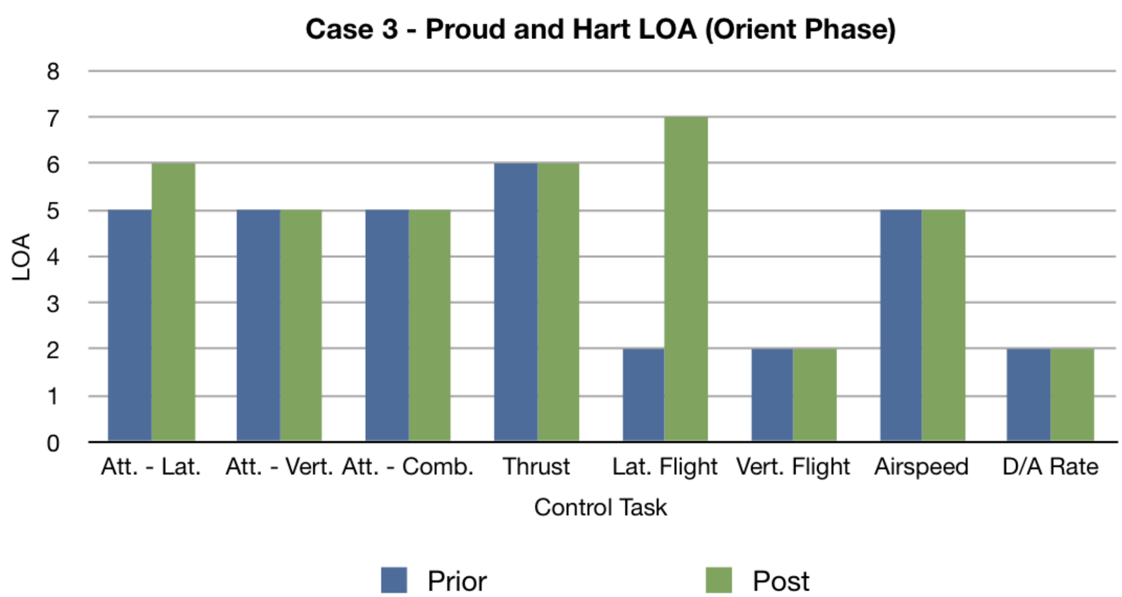

Figure E.18: Case 3 - Proud and Hart (Orient Phase)

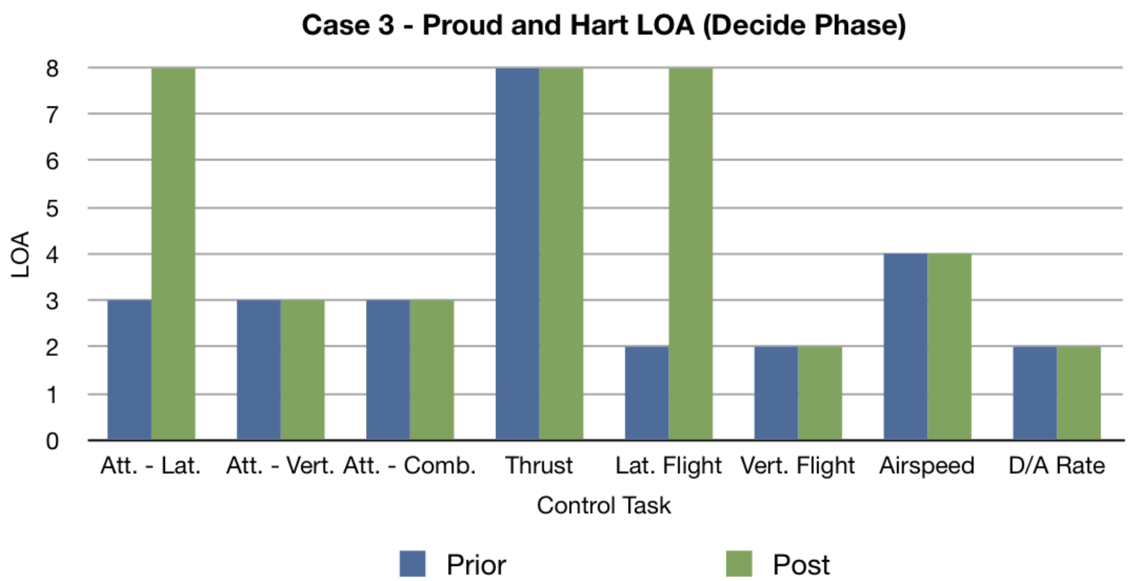

Figure E.19: Case 3 - Proud and Hart (Decide Phase)

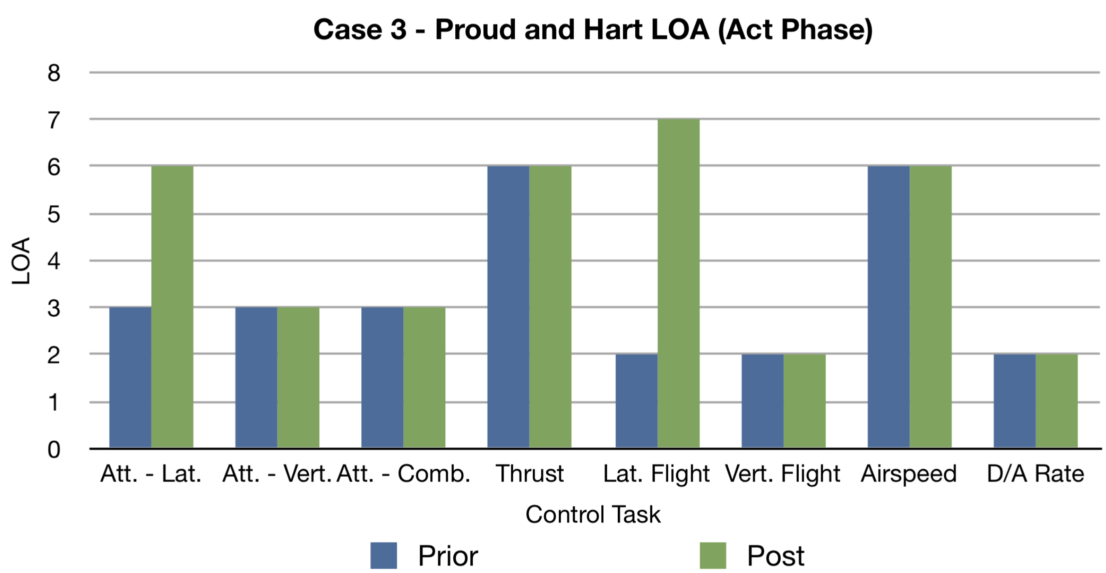

Figure E.20: Case 3 - Proud and Hart (Act Phase)

Table E.7: Case 3 - Proud and Hart LOA

Case 3 - Proud and Hart LOA								
Control Task	Observe		Orient		Decide		Act	
	Prior	Post	Prior	Post	Prior	Post	Prior	Post
Att. - Lat.	6	6	6	5	3	8	3	6
Att. - Ver.	6	6	5	5	3	3	3	3
Att. - Comb.	6	6	5	5	3	3	3	3
Thrust	6	6	6	6	8	8	6	6
Lat. Flight Path	6	6	2	7	2	8	2	7
Vert. Flight Path	6	6	2	2	2	2	2	2
Airspeed	6	6	5	5	4	4	6	6
Descent/Ascent Rate	6	6	2	2	2	2	2	2

trigger is comes from the internal architecture and logic of the automation design; however, previous mode activity by the user also set the stage for this to occur.

Using the updated Endsley model, the following factors can be can be identified as involved in the triggering the transition:

- Automation Mode
- Performance of Actions
- System State

Automation Mode - The architecture of the automation led to this particular mode switch directly, as the mode in which the system was operating was actively searching for the localiser and the glide slope.

System State - The achievement of a particular system state allowed for the reacquisition of the localiser, which was the substance of this mode change.

Performance of Actions - The past actions of the pilot of attempting to switch back to APP mode, as well as all control actions of to the point of this transition placed the automation into a state in which the localiser was able to reacquire.

These triggering factors are shown in Figure E.21.

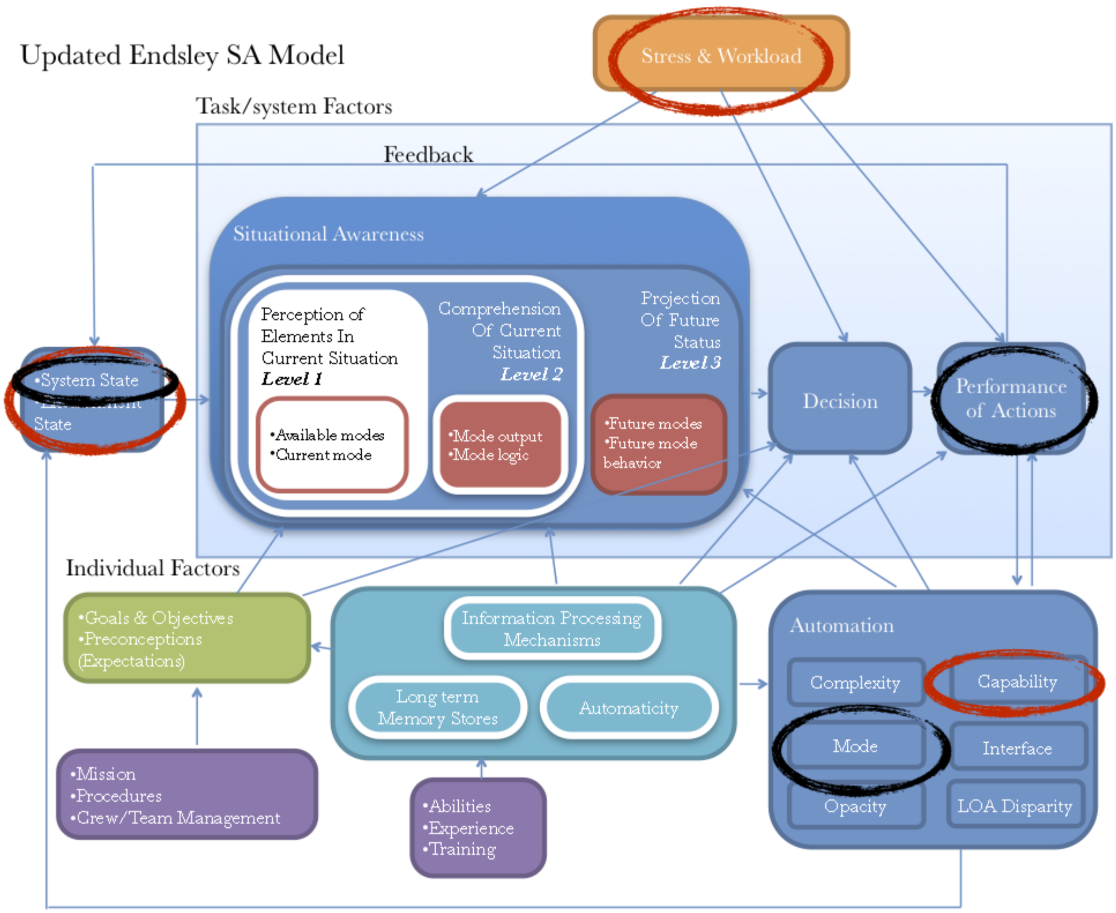

Figure E.21: Factors in TNT Airways Cargo Flight 325N Transition Case 3

E.4.3 Factors, Mechanisms, and Design Lessons

Factors in the Transition

Based on the Endsley's updated model of the human decision making, the following factors can be identified as particularly relevant in this case of transition as it pertains to the manner in which the system reverted:

- System State
- Environment State
- Stress & Workload
- Automation Capability

System State - The achievement of a particular system state was a factor in the triggering of this transition; however this was also a major factor in the way in which the system reverted. Prior to the transition the system states were deviated from the centerline. In acquiring the localiser and changing modes, the system states were controlled to reduce this error. Hence, as soon as this mode engaged the system immediately experienced proactive control input.

Additionally, the plane states were operating within the overall context of landing, placing significant constraints on performance requirements and acceptable deviation.

Environment State - As described before, the system was operating in bad weather, which increased the stress and workload of the pilot involved.

Stress & Workload - This was negatively impacted by the environmental state and system state. With these increased attention resources were not a peak efficiency and were also being exhausted.

Automation Capability - The automation was only capable of reacquiring the localiser; the glideslope was never reacquired. This additional transition, which though not intended by this particular transition case, was originally intended by the pilot. It was outside of the automation's capability.

These factors in the gracefulness of the transition are shown in Figure E.21.

Mechanisms of Gracefulness

Using the mechanisms model that was originally developed by Endsley for explaining situational awareness and augmenting with automation processes, an understanding of the mechanisms inhibiting the gracefulness of the transition in this system can be determined. In particular this system was ungraceful because the operator did not maintain the state of the vehicle within acceptable parameters to achieve the mission object (ie. landing).

The mechanism responsible for the ungraceful nature of this transition were identified as follows:

- Attention Resources
- Mode Setting
- Operator Perception
- Operator Interpretation, Comprehension, and Projection
- Operator Schema

These identified mechanisms are acting similar to the way in which they affected the two previous transition studies. Specifically in this case:

Attention Resources - The operator is still suffering from a high workload, which is placing insatiable demands on his attention resources.

Mode Setting - The mode setting prior and following this transition do not optimally fit the situation. As such, in order to reconcile this problem with the current schema of the pilot to still land the plane an additional amount attention resources are required.

Operator Perception - Perceptual errors are occurring, reflected in the improper selection of schema for the current situation, due to attention deficiency.

Operator Interpretation, Comprehension, and Projection - Improper schema and incomplete perception result in poor interpretation, comprehension, and projection of the current state of the system and its future states.

Operator Schema - An improper schema is still being applied to current situation (continuation bias): the pilot is still trying to maintain the prior system goal of landing instead of modifying the plan to a go-around.

These mechanisms of gracefulness are shown in Figure E.22.

Design Principles and Lessons
Based on these observations and the particulars of this transition the following design lessons can be learned and applied:

- Reducing the attention demands on the operator would have improved the gracefulness of the transition. This could have been done by reducing the taskload on the pilot, such as communication with ATC.
- Salient mode cues, particularly in such bounded operational environments as that encountered during take-off and landing of aircraft. Such cues should provide for the correct transition of operators into schema appropriate for the given situation (in this case a go-around).
- Enhanced perception during mode transitions using augmented reality displays would hopefully reduce the attention demand for the perceptual block and improve the

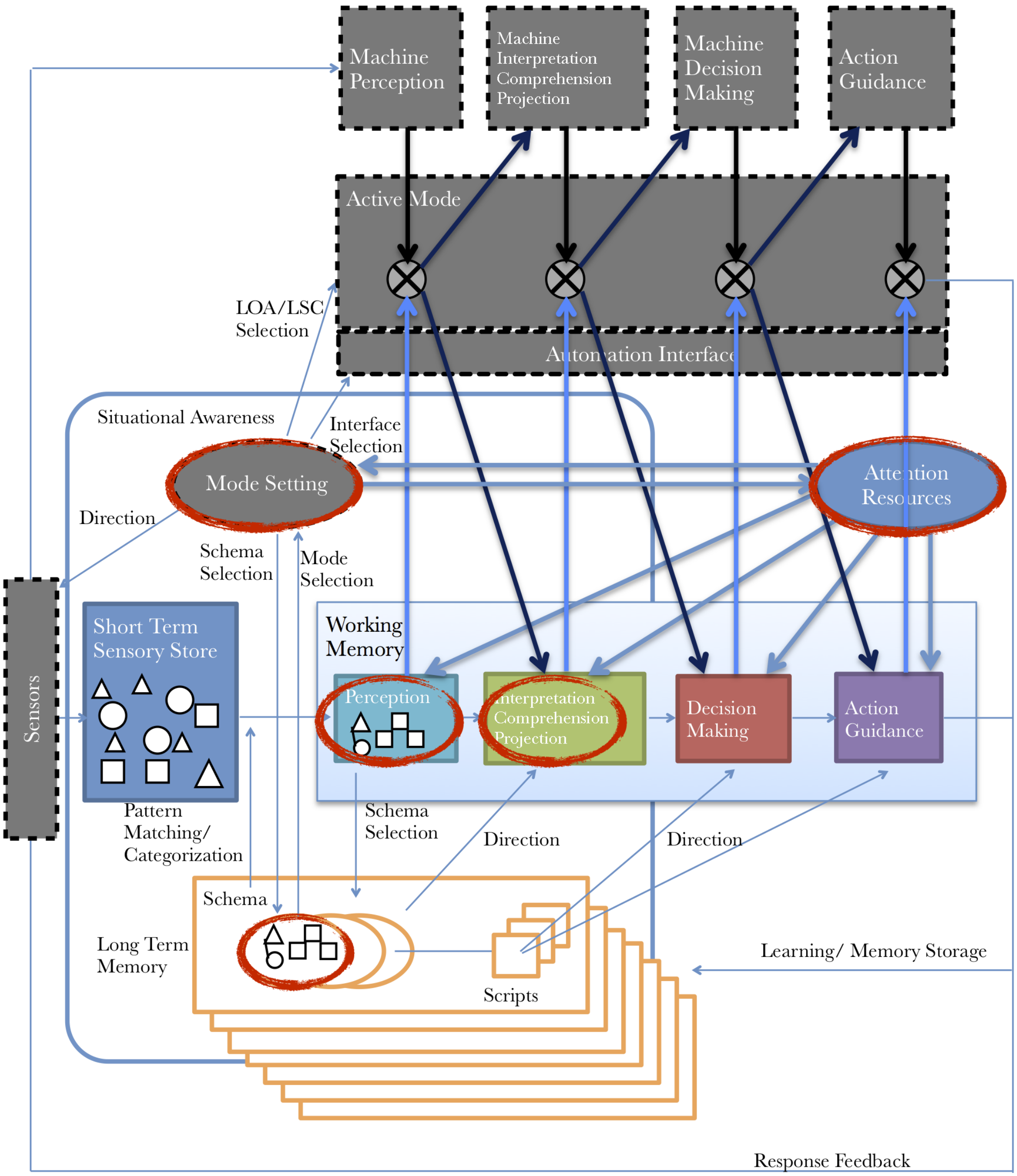

Figure E.22: Mechanisms in TNT Airways Cargo Flight 325N Transition Case 3

functioning of this block.

- Enhanced integration displays during mode transition using information integration displays could reduce the attention requirements of the perception block.
- Reduce the attention demands of the perception and interpretation blocks by reverting to intermediate levels of automation which still retain these functions. Only as a last resort should these be completely bypassed during a transition to a lower level of automation.

E.5 Transition Case 4

The fourth transition to be consider is the final transition into TOGA mode. The report describes the transition as follows:

> The co-pilot then gave the "APPROACHING MINIMUMS" callout but, by this time, the aircraft was 130 ft aal, 1.5 dots above the glideslope and descending at an increasing rate of descent of more than 1,500 pfm. At an RA of between 87 ft and 59 ft an EGPWS "SINK RATE PULL UP" warning was recorded.
>
> Almost immediately, the autopilot and autothrust modes went to TOGA mode. Between 1.5 and 2.5 seconds before impact, the autothrust dropped out of MCP speed mode and entered GA mode. AS TOGA mode was activated, the control column was brought back, the pitch of the aircraft increased, the wings leveled and the audible autopilot disconnect warning was triggered. After the autopilot was disengaged for the go-around, it was not re-engaged for the rest of the flight.

When the TOGA mode is activated, the throttles advance to a takeoff thrust. At the same time, this mode automatically rolls the wings to level to maintain the current heading and pitches the plane up in order to establish a positive rate of climb at 2000 fpm.

E.5.1 The Modes

Sheridan and Verplank LOA

Attitude Control - Prior to the transition the system was operating at Level 5 (see the previous transition case). With the implementation of the initial TOGA mode, the computer was essentially operating at Level 7 in implementing the action and informing the human necessarily. During the secondary TOGA phase the system was operating at near manual mode, with the pilot in charge of attitude management.

Thrust Control - Prior to the transition the system was operating at Level 7 (see the previous transition case). With the activation of the TOGA button, this continued to be the case. TOGA is a mode which commands the autothrottle to gradually advance the throttle until takeoff thrust is achieved.

Lateral Flight Path Control - Prior to the transition the system was operating at Level 7 (see the previous transition case). With the activation of the TOGA button the wings are rolled to level. Lateral path was being controlled to the extent that the computer was set to maintain the current heading. This places the system still at Level 7.

Vertical Flight Path Control - Prior to the transition the system was operating at Level 2 (see the previous transition case). With the activation of the TOGA button the airplane automatically sought to achieve a rate of climb of 2000 fpm. Hence, the vertical path was being controlled to an extent, but only as a side effect of the descent/ascent rate. This places the system at Level 7.

Airspeed Control - Prior to the transition the system was operating at Level 7 (see the previous transition case). This did not change throughout the transition.

Descent/Ascent Rate Control - Prior to the transition the system was operating at Level 2 (see the previous transition case). With the activation of the TOGA mode the computer sought to establish a positive rate of climb. As such, the system was operating at Level 7.

These levels are shown in Figure E.23 and E.8.

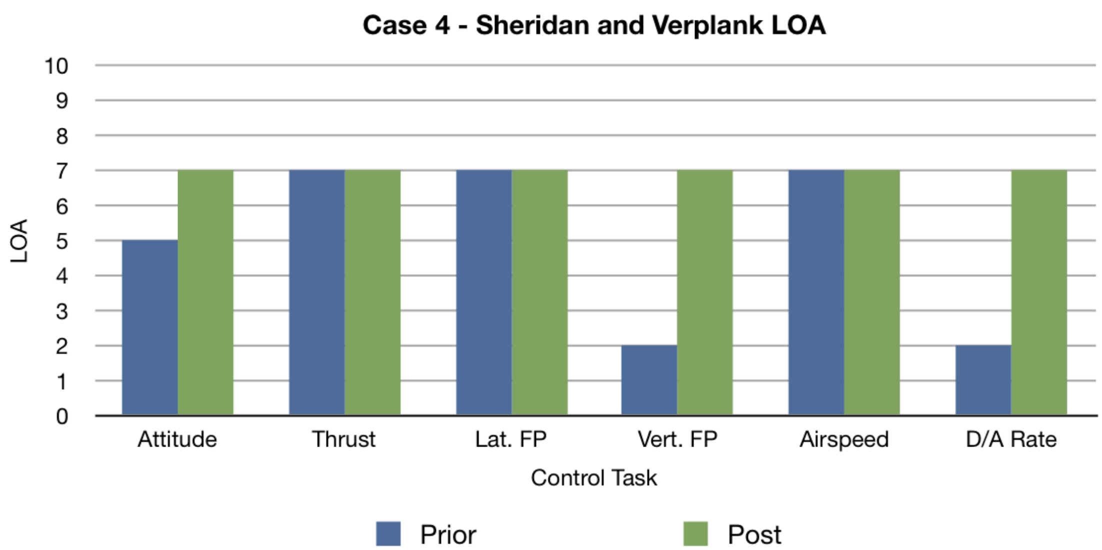

Figure E.23: Case 4 - Sheridan and Verplank LOA

Proud and Hart LOA

The system can be analyzed based on Proud and Hart in the following manner. A breakdown into the individual tasks becomes necessary for the Orient, Decide, and Act phase.

Table E.8: Case 4 - Sheridan and Verplank LOA

Case 4 - Sheridan and Verplank LOA		
Control Task	*Prior*	*Post*
Attitude	5	7
Thrust	7	7
Lat. Flight Path	7	7
Vert. Flight Path	2	7
Airspeed	7	7
Descent/Ascent Rate	2	7

Such a breakdown is unnecessary for the Observe phase because this phase is concerned with raw data which had not yet been sorted by task relevance.

Attitude Control

- Orient - Prior to the transition the system was operating at Level 5 (see the previous transition case). Following the transition the system was operating at Level 7, in which the computer was completing these tasks with the human as backup.
- Decide - Prior to the transition the system was operating at Level 3 (see the previous transition case). Following the transition the system was operating at Level 8, as control decisions regarding attitude were being made by the computer.
- Act - Prior to the transition the system was operating at Level 3 (see the previous transition case). Following the transition the system was operating at Level 7, in which the human was informed of system actions on a contextual basis.

Thrust Control

- Orient - Prior to the transition the orientation task regarding thrust was being controlled at Level 6 (see the previous transition case). This did not change throughout this transition.
- Decide - Prior to the transition the system was operating at Level 8 (see the previous transition case). This did not change following the transition.
- Act - Prior to the transition the system was operating at Level 6 (see the previous transition). This did not change following the transition.

Lateral Flight Path Control

- Orient - Prior to the transition the system was operating at Level 7 (see the previous transition case). This not change following the transition.
- Decide - Prior to the transition the system was operating at Level 8 (see the previous transition case). This did not change following the transition.
- Act - Prior to the transition the system was operating at Level 7 (see the previous transition case). This did not change following the transition.

Vertical Flight Path Control

- Orient - Prior to the transition the system was operating at Level 2 (see the previous transition case). Following the transition the computer assumed the task of orientation in regard to vertical flight path, with the human as contingency back up, placing the system at Level 7.
- Decide - Prior to the transition the system was operating at Level 2 (see the previous transition case). Following the transition the computer assumed all active decision making tasks regarding flight path control, placing the system at Level 2.
- Act - Prior to the transition the system was operating at Level 2 (see the previous transition case). Following the transition the system began operating at Level 7, in which the human was informed contextually of the system actions.

Airspeed Control

- Orient - Prior to the transition the system was operating at Level 5 (see the previous transition case). Following the transition the system began to operate ate Level 7, in which the computer assumed the main responsibilities regarding airspeed, with the human as a backup.
- Decide - Prior to the transition the system was operating at Level 4 (see the previous transition case). Following the transition the system began operating at Level 8, with the computer making all control decisions while disregarding the human.
- Act - Prior to the transition the system was operating at Level 6 (see the previous transition case). Following the transition the computer was in charge of all airspeed related control actions while contextually informing the human of any actions, placing the system at Level 7.

Descent/Ascent Rate Control

- Orient - Prior to the transition the system was operating at Level 2 (see the previous transition case). Following the transition the system began operating at Level 7, with the computer handling all orientation tasks regarding the descent/ascent rate in order to achieve 2000 fpm ascent. The human was kept as a backup.

- Decide - Prior to the transition the system was operating at Level 2 (see the previous transition case). Following the transition the system was operating at Level 8, with all control decisions being enumerated and determined by the computer while ignoring the human.
- Act - Prior to the transition the system was operating at Level 2 (see the previous transition case). Following the transition the system was operating at Level 7, with the computer in charge of all control output and saving the human for emergency override.

These levels are shown in Figures E.24-E.27 and Table E.9.

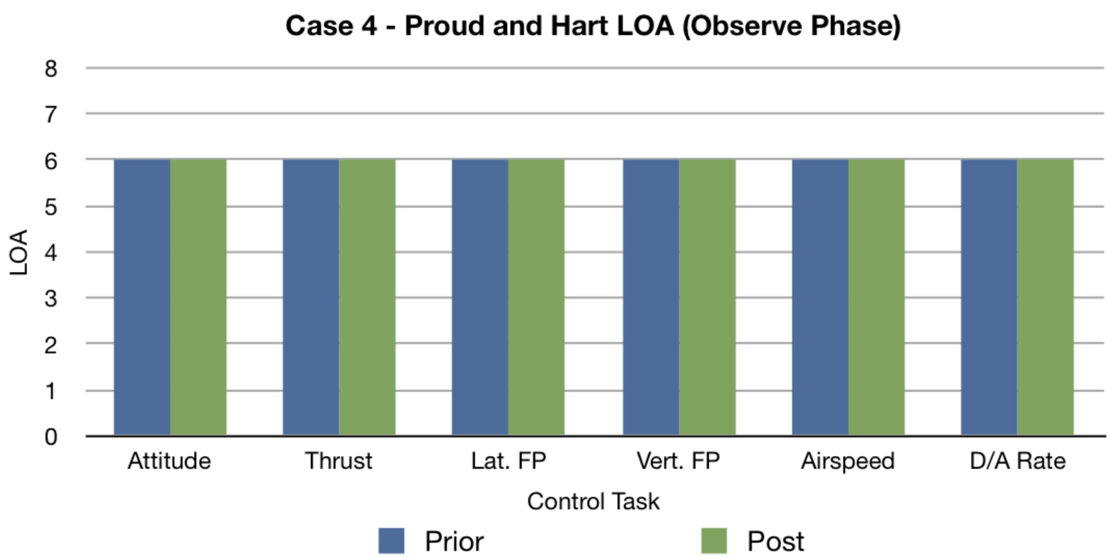

Figure E.24: Case 4 - Proud and Hart (Observe Phase)

E.5.2 The Trigger

The trigger was an audio alert from the EGPWS alert at an altitude of between 87 and 59 ft aal. which presented the pilot with the words “SINK RATE PULL UP.” As the report details, the autothrust and autopilot modes almost immediately went to TOGA mode. Hence from this trigger can be sourced to two major places on Endsley’s updated model:

- System State
- Automation Mode
- Automation Interface

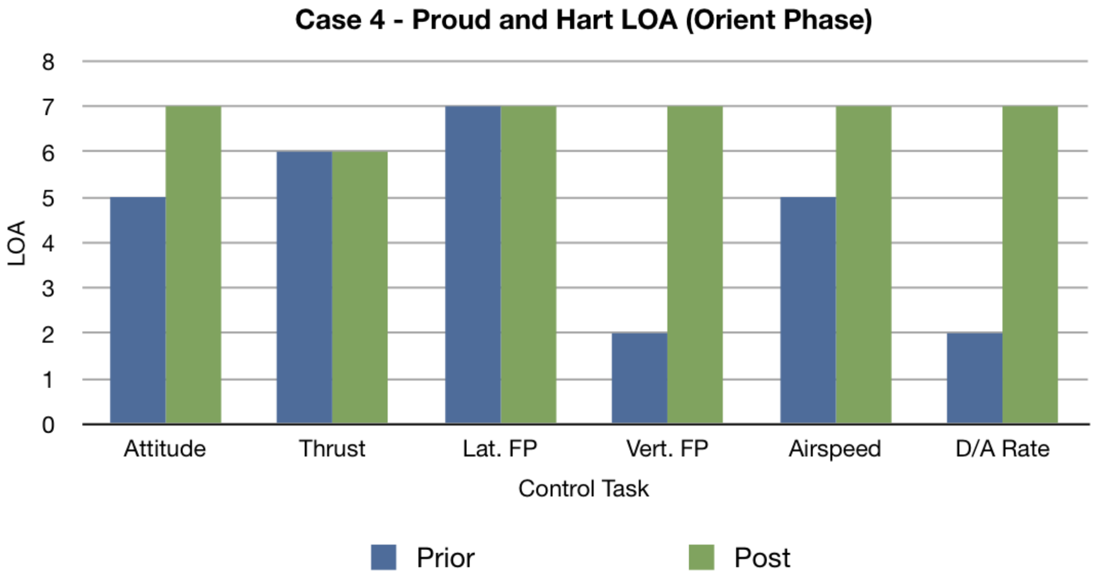

Figure E.25: Case 4 - Proud and Hart (Orient Phase)

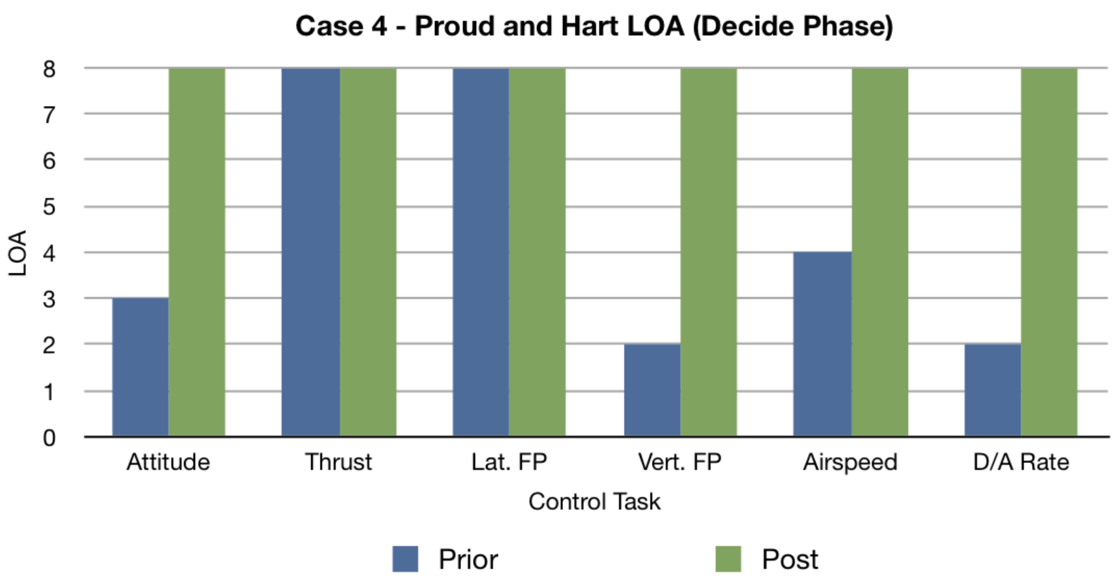

Figure E.26: Case 4 - Proud and Hart (Decide Phase)

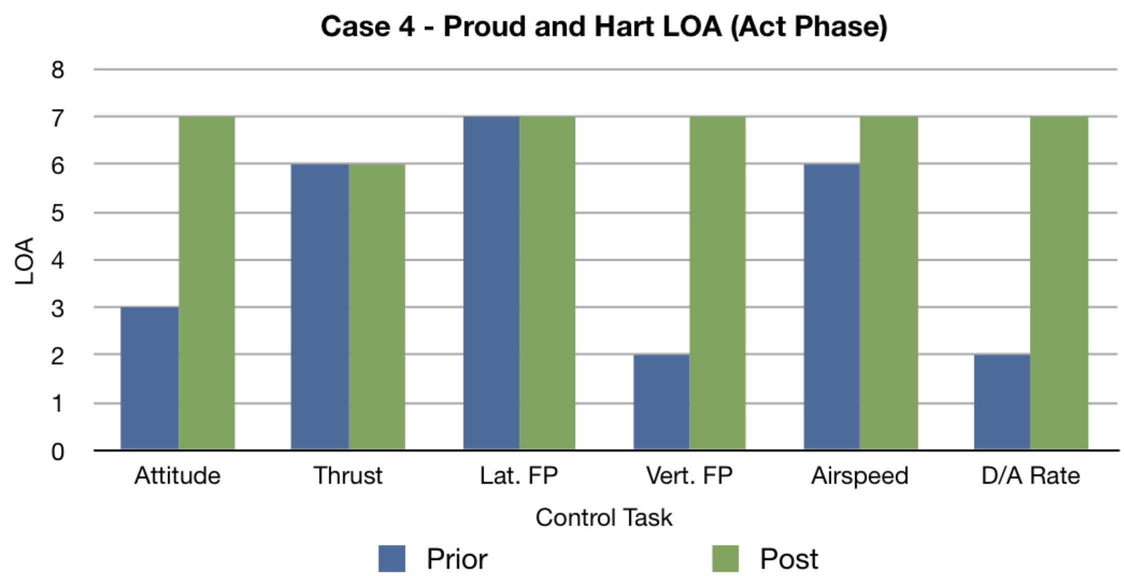

Figure E.27: Case 4 - Proud and Hart (Act Phase)

Table E.9: Case 4 - Proud and Hart LOA

Case 4 - Proud and Hart LOA								
Control Task	Observe		Orient		Decide		Act	
	Prior	Post	Prior	Post	Prior	Post	Prior	Post
Attitude	6	6	5	7	3	8	3	7
Thrust	6	6	6	6	8	8	6	6
Lat. Flight Path	6	6	7	7	8	8	7	7
Vert. Flight Path	6	6	2	7	2	8	2	7
Airspeed	6	6	5	7	4	8	6	7
Descent/Ascent Rate	6	6	2	7	2	8	2	7

System State - The EGPWS alert was itself triggered by the system reaching a particularly unsafe state as determined by the automation mode.

Automation Mode - The Automation Mode encompasses the logic of the particular mode being used throughout the system and as such includes the logic which determined the EGPWS alert. Hence, the automations design, and hence its mode, was a primary factor in triggering the operator to revert to TOGA.

Automation Interface - While the system state and automation mode could have been alerting each other, the job of triggering the user ultimately fell to the automation's audio interface. Had the interface been poorly designed or malfunctioned, no trigger would have been presented to the user (perhaps until ground contact).

The triggering factors are shown in Figure E.28.

E.5.3 Factors, Mechanisms, and Design Lessons

Factors in the Transition

The following factors, based on Endley's updated model played a part in this transition:

- Stress and Workload
- Environmental State
- Operator Experience & Training
- Operator Automaticity
- General SA (Level 2 & 3)

Stress and Workload - This transition took place under high stress and a large amount of workload. Hence, this affected the allocation of attention by the operator.

Environmental State - The environment was not ideal for operating in and, as such, was a source of the high workload and stress of the pilot

Operator Experience & Training - The operator's experience and training was extensive enough to have "programmed" this mode transition response to the trigger described above. Hence, the training and experience were a factor in this transition.

Operator Automaticity - This was more of a factor in the sense that the pilot's reaction time, as described by the report, suggests an almost automatic reaction time. Additionally, it is reasonable to assume that the pilot was spring-loaded to execute a Go-Around if the EGPWS audio alert went off during a landing.

General SA (Level 2 & 3) - The trigger was able to, in some senses, inject a certain amount of Level 2 & 3 awareness into the system. In hearing the EGPWS alert, the pilot was immediately made aware of a pertinent piece of information and what, if left unchecked,

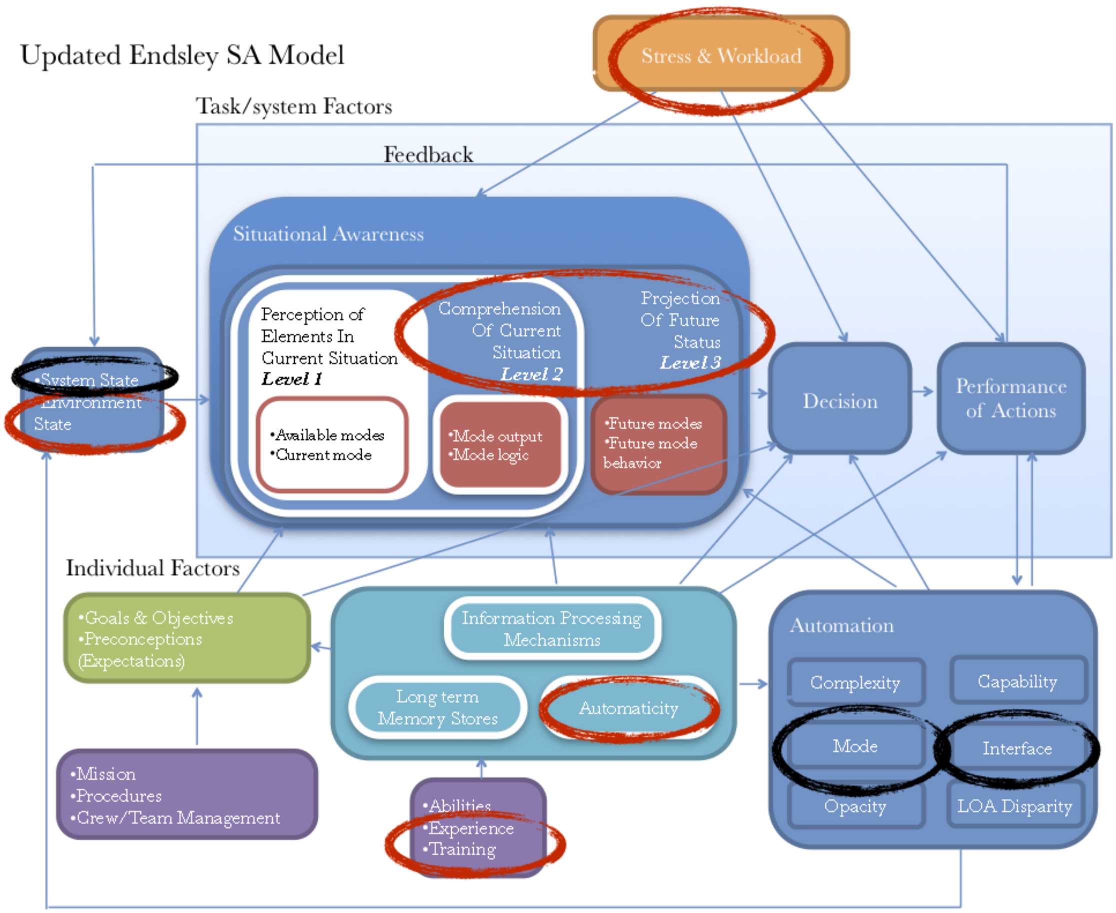

Figure E.28: Factors in TNT Airways Cargo Flight 325N Transition Case 4

that would mean for the future states of the plane. Hence, while Level 1 SA was arguably quite poor, and even Level 2 SA was still quite poor, this trigger was able to inject a sufficient amount to elicit the correct response (initiation of a Go-around). This injection only sufficed to initiate the transition; it did not aid in its gracefulness.

These factors in determining the gracefulness of this transition are shown in Figure E.28.

Mechanisms in Gracefulness

This transition was particularly ungraceful as the states of the vehicle were not being maintained prior to, during, or following the transition. This is evidenced prior to the transition by the very fact that the trigger was based on the sensing of an unsafe system state. During and following the transition the plane impacted the ground, which is most decidedly not a controlled system. Hence, the following mechanisms were identified using Endsley's updated model mechanisms in situational awareness:

- Operator Perception
- Operator Interpretation, Comprehension, and Projection
- Operator Decision Making
- Operator Action Guidance
- Operator Attention Resources
- Operator Schema

Operator Perception - The lack of perception of the current situation was a hang over from the previous transition and did not become resolved until a significant amount of time had passed since the transition being considered here.

Operator Interpretation, Comprehension, and Projection - Additionally, the lack of interpretation, comprehension, and projection were a hang over as well; however; this was briefly aided by the EGPWS, which infused a comprehension of the emergency at hand an the required fix. This was a very temporary fix, as the pilot is recorded as making sure he had "recovered his senses" following the transition.

Operator Decision Making - Decision making was invariably affected by the lack of attentional resources. Not only this, but the inherent lag time required for human decision making, coupled with just moving to act took longer than was required to regain and maintain system control in the new mode.

Operator Action Guidance - The operator was not able to react quickly enough with the transition and within the transition to maintain adequate control of the system. This is shown in the presence of the ground impact.

Operator Attention Resources - Attention resources, in like manner to the rest of the transitions considered in this study, was quite poor. As this deficit piled up through the course of all these transitions, the effect spread to the entirety of the pilot's working memory, affecting perception, interpretation, decision making, and action guidance.

Operator Schema - At this point the operator was finally made aware of his improper choice of schema in dealing with the situation, which ultimately led to complete discard. This, as the mechanisms model would suggest, left a void which needed to be filled in, which was done quickly by the EGPWS, which had him briefly adopt a schema that suggested the mode switch to TOGA. This schema, while eliciting the correct control output, was largely incomplete, and the pilot had to spend some time completing his picture of the current situation (described in the report).

These mechanisms of gracefulness are shown in Figure E.29.

Design Principles and Lessons

The following lessons can be learned from this transition case:

- Warning systems can briefly infuse a temporary eleveated situational awareness, which may be used to elicit the correct mode response; however, this is only a stop-gap. Measures need to be taken to help quickly fill-in an operator's schema of the situation.
- In emergency situations where the response is standard (Go-around in this case), the automation should aid the human in order to increase response times. In some cases, this might mean altogether removing the human from the triggering loop, and placing the computer in charge (if the EGPWS goes off, execute a go-around).
- Understanding the current situation is key to executing a graceful transition. Introducing displays to help keep the user informed, such as trend displays or glideslope deviation readouts, is important.

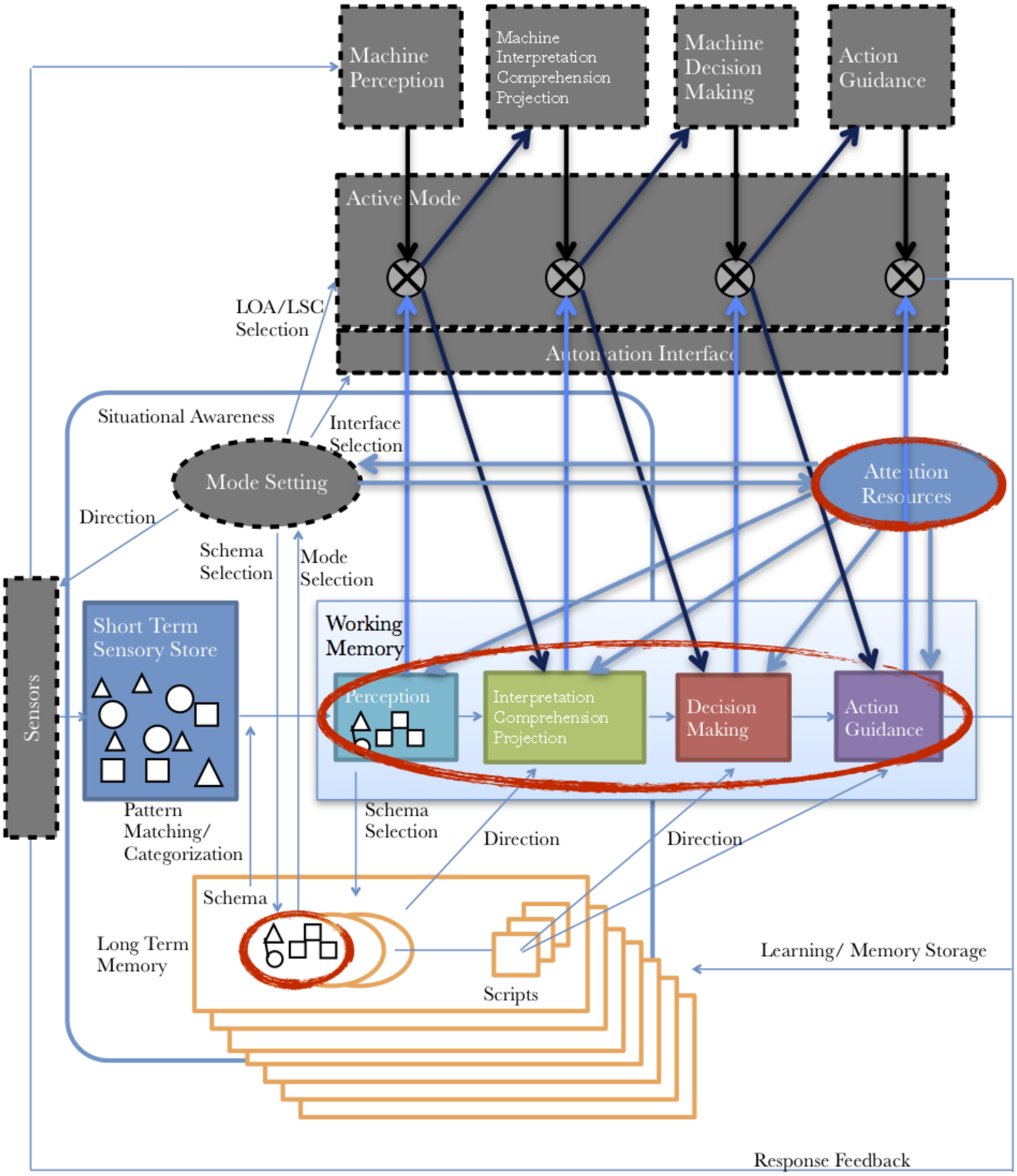

Figure E.29: Mechanisms in TNT Airways Cargo Flight 325N Transition Case 4

Appendix F

Case Study: STS-3 Pilot Induced Oscillations

Throughout the initial missions of the space shuttle, a major portion of operations was devoted to final validation of the shuttle's systems. In particular, the autoland system capabilities and its interaction with the pilot was of particular concern to designers and operational managers. In STS-3, a scheduled transition to CSS mode (manual mode) resulted in a pilot-induced-oscillation (PIO) which, while it didn't cause a mission failure, led to a reevaluation of the ability of pilots to re-engage themselves in the control loop task.

F.1 The Transition

The only transition being studied in this particular case study is that procedural transition which took place between autoland to manual.

The two modes that were switched between were autoland and manual. The autoland took care of all landing operations, apart from the lowering of the landing gear and braking operations. Aside from these two functions, pitch, roll, yaw, etc. were all controlled by the computer, and this process was monitored by the human. The manual mode provided the pilot with superaugmented vehicle dynamics, essentially meaning that control for the pilot was not fully manual, but was mediated through computer-closed control loops. The manual mode was RCAH, in which the pilot directly commanded attitude rates.

F.1.1 The Modes

Sheridan and Verplank LOA

According to Sheridan and Verplank, the autoland system would be classified as Level 7, on the whole. Following the transition, the system began operating at Level 1. This breakdown does not describe the requirement of the pilot to extend the gear and apply the braking in the autoland mode. These levels is shown in Figure F.1 and Table F.1.

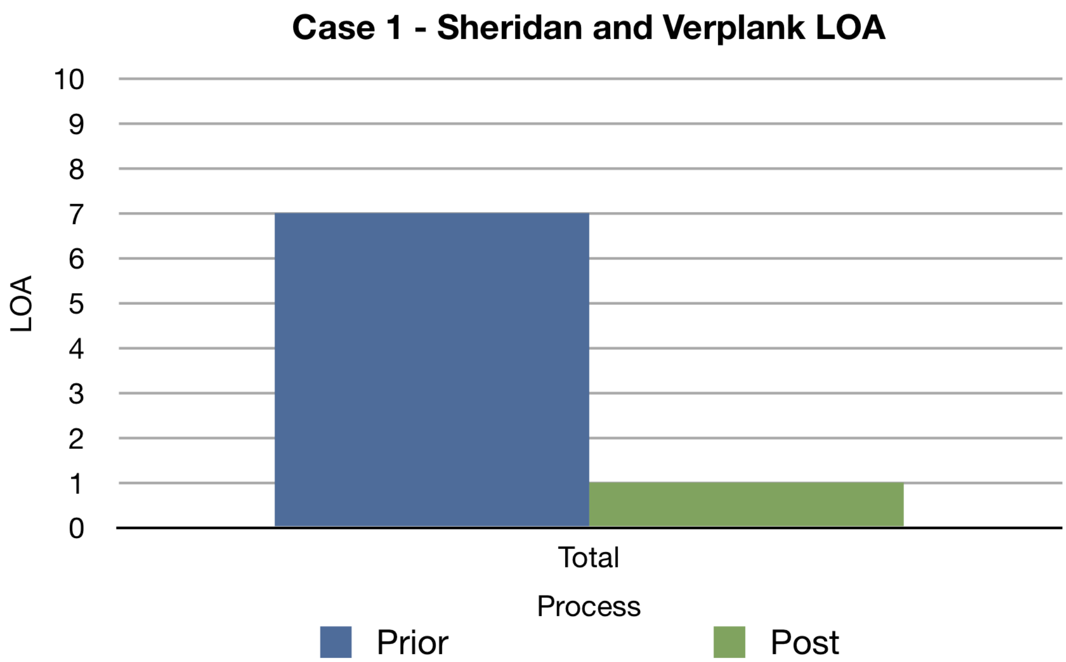

Figure F.1: STS-3 Sheridan and Verplank LOA

Table F.1: STS-3 Sheridan and Verplank LOA

STS-3 Sheridan and Verplank LOA	
Prior	*Post*
7	1

Proud and Hart LOA

Breaking the Levels of Automation into the OODA phases suggests the following levels:

Observe Phase - Prior to the transition, the system was operating at Level 3, as information was still being presented to the user while in autoland mode, but this information was not being implemented by the user. Following the transition, the system was still operating at Level 3.

Orient Phase - Prior to the transition, the system was operating at Level 7, with the computer analyzing, predicting, and interpreting data in order to fly the craft. Following the transition, the system was operating at Level 1, with the human predicting all of the craft responses and integrating all information.

Decide Phase - Prior to the transition, the system was operating at Level 8. Following the transition, the system was operating at Level 1.

Act Phase - Prior to the transition, the system was operating at Level 7. Following the transition, the system was operating at Level 1.

These levels are shown in Figures F.2-F.5 and Table F.2.

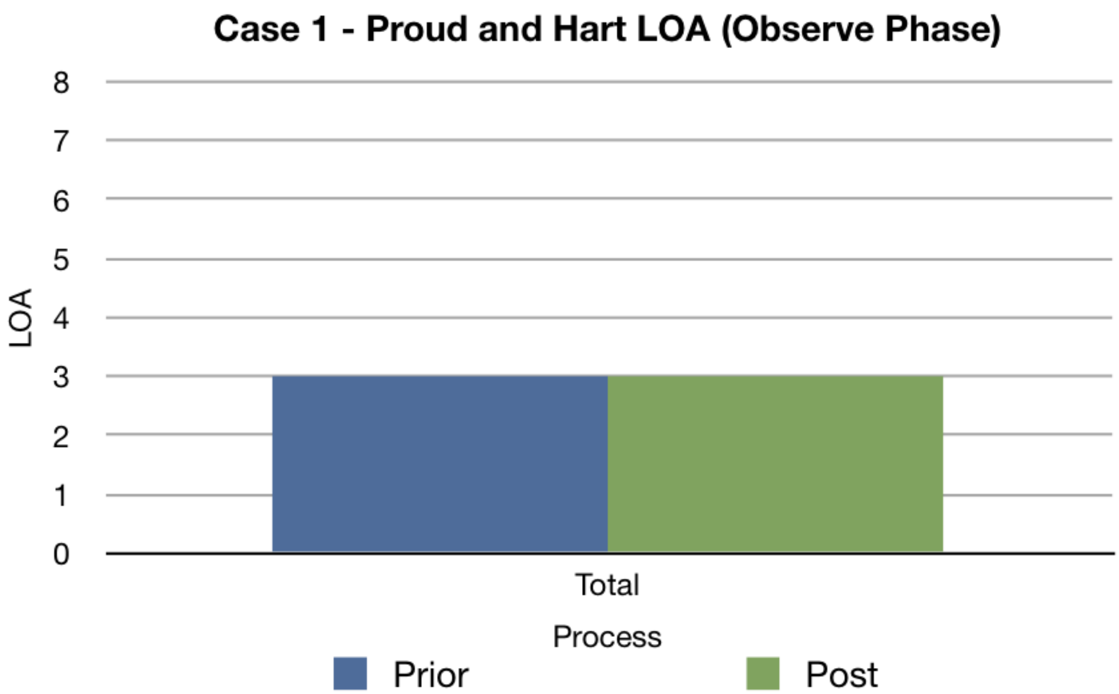

Figure F.2: STS-3 Proud and Hart LOA (Observe Phase)

F.1.2 The Trigger

The trigger involved here was solely mission procedure. The mission plan called for the pilot to switch to manual flight at 125 ft elevation. While there were extenuating circumstances

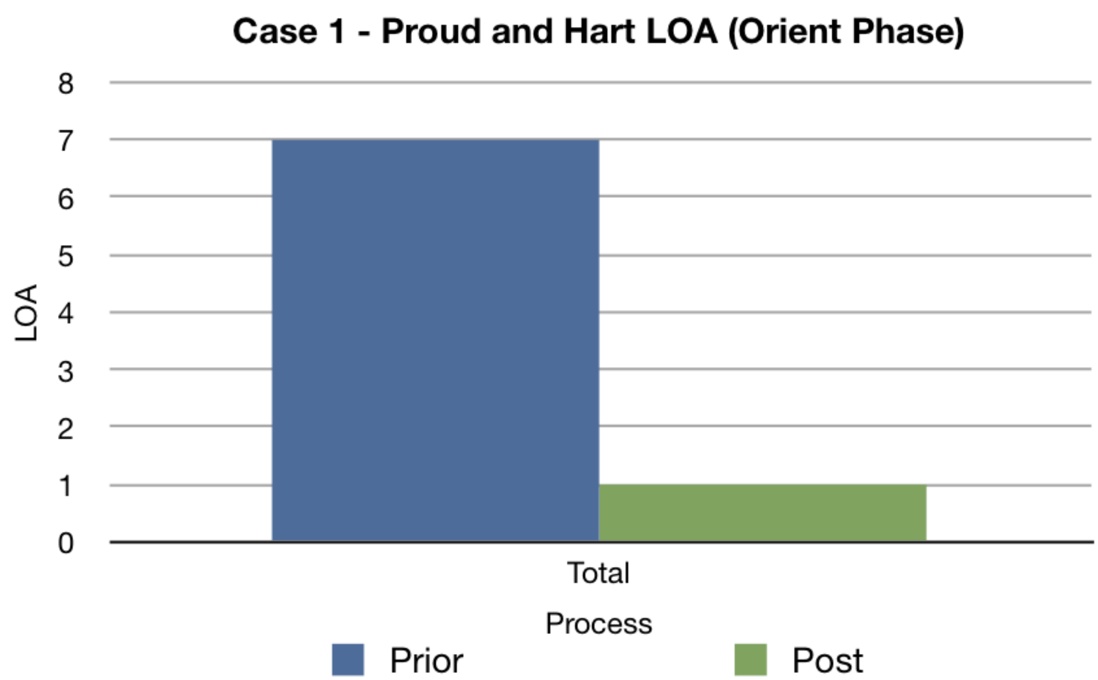

Figure F.3: STS-3 Proud and Hart LOA (Orient Phase)

Table F.2: STS-3 Proud and Hart LOA

STS-3 Proud and Hart LOA							
Observe		Orient		Decide		Decide	
Prior	Post	Prior	Post	Prior	Post	Prior	Post
3	3	7	1	8	1	7	1

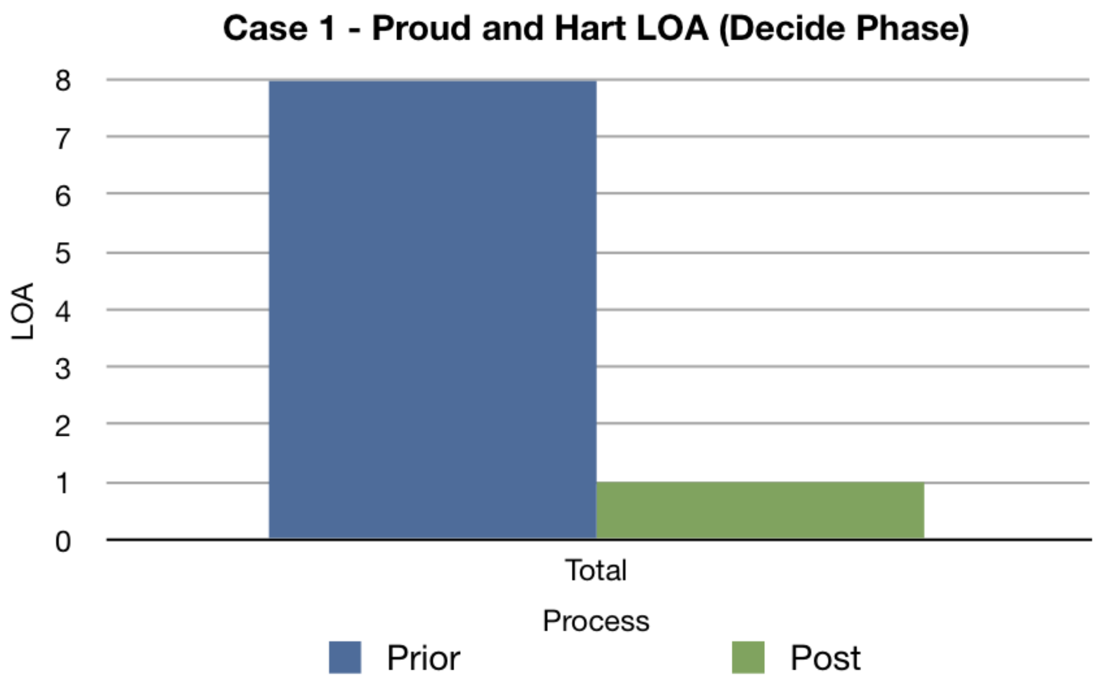

Figure F.4: STS-3 Proud and Hart LOA (Decide Phase)

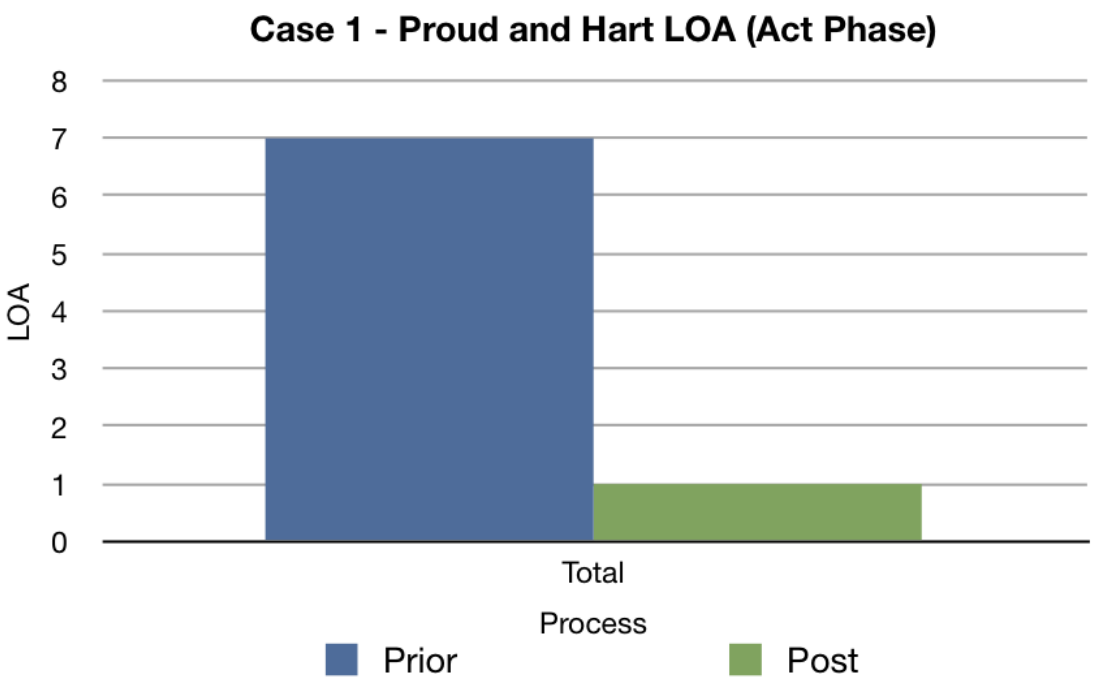

Figure F.5: STS-3 Proud and Hart LOA (Act Phase) that may have resulted in an ungraceful switch for the pilot, the source and trigger for the transition were from the mission and the pilot's execution of the procedure.

Hence, the following were identified as active in the triggering of this transition:

- Procedures
- System State
- Performance of Actions

Procedures - This particular transition occurred due to a condition set by the mission procedure: switch to manual at 125 ft elevation.

System State - The achievement of a particular system state was the condition upon which the mission procedural requirement was founded.

Performance of Actions - The operator, while governed by their adherence to the procedures and perception of the system states, was ultimately in charge of triggering this transition. As such, this transition would not have taken place were in not for their physical triggering of the mode transition.

These triggering factors are shown in Figure F.6.

F.1.3 Factors, Mechanisms, and Design Lessons

Factors in the Transition

Due to the loss of a performance, manifest by the PIO immediately following touchdown, this mode transition cannot be considered as graceful. The following factors are seen as affecting this transition:

- Stress and Workload
- System State
- Environment State
- Mode situational awareness (Level 3)
- Automation Complexity
- Mode
- LOA Disparity

Stress and Workload - The moment at which this transition took place was one in which the operator was under a high workload. This negatively affected the amount of attentional resources the operator had to devote to making this transition.

System State - The system was in a highly dynamic state at the time of the transition, which made it more difficult for the operator to gain a knowledge of the internal system states.

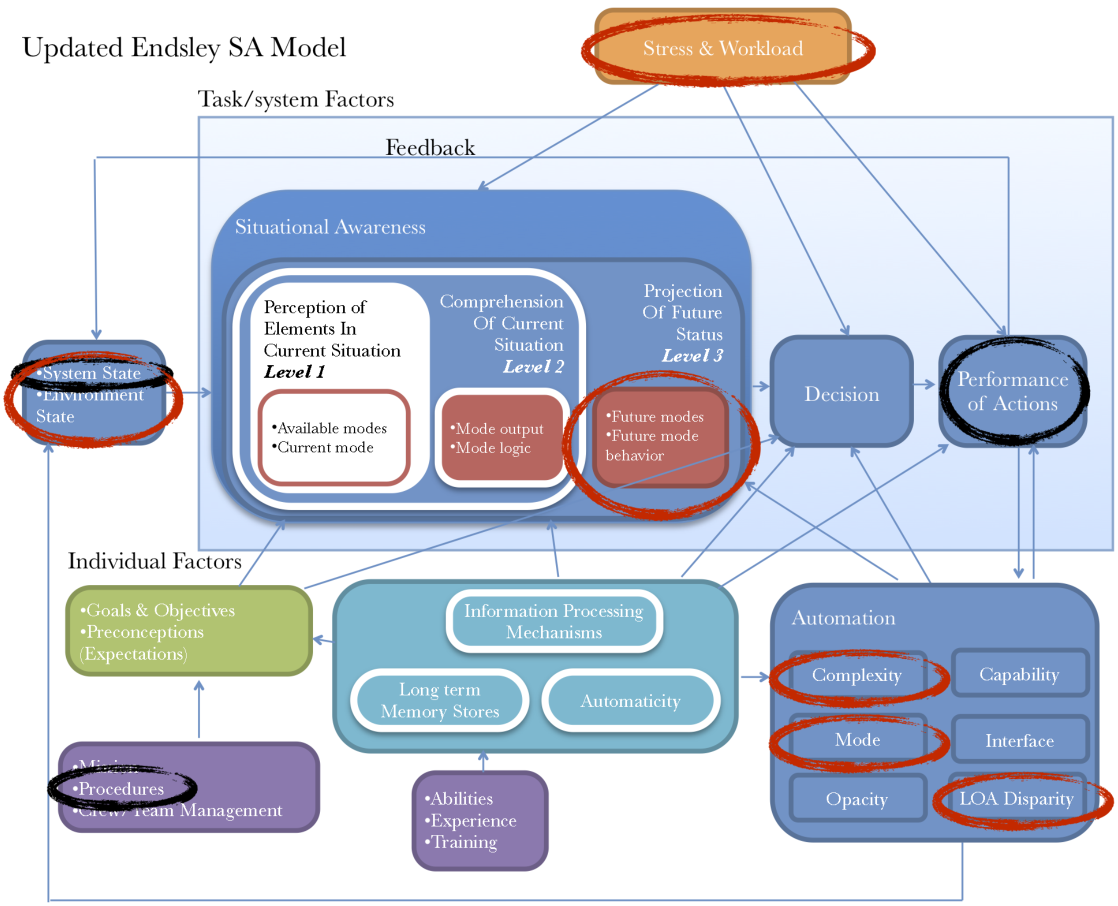

Figure F.6: Factors in the STS-3 PIO Transition Case Study

Due to this, it was much easier for performance to degrade even with active involvement from the operator; not enough lead had been generated yet.

Environment State - In a NASA contractor report, Myers, Johnston, and McRuer [49] suggested that part of the difficulty in this transition may have stemmed from the unusual environment that surrounded the orbiter while landing. STS-3 landing on a sand-strip, on which there was an interesting visual distraction of blowing sand that may have been obscuring the pilot'ss judgement of the runway surface.

Mode situational awareness (Level 3) - This describes the phenomenon generated by the dynamic system state. While the operator knew what the future mode would be, the behavior of the future mode was not entirely known (i.e. the proper control gains and inputs were not known). Had these been known, the transition would have been graceful because performance would most likely have been maintained.

Automation Complexity - The modes which was the operator was transitioning from and to were both highly complex in their operation, with a large number of processes requiring monitoring and controlling actions.

Mode - The mode into which was transitioned is not an easy mode to control in and of itself. This is different than the complexity, this describes the sensitivity required in controlling the shuttle in flight. Complexity can be managed, but the ease with which a particular process within that complexity is a separate dimension, and in this case was quite difficult to control; in some senses this describes the amount of lead that was required to be generated by the operator, a task that was already made difficult by the highly dynamic system states.

LOA Disparity - The disparity between the modes was quite high, meaning that the number of states which the user was required to gain knowledge and control over was quite high.

These factors in determining the gracefulness of the transition are shown in Figure F.6.

Mechanisms of Gracefulness
Based on the update Endsley model of SA, the following mechanisms were identified as negatively affecting the grace with which the transition occurred:

- Attention Resources
- Operator Schema
- Operator Perception
- Operator Scripts
- Action Guidance

Attention Resources - Due to the high workload and time-pressure encountered in this situation there was a high demand of attentional resources which most likely was pushed slightly more than it should have been. This was not as drastic a problem as in other transition case studies, but this is most likely because of the high amount of training that the operator had in this case, training which improved his ability to allocate limited attentional resources.

Operator Schema - The operator was aware of the new mode setting; however, a complete awareness did not develop in an instantaneous manner. The mode was changed, but the rate at which the operator's schema was updated (i.e. the rate at which they generate control lead) was not sufficient to make this transition completely graceful.

Operator Perception - Due to the time pressures and demand on attentional resources, the perception of the operator was not able to adequately update the operators schema with the new mode setting. This is not to say that this block malfunctioned: it was not able to provide enough information to the operator for them to update their schema in a timely enough manner.

Operator Scripts - Due to the slowly evolving schema, the control scripts were also slow to update. This was suggested by the pilot when he remarked that he saw the nose dropping faster than he like and pulled back on the stick to correct. This control reaction is characteristic of an instinctual reaction that was only informed of direction but not of a correct input magnitude, such as might occur from an underdeveloped user script.

Action Guidance - Ultimately, the ungraceful nature of the transition was manifested in the action guidance block, which resulted in the over correction by the pilot and the PIO.

These mechanisms of gracefulness are shown in Figure F.7.

Design Principles and Lessons
This particular transition was seen to be ungraceful because of the operator's inability to re-enter the control loop. The difficulties encountered which made this a problem were threefold:

- Environmental states which may have cause perceptive illusions that resulted in wrongly timed inputs
- Time and performance pressures which made the pilot more sensitive to system deviations
- Unfamiliarity of the pilot with system response to control inputs

These issues might have been mitigated had the following been considered and implemented:

- Improving display fidelity might have improved operator trust in the displays and

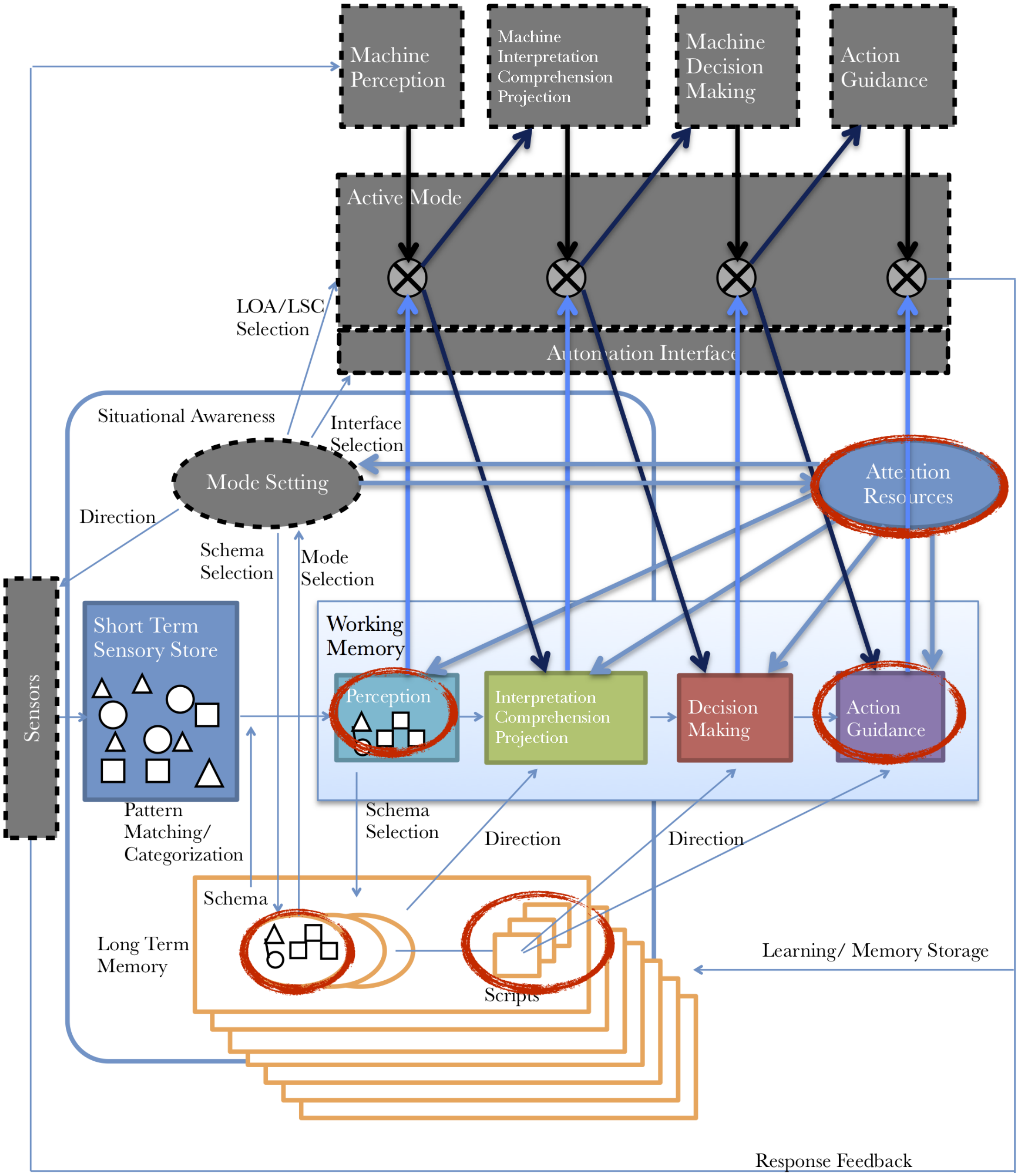

Figure F.7: Mechanism in STS-3 PIO Transition Case Study led them to have relied on their instrumentation more. This reliance on the instrumentation would have mitigated any perceptual illusions that were a result of the blowing sand, as this would not have entered the visual field of the pilot.

- Augmented visual reality display. Such a display might have removed the illusion created by the blowing sand.

- As this transition was triggered by mission procedures, it could have conceivably happened earlier with less time and performance pressure. This particular fix was implemented in future flights. To be fair, the reason this transition happened so late was for experimental purposes.

- Transitioning to a slightly higher level of automation or supervisory control, instead of going to full manual, would have reduced the knowledge disparity and may have allowed the pilot gain control of the system quicker. An example might be the take over of only the pitch or only the roll axes. Another option might have been the use of a Flight Director.

- If full manual is required, beginning in a semi-manual mode, such as single axis pitch control would allow the pilot not only to generate lead into one of the axes in which he would normally be transitioning, but it would also give incite into the rough magnitude of any roll inputs being required in a transition to full manual. In this way, the disparity in LOA could be reduced during the transition as well.

- A trend display, overlaid on a desired trajectory, could vary well have informed the pilot of the context of his situation more, and thus have reduced the confusion in the magnitude or time of input.

- Of particular note, the report detailing the circumstances of the STS-3 PIO suggests that at some point, the control of the craft becomes proprioceptive, or open-loop. This implies that the pilot gains a sufficient amount of knowledge of the current situation to project the eventual action of the system and adopt a control strategy without regard to additional system feedback. This is a double-edged sword: it allows the operator to control at a much higher bandwidth, but it also partially deafens the operator to any hazardous feedback from the system. It is, therefore, imperative that this initial picture gained by the operator (before an open-loop control strategy is adopted) is of the highest fidelity. In essence, extremely high level 3 situational awareness is crucial. The design suggestions previously mentioned (most notably the trend display) seek to aid in this acquisition of situational awareness.

Appendix G

Case Study: Apollo 11

The Apollo 11 Mission report describes the transition(s) as follows: At about 5000 feet, the Commander switched his control mode from automatic to attitude-hold to check manual control in anticipation of the final descent.

> After the pitch over at high gate, the landing point designator indicated that the approach path was leading into a large crater. An unplanned redesignation was introduced at this time. To avoid the crater, the Commander again switched from automatic to attitude-hold control and manually increased the flight-path angle by pitching to a nearly vertical attitude for range extension. Manual control began at an altitude of approximately 600 feet. Ten seconds later, at approximately 400 feet, the rate-of-descent mode was activated to control descent velocity. In this manner, the spacecraft, the spacecraft was guided approximately 1100 feet downrange from the initial aim point.

Armstrong reported in the technical debriefs regarding the reversion:

> In the early phases of P64, I did find time to go out of AUTO-control and check the manual control in both pitch and yaw and found its response to be satisfactory. I zeroed the error needles and went back into AUTO. I continued descent in AUTO. At that point, we proceeded on the flashing 64 and obtained the LPD availability, but we did not use it because we really weren't looking outside the cockpit during this phase. As we approached the 1500-foot point, the program alarm seemed to be settling down ad we committed ourselves to continue. We could see the landing area and the point at which the LPD was pointing, which was indicating we were landing just short of a large rocky crater surrounded with the large boulder field with very large rocks covering a high percentage of the surface. I initially felt that that might be a good landing area

> if we could stop short of that crater, because it would have more scientific value to be close to a large crater. Continuing to monitor LPD, it became obvious that I could not stop short enough to find a safe landing area.
>
> We then went into MANUAL and pitched the vehicle over to approximately zero pitch and continued...I then proceeded to look for a satisfactory landing area and the one chosen was a relatively smooth area between some sizable craters and a ray-type boulder field. I first noticed that we were, in fact, disturbing the dust on the surface when we were at something less than 100 feet; we were beginning to get a transparent sheet of moving dust that obscured visibility a little bit. As we got lower, the visibility continued to decrease. I don't think that the altitude determination was severely hurt by this blowing dust, but the thing that was confusing to me was that it was hard to pick out what your lateral and downrange velocities were, because you were seeing a lot of moving dust that you had to look through to pick up the stationary rocks and base your translational velocity decisions on that. I found that to be quite difficult. I spent more time trying to arrest translational velocities more than I though would be necessary. As we got below 30 feet or so, I had selected the final touchdown area. For some reason that I am not sure of, we started to pick up left translational velocity and a backward velocity. That's the thing that I certainly didn't want to do, because you don't like to be going backwards, unable to see where you're going. So I arrested the backward rate with some possibly spastic control mosts, but I was unable to stop the left translational rate. As we approached the ground, I still had a left translational rate which made me reluctant to shut the engine off while I still had that rate. I was also reluctant to slow down my descent rate anymore than it was or stop because we were close to running out of fuel. We were hitting our abort limit.

As was the case for control in the aircraft systems, the major control tasks being considered here are as follows:

- Attitude
- Thrust
- Lateral Flight Path
- Vertical Flight Path
- Translational Velocity
- Vertical Velocity (Descent/Ascent Rate)

Hence, this transition can be analyzed in a way similar to the studies of the Aeroflot-Nord accident and the TNT Airways Accident.

G.1 Transition Case 1

The first case of transition to be considered will be the commander's initial transition from AUTO (P64) into attitude-hold manual and then back to P64. This was described above, but will be reproduced here:

> At about 5000 feet, the Commander switched his control mode from automatic to attitude-hold to check manual control in anticipation of the final descent.

Additionally, the technical debrief describes it as such:

> In the early phases of P64, I did find time to go out of AUTO-control and check the manual control in both pitch and yaw and found its response to be satisfactory. I zeroed the error needles and went back into AUTO. I continued descent in AUTO.

G.1.1 The Modes

Hence, this is a multi-phased transition, with the following phases:

1. Prior (to the transition)
2. Manual (attitude-hold mode)
3. Post (back in P64)

Sheridan and Verplank LOA

Attitude Control - Prior to the transition the system was operating at Level 7, in which the computer was controlling the attitude and necessarily informing the human through the attitude indicator. In transitioning to "manual" mode, the commander entered into a Rate Control Attitude Hold (RCAH) mode. This system is most aptly described within the Sheridan and Verplank levels as Level 4, as this describes a system in which the computer selects an option (attitude hold), but the human may select a different action (rate control). Following this the commander transitioned back to Level 7.

Thrust Control - Prior to the transition the system was operating at Level 7, as the computer handled the throttling of the engines with a mandatory readout to the human. This did not change throughout the course of the transition.

Lateral Flight Path Control - Prior to the transition the system was operating at Level 6, in which the lateral flight path was automatically being controlled by the computer with only contextual readouts to the human (window etchings, out-the-window view, etc.). The human was afforded the ability to update the landing point through incremental stick inputs, hence this mode of operation can be likened to computer action with time-to-veto for the human. Once operating in manual, the human was now in complete control of the lateral flight path, with very little computer aid. Hence, this can be considered a full transition to Level 1 with respect to lateral flight path control. In transitioning back to P64 the system went back to Level 6.

Vertical Flight Path Control - Prior to the transition the system was operating at Level 6 in respect to vertical flight path, with same affordances for human input as described for lateral flight path control. Following the transition to manual, the system transitioned to Level 1 in this respect. In transitioning back to P64, the system was back at Level 6.

Lateral Velocity Control - Prior to the transition the system was operating at Level 7, with contextual readouts of the lateral velocities to the commander by the LMP as well as access through the displays. Once in manual, these were being controlled at Level 2, with automation only providing sensory help. The transition back to P64 reset the system to Level 7.

Vertical Velocity Control - Vertical velocity control followed the same LOA transition sequence as was seen in lateral velocity control.

These levels are shown in Figure G.1 and Table G.1.

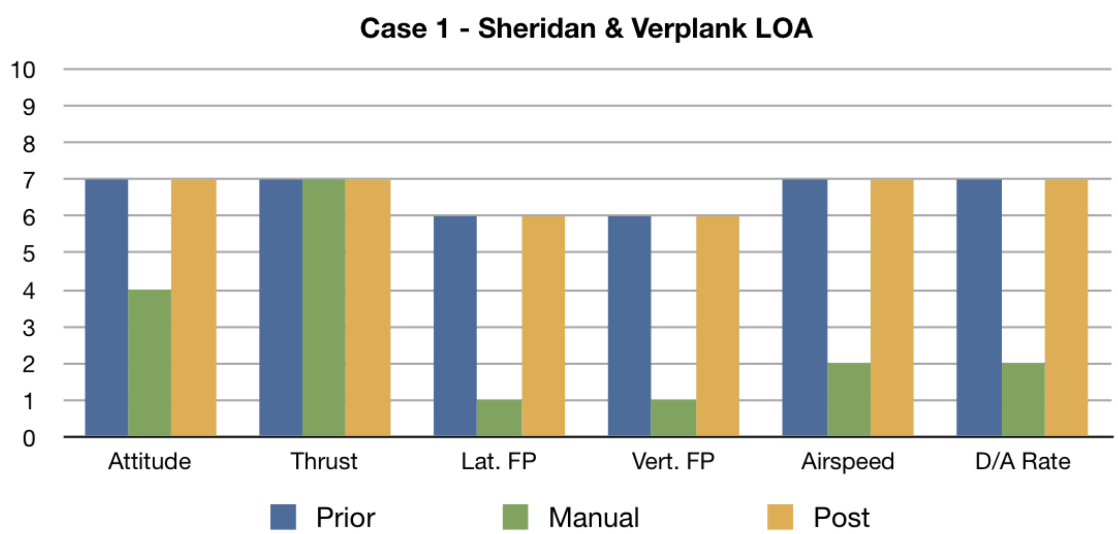

Figure G.1: Case 1 - Sheridan and Verplank LOA

Proud and Hart LOA

Observe Phase - Prior to the transition the computer handled most of the active information processing, and hence the system was operating at Level 6. Following the transition to manual they computer was still involved in presenting the human with information, however, the system was much more reliant on the human preprocessing of the information,

Table G.1: Case 1 - Sheridan and Verplank LOA

Case 1 - Sheridan and Verplank LOA			
Control Task	*Prior*	*Manual*	*Post*
Attitude	7	4	7
Thrust	7	7	7
Lat. Flight Path	6	1	6
Vert. Flight Path	6	1	6
Lat. Velocity	7	2	7
Vert. Velocity	7	2	7

and hence it was operating at Level 3. Following the transition the system was back at Level 6.

Attitude Control

- Orient - Prior to the transition system was operating at Level 6, with the computer in charge of all active orientation process; however, all of these processes were extensively monitored by the human. Once in manual, the human was responsible for all orientation tasks with minimal help from the computer, placing the system at Level 2. Following this the system reverted back to Level 6.
- Decide - Prior to transition the system was operating at Level 8, with all decisions being made without the human's knowledge except through feedback from the action phase. Once in manual the human was placed in charge of all decision tasks with the computer operating as a tool for assistance, setting the system at Level 2. Following this the system reverted back to Level 8.
- Act - Prior to the transition the computer was in charge of all major control inputs, save for the human incremental control in LPR (landing point redesignation). This places the system at Level 6. Once in manual the system was operating at Level 1, with the human in charge of all attitude actions. The system then reverted back to level 6.

Thrust Control

- Orient - Prior to the transition the system was operating at Level 6, as the human extensively monitored the orientation process in thrust control and was placed in the a position to potentially override if needed. This did not change throughout the course of the transition.

- Decide - Prior to the transition the system was operating at Level 8, as all control decisions happened without the human being informed, save through feedback from the action phase. This did not change through the course of the transition.
- Act - Prior to the transition the system was operating at Level 7, with override ability retained and output being contextually provided for the operator. This did not change throughout the transition.

Lateral Flight Path Control

- Orient - Prior to the transition the system was operating at Level 6, as the human extensively monitored the lateral flight path through the computer and incoming data. Once in manual, the system was operating at Level 2, with the computer only serving as a tool when needed. The system then reverted back to Level 6.
- Decide - Prior to the transition the system was operating at Level 8, with the computer making all control decisions without regard to the human. It should be noted that the human was performing ranking tasks in parallel; however, to include this would place the system at Level 4; however, this level suggests that the rankings of the computer were displayed to the human, which was not the case. Once in manual, the human was placed in charge of all decision tasks in this regard with the computer providing limited assistance as a tool. Hence, the system was operating at Level 2. The system then reverted back to Level 8.
- Act - Prior to the transition the system was completely in charge of all action output, with the human given override capability following control output from the computer. This places the system at Level 7. Once in manual the system was operating at Level 1. Following this the system reverted back to Level 7.

Vertical Flight Path Control

- Orient - Prior to the transition the system was operating at Level 6, as the human extensively monitored the lateral flight path through the computer and incoming data. Once in manual, the system was operating at Level 2, with the computer only serving as a tool when needed. The system then reverted back to Level 6.
- Decide - Prior to the transition the system was operating at Level 8, with the computer making all control decisions without regard to the human. Once in manual, the human was placed in charge of all decision tasks in this regard with the computer providing limited assistance as a tool. Hence, the system was operating at Level 2. The system then reverted back to Level 8.
- Act - Prior to the transition the system was completely in charge of all action output, with the human given override capability following control output from the computer. This places the system at Level 7. Once in manual the system was operating at Level

1. Following this the system reverted back to Level 7.

Lateral Velocity Control

- Orient - Prior to the transition the system was operating at Level 6, with the computer handling all orientation tasks with the human extensively involved in monitoring and positioned for override. Once in manual the system was operating at Level 2, with the computer only providing limited display support. Following the transition the system was operating at Level 6 again.
- Decide - Prior to the transition the system was operating at Level 8, with all control decisions being made by the computer. Once in manual, the human was in charge of all decisions with the computer being used in a limited way as decision support tool, placing the system at Level 2. Following this the system was operating at Level 8
- Act - Prior to the transition the system was operating at Level 7, with the human being informed contextually of the computer's actions and being placed in a position for override. Once in manual the human was fully in charge of all control actions, placing the system at Level 1. Following this the system reverted to Level 7.

Descent/Ascent Rate Control

- Orient - Prior to the transition the system was operating at Level 6, with the computer handling all orientation tasks with the human extensively involved in monitoring and positioned for override. Once in manual the system was operating at Level 2, with the computer only providing limited display support. Following the transition the system was operating at Level 6 again.
- Decide - Prior to the transition the system was operating at Level 8, with all control decisions being made by the computer. Once in manual, the human was in charge of all decisions with the computer being used in a limited way as decision support tool, placing the system at Level 2. Following this the system was operating at Level 8
- Act - Prior to the transition the system was operating at Level 7, with the human being informed contextually of the computer's actions and being placed in a position for override. Once in manual the human was fully in charge of all control actions, placing the system at Level 1. Following this the system reverted to Level 7.

These levels are shown in Figures G.2-G.2 and Table G.2.

G.1.2 The Trigger

The trigger in this transition was a result of the commander's intention to gain familiarity with the control response of the vehicle. Hence, there was no external trigger in this system, it was internal to the pilot.

The following were relevant to the triggering of this transition:

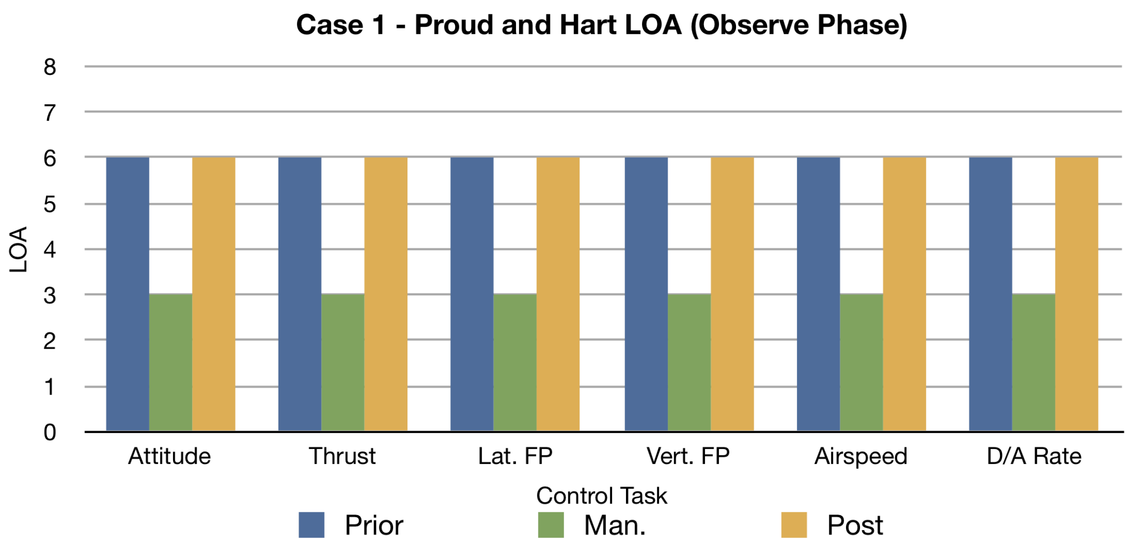

Figure G.2: Case 1 - Proud and Hart LOA (Observe Phase)

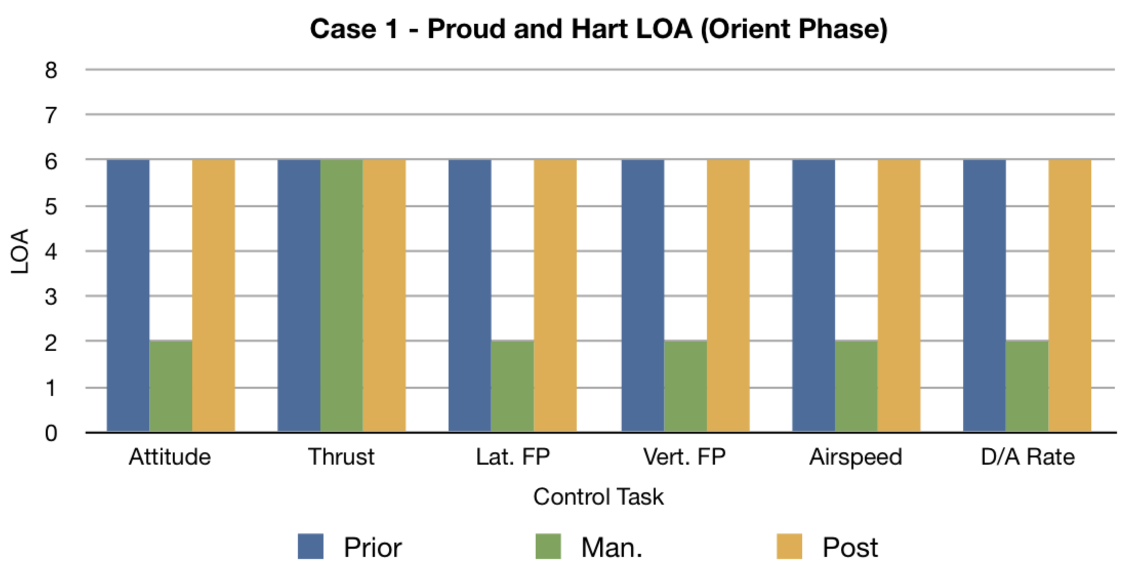

Figure G.3: Case 1 - Proud and Hart LOA (Orient Phase)

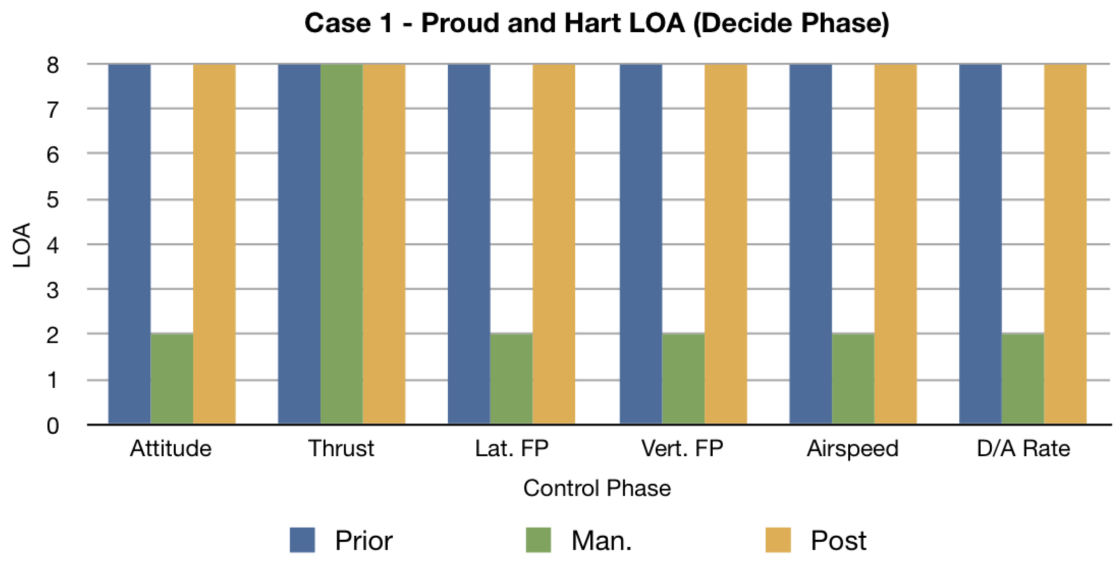

Figure G.4: Case 1 - Proud and Hart LOA (Decide Phase)

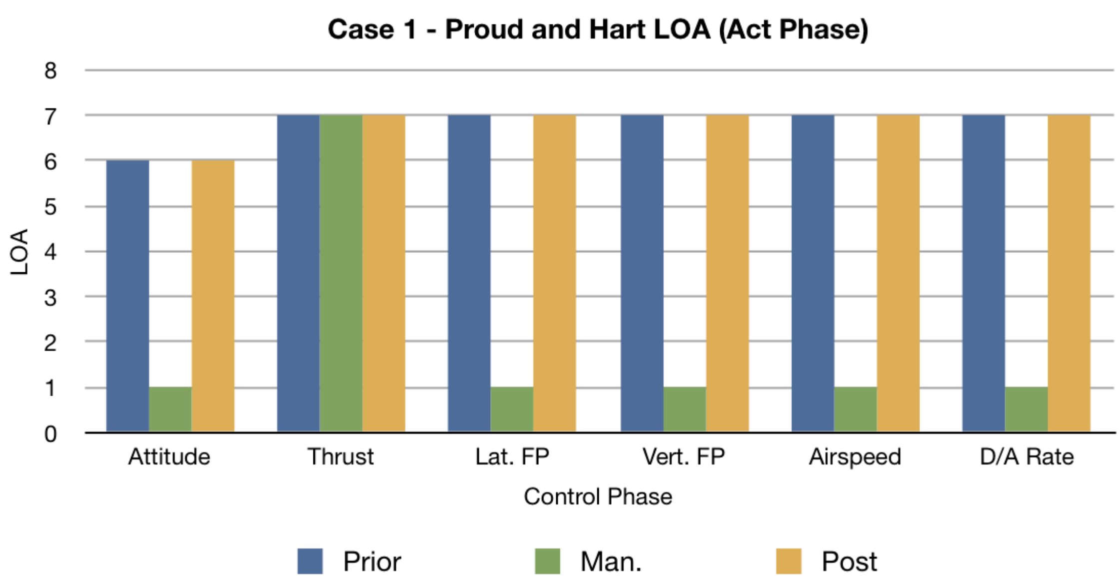

Figure G.5: Case 1 - Proud and Hart LOA (Act Phase)

Table G.2: Case 1 - Proud and Hart LOA

Case 1 - Proud and Hart LOA												
Control Task	Observe			Orient			Decide			Act		
	Prior	Man.	Post	Prior	Man.	Post	Prior	Man.	Post	Prior	Man.	Post
Attitude	6	3	6	6	2	6	8	2	8	6	1	6
Thrust	6	3	6	6	6	6	8	8	8	7	7	7
Lat. F.P.	6	3	6	6	2	6	8	2	8	7	1	7
Vert. F.P.	6	3	6	6	2	6	8	2	8	7	1	7
Lat. Vel.	6	3	6	6	2	6	8	2	8	7	1	7
Vert. Vel.	6	3	6	6	2	6	8	2	8	7	1	7

- Mode situational awareness (Level 3)
- System State
- Stress and Workload

Mode situational awareness (Level 3) - The main trigger in this transition was a desire to understand the future modes of the craft, particularly the handling characteristics that the pilot would phase in a future transition into P66. Hence, a desire for increased Mode situational awareness (Level 3) and a recognition of deficient awareness in that respect was the main trigger.

System State - The system was in a controlled and known state, which allowed for the operator to take the time to make this transition. Had not the system states been in an acceptable place, the previous factor in the triggering would not have been sufficient.

Stress and Workload - While in general the stress and workload encountered throughout this mission was rather high, the relatively low amount at this phase of the mission also enabled the triggering of this mode in like manner to the system states.

These triggering factors are shown in Figure G.6.

G.1.3 Factors, Mechanisms and Design Lessons

Factors in the Transition

The following factors were identified as relevant in determining the gracefulness of this transition:

- General situaitonal awareness (All Levels)

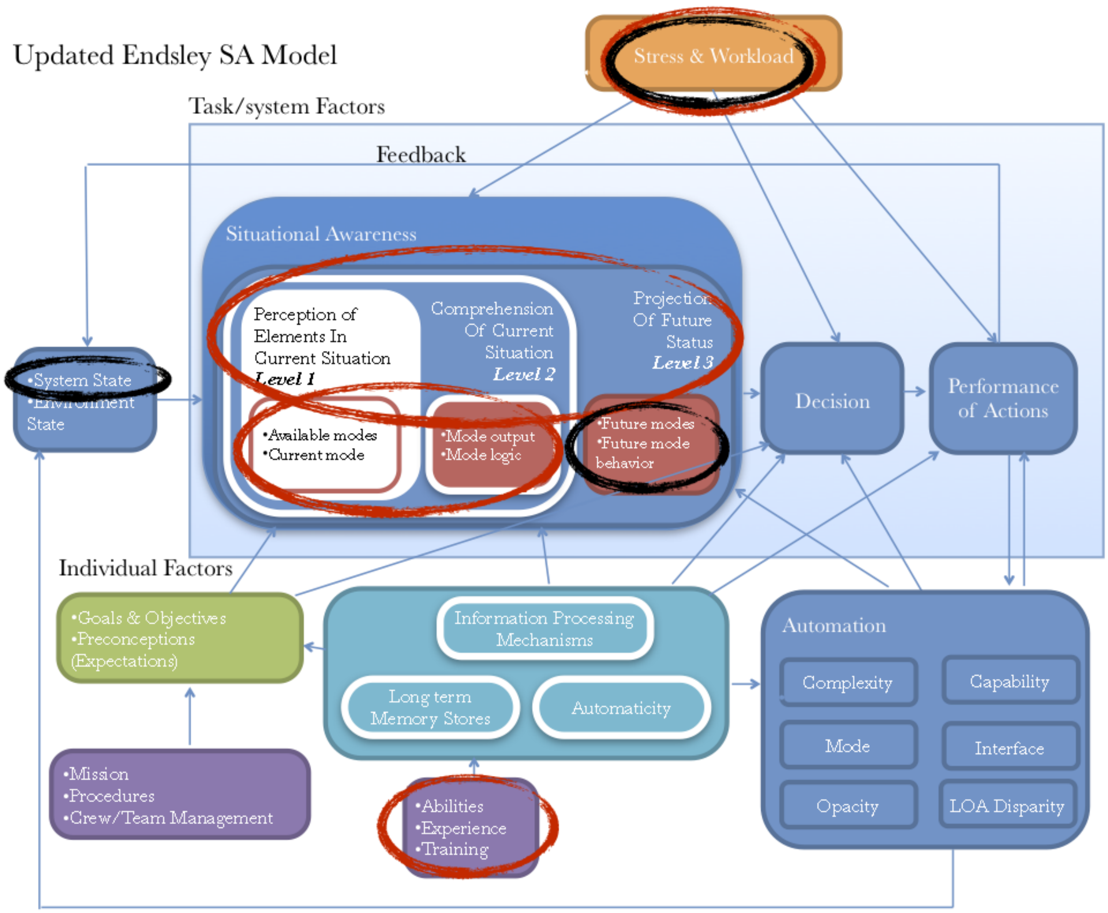

Figure G.6: Factors in Apollo 11 Transition Case 1

- Mode situational awareness (Levels 1 & 2)
- Operator Abilities, Experience, and Training
- Stress and Workload

General situational awareness (All Levels) - The operator at the time of the transition had a very high situational awareness in all three levels. The state of the vehicle was known, comprehended, and were being projected correctly. As such, this allowed for a greater understanding of the vehicle states and how they would be affected (their initial states) given a mode switch.

Mode situational awareness (Levels 1 & 2) - The operator understood the current mode as well as its functioning capabilities, further providing a better understanding of the initial states from which a mode switch would begin from.

Operator Abilities, Experience, and Training - The high abilities, experience, and training of the operator affected the ability of the operator to anticipate the changes of the system as well as maintain control of the system through the transition. A pilot with less ability, experience, and training would most likely have not made such a graceful transition.

Stress and Workload - The stress and workload at the time of the transition were at levels that enhanced the performance of the pilot by stimulating them in a reasonable fashion. Had the workload and stress increased, as will be seen in transition Case 2, this transition would not have been as graceful.

These factors in the gracefulness of the transition are shown in Figure G.6.

Mechanisms of Gracefulness
This particular transition is an example of an ideal transition, in which the commander maintain control of system without sacrificing goals. As such, the ideal flow occurred, and no faulty mechanisms can be identified. Attention resources were not overwhelmed, schema were changed correctly, and the operator interacted with the system in an appropriate manner. Hence, the mechanisms model functioned perfectly, as seen in G.7.

Design Principles and Lessons
The following design lessons can thus be learned from this graceful transition:

- High levels of situational awareness can mitigate large jumps in levels of automation. Using displays which promote situational awareness, such as trend displays and preview displays, as well as highlighting the of pertinent information can help improve the gracefulness of a system which requires or contains drastic transitions.
- Large amounts of user training and experience can greatly improve the gracefulness of a system, as they will be more informed of the available modes, the possible responsiveness or functioning of those modes, and prepare them to handle any contingencies

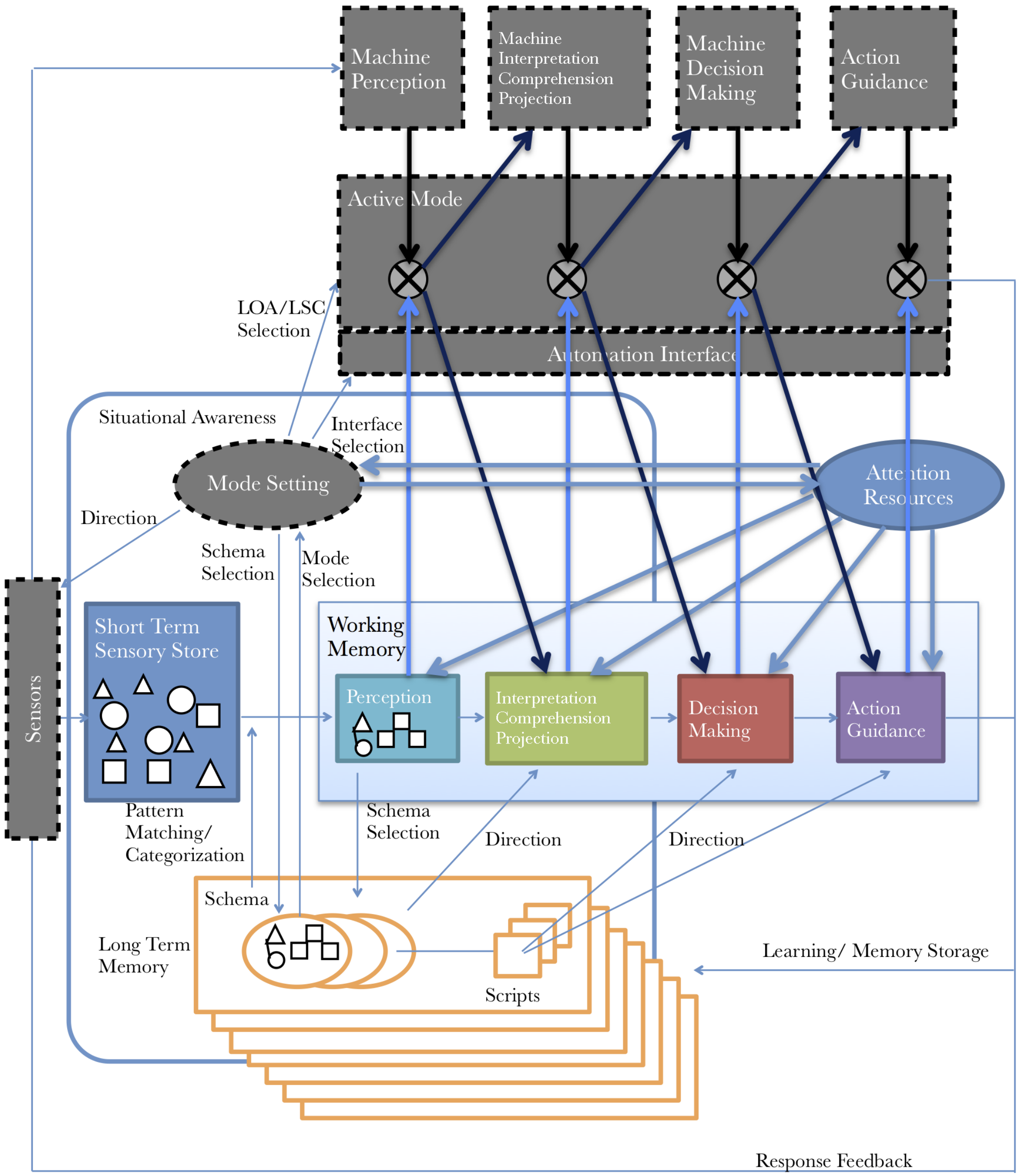

Figure G.7: Mechanisms in Apollo 11 Transition Case 1 that might arise.

- Moderate levels of workload prior to a transition can place a user in a state that is more ready to respond to mode changes and any contingencies that may arise. Designing systems which engage the user prior to transition would be advisable.
- Keep the operator informed regarding the current mode of operation, not just the eventual mode of operation.
- Time transitions to take place when system states are not drastically changing when possible. This only applies to procedurally triggered transitions or non-emergency situations – it is obvious that this will rarely be possible in an emergency.

G.2 Transition Case 2

The transition being considered here is the transition from P64 into manual mode. This transition is described in the report as follows:

> An unplanned redesignation was introduced at this time. To avoid the crater, the Commander again switched from automatic to attitude-hold control and manually increased the flight-path angle by pitching to a nearly vertical attitude for range extension. Manual control began at an altitude of approximately 600 feet. Ten seconds later, at approximately 400 feet, the rate-of-descent mode was activated to control descent velocity.

Additionally, the technical debrief quotes Neil Armstrong as saying:

> We then went into MANUAL and pitched the vehicle over to approximately zero pitch and continued...I then proceeded to look for a satisfactory landing area and the one chosen was a relatively smooth area between some sizable craters and a ray-type boulder field... I don't think that the altitude determination was severely hurt by this blowing dust, but the thing that was confusing to me was that it was hard to pick out what your lateral and downrange velocities were, because you were seeing a lot of moving dust that you had to look through to pick up the stationary rocks and base your translational velocity decisions on that. I found that to be quite difficult. I spent more time trying to arrest translational velocities more than I though would be necessary... For some reason that I am not sure of, we started to pick up left translational velocity and a backward velocity. That's the thing that I certainly didn't want to do, because you don't like to be going backwards, unable to see where you're going. So I arrested the backward rate with some possibly spastic control mosts, but I was unable to stop the left translational rate.

G.2.1 The Modes

Sheridan and Verplank LOA

Attitude Control - Prior to the transition the system was operating at Level 7 (see the previous transition case). Following the transition the commander entered into a Rate Control Attitude Hold (RCAH) mode. This system is most aptly describe within the Sheridan & Verplank context as a Level 4, as this describes a system in which the computer selects an option (attitude hold), but the human may select a different action (rate control).

Thrust Control - Prior to the transition the system was operating at Level 7 (see the previous transition case). This did not change throughout the course of the transition.

Lateral Flight Path Control - Prior to the transition the system was operating at Level 6 (see the previous transition case). Following the transition the human was in complete control of the lateral flight path, with very little computer aid. Hence, this can be considered a full transition to Level 1 with respect to lateral flight path control.

Vertical Flight Path Control - Prior to the transition the system was operating at Level 6(see the previous transition case). Following the transition, the system reverted to Level 1 in this respect.

Lateral Velocity Control - Prior to the transition the system was operating at Level 7 (see the previous transition case). Following the transition, the lateral velocity was being controlled at Level 2, with automation only providing sensory help.

Vertical Velocity Control - Vertical velocity control followed the same LOA transition sequence as was seen in lateral velocity control.

These levels are shown in Figure G.8 and TAble G.3

Table G.3: Case 2 - Sheridan and Verplank LOA

Case 2 - Sheridan and Verplank LOA		
Control Task	*Prior*	*Post*
Attitude	7	4
Thrust	7	7
Lat. Flight Path	6	1
Lat. Flight Path	6	1
Lat. Velocity	7	2
Vert. Velocity	7	2

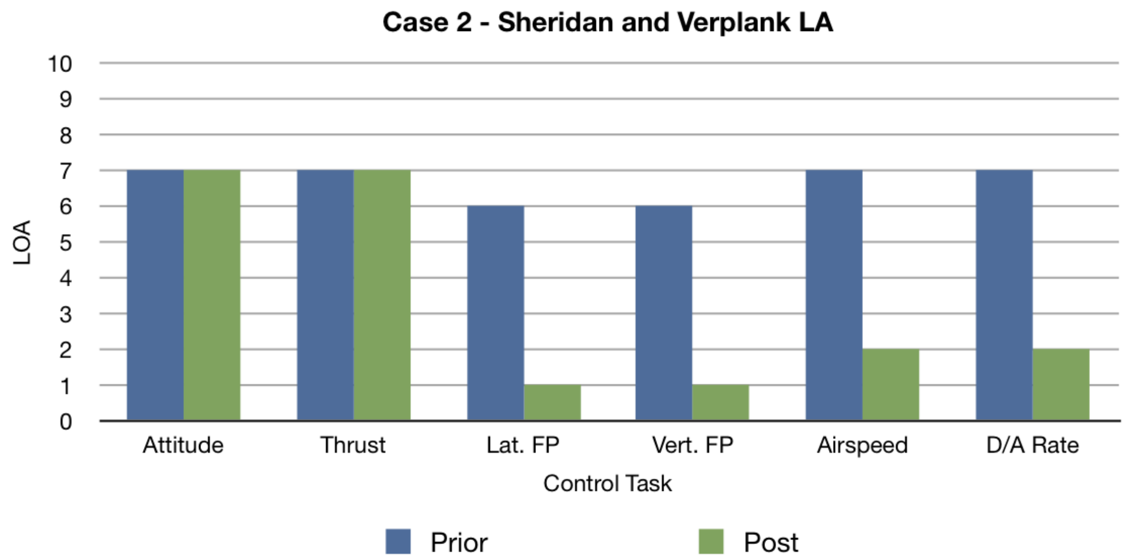

Figure G.8: Case 2 - Sheridan and Verplank LOA

Proud and Hart LOA

Observe Phase - Prior to the transition the system was operating at Level 6 (see the previous transition case). Following the transition to manual they computer was still involved in presenting the human with information, however, the system was much more reliant on the human preprocessing of the information, and hence it was operating at Level 3.

Attitude Control

- Orient - Prior to the transition system was operating at Level 6 (see the previous transition case). Following the transition the human was responsible for all orientation tasks with minimal help from the computer, placing the system at Level 2.
- Decide - Prior to transition the system was operating at Level 8 (see the previous transition case). Following the transition the human was placed in charge of all decision tasks with the computer operating as a tool for assistance, setting the system at Level 2.
- Act - Prior to the transition the system was operating at Level 6 (see the previous transition case). Following the transition the system was operating at Level 1, with the human in charge of all attitude actions.

Thrust Control

- Orient - Prior to the transition the system was operating at Level 6 (see the previous transition case). This did not change throughout the course of the transition.

- Decide - Prior to the transition the system was operating at Level 8 (see the previous transition case). This did not change through the course of the transition.
- Act - Prior to the transition the system was operating at Level 7 (see the previous transition case). This did not change throughout the transition.

Lateral Flight Path Control

- Orient - Prior to the transition the system was operating at Level 6 (see the previous transition case). Following the transition the system was operating at Level 2, with the computer only serving as a tool when needed.
- Decide - Prior to the transition the system was operating at Level 8 (see the previous transition case). Following the transition the human was placed in charge of all decision tasks in this regard with the computer providing limited assistance as a tool. Hence, the system was operating at Level 2.
- Act - Prior to the transition the system was operating at Level 7 (see the previous transition case). Following the transition the system was operating at Level 1.

Vertical Flight Path Control

- Orient - Prior to the transition the system was operating at Level 6 (see the previous transition case). Following the transition the system was operating at Level 2, with the computer only serving as a tool when needed.
- Decide - Prior to the transition the system was operating at Level 8 (see the previous transition case). Following the transition the human was placed in charge of all decision tasks in this regard with the computer providing limited assistance as a tool. Hence, the system was operating at Level 2.
- Act - Prior to the transition the system was operating at Level 7 (see the previous transition case). Following the transition the system was operating at Level 1.

Lateral Velocity Control

- Orient - Prior to the transition the system was operating at Level 6 (see the previous transition case). Following the transition the system was operating at Level 2, with the computer only providing limited display support.
- Decide - Prior to the transition the system was operating at Level 8 (see the previous transition case). Following the transition the human was in charge of all decisions with the computer being used in a limited way as decision support tool, placing the system at Level 2.

- Act - Prior to the transition the system was operating at Level 7 (see the previous transition case). Following the transition the human was fully in charge of all control actions, placing the system at Level 1.

Descent/Ascent Rate Control

- Orient - Prior to the transition the system was operating at Level 6 (see the previous transition case). Following the transition the system was operating at Level 2, with the computer only providing limited display support. Following the transition the system was operating at Level 6 again.
- Decide - Prior to the transition the system was operating at Level 8 (see the previous transition case). Following the transition the human was in charge of all decisions with the computer being used in a limited way as decision support tool, placing the system at Level 2. Following this the system was operating at Level 8
- Act - Prior to the transition the system was operating at Level 7 (see the previous transition case). Following the transition the human was fully in charge of all control actions, placing the system at Level 1. Following this the system transitioned to Level 7.

These levels are shown in Figures G.9-G.12 and Table G.4.

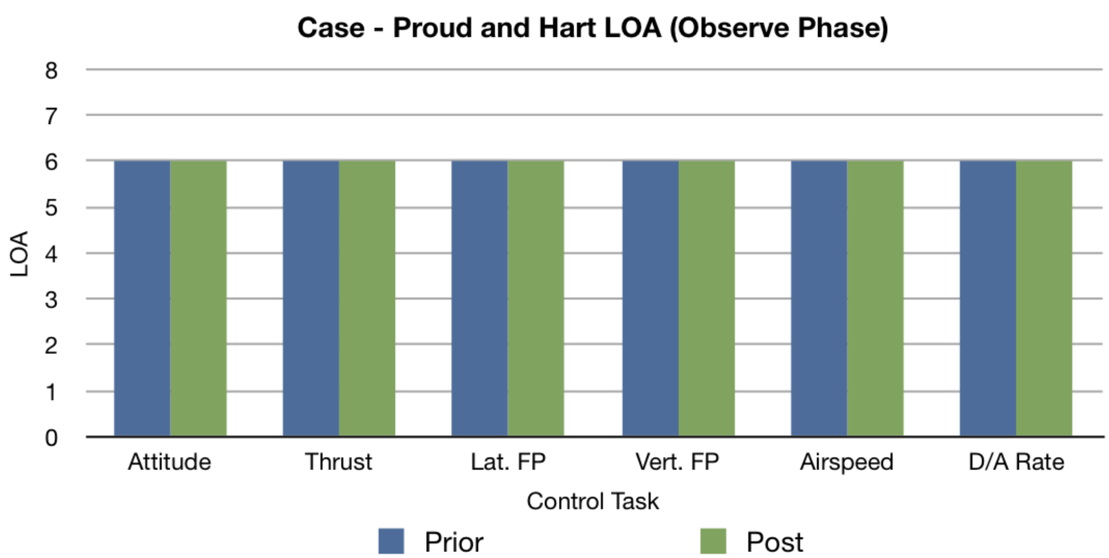

Figure G.9: Case 2 - Proud and Hart LOA (Observe Phase)

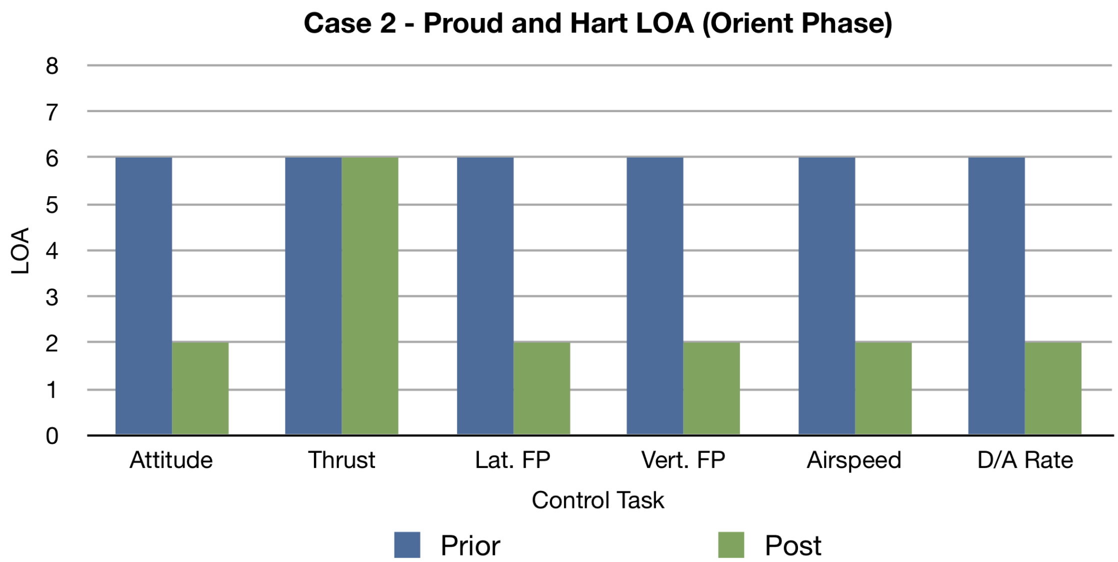

Figure G.10: Case 2 - Proud and Hart LOA (Orient Phase)

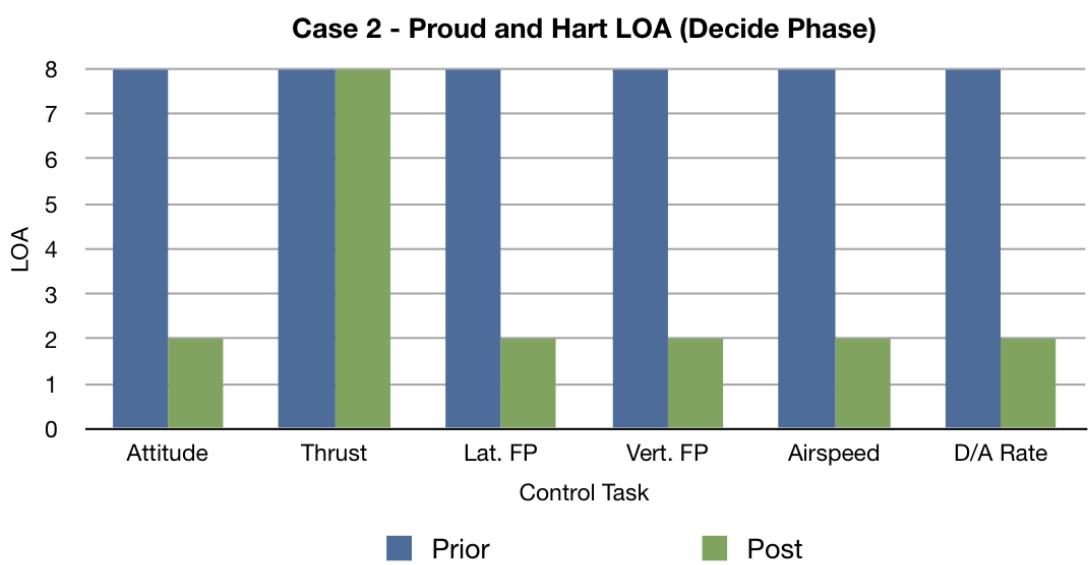

Figure G.11: Case 2 - Proud and Hart LOA (Decide Phase)

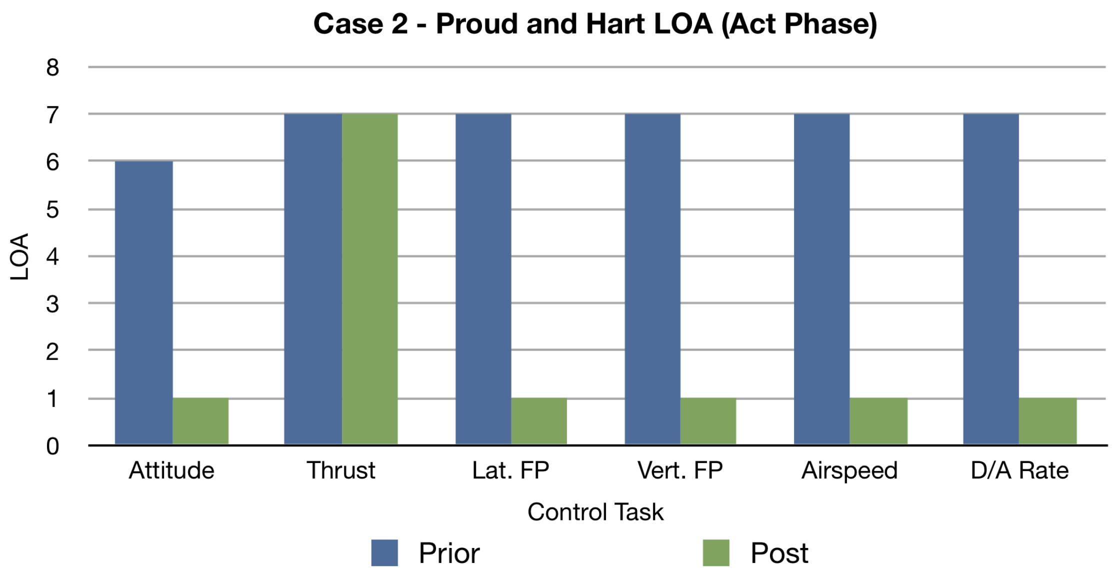

Figure G.12: Case 2 - Proud and Hart LOA (Act Phase)

Table G.4: Case 2 - Proud and Hart LOA

Case 2 - Proud and Hart LOA								
Control Task	Observe		Orient		Decide		Act	
	Prior	Post	Prior	Post	Prior	Post	Prior	Post
Attitude	6	6	6	2	8	2	6	1
Thrust	6	6	6	6	8	8	7	7
Lat. Flight Path	6	6	6	2	8	2	7	1
Vert. Flight Path	6	6	6	2	8	2	7	1
Lat. Velocity	6	6	6	2	8	2	7	1
Vert. Velocity	6	6	6	2	8	2	7	1

G.2.2 The Trigger

The trigger in this transition was the commander's assessment that they were headed towards a hazardous landing area and his decision that the automation would not sufficiently be able to cope with this. Hence, he pressed the button which transferred the system to "manual" control (P65). The following factors were key in the triggering of this transition:

- Environmental State
- System State
- Automation Capabilities
- Operator Abilities, Experience, and Training

Environmental State - The major trigger in this transition was the pilot's observation that the environment in which he was going to be operating in the future was hazardous. This was done through an integration of the state of the environment and a projection of the current system states.

System State - In projecting the system states (good Level 3 General SA) the pilot was triggered to perform this transition, as it was necessary given the current trust in the automation's capability to deal with the current contingency.

Automation Capabilities - The automation's capabilities, and to some extent the pilot's own conceptions of the automation's capabilities enabled this trigger to call for a mode transition. Had the automation been deemed capable of handling this situation a transition may have never taken place. Most decidedly any level of trust regarding the automation's capabilities would have triggered transition to a different mode if at all.

Operator Abilities, Experience, and Training - The high level of confidence of the user in his own abilities, given the experience and training that he possessed affect the trust in the automation to be capable of handling this situation. As such, the level of abilities, experience, and training enabled this trigger to effect this mode transition.

These triggering factors are shown in Figure G.13.

G.2.3 Factors, Mechanisms, and Design Lessons

Factors in the Transition

This particular transition was ungraceful in the sense that there was an appreciable increase in the workload experienced by the operator in order to maintain system states and achieve the mission goal. This transition is unlike those in the past, as the mission goal was still retained; however, this was at a very high workload cost. The following factors were identified as contributing to the ungraceful nature of this transition:

- Environmental State

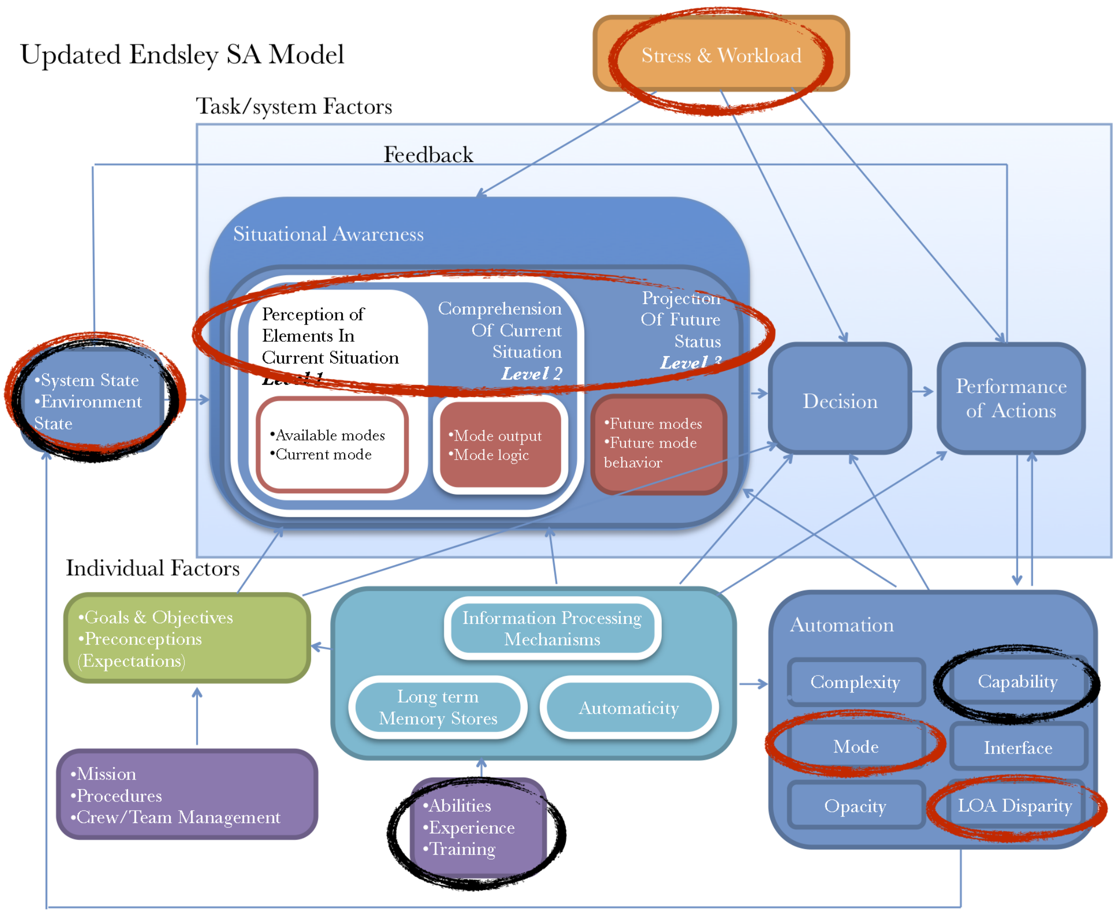

Figure G.13: Factors in Apollo 11 Transition Case 2

- System State
- Automation Mode
- Stress & Workload
- LOA Disparity
- General situational awareness (All Levels)

Environmental State - The relative unfamiliarity of the operator with the environmental state was a factor in the way this transition took place. Had more familiarity been present this transition would have been more graceful as it would have increased the General SA of the operator, allowing for more informed control inputs toward the desired goal (landing).

It is also quite possible that novel vestibular and visual effects were affecting the user in a way that was not conducive to maintaining control of the vehicle.

System State - The fact that this transition took place within the context of the final stages of lunar landing placed high performance constraints, which increased the sensitivity of the operator to any perturbations in the control of the craft.

Automation Mode - The automation mode (P66) which was was active following the transition was notoriously difficult to control, and was such was a large factor in the ability of the operator to maintain control of the system without increased workload and stress. Due to the difficulty in controlling with this mode, there was an understandable increase in the workload. Due to the extended nature of this transition (the last transition case only saw a momentary switch), this also required a higher amount of vigilance from the operator.

Stress & Workload - The situation itself was highly stress. Additionally, other system factors, such as the 1200 errors that plagued the landing (5 total) increased the workload and stress of the operator while reverting to this mode.

LOA Disparity - As can be seen from the pervious LOA analysis, there were a significant amount of LOAs skipped in this transition. Because of this, the relative workload increase from the prior mode was greater.

General siutiatonal awareness (All Levels) - As in the past transition case, General situaitonal awareness of the pilot was high, which was proactive in achieving a more graceful transition.

These factors in ungracefulness are shown in Figure G.13.

Mechanisms of Gracefulness
In this particular transition, while the pilot did mostly maintain control over the system and ultimately achieve the mission objectives, the size of the workload increase for the operator was considerable. As the Neil Armstrong described in the technical debrief there were particular system behaviors which arose that he was unable to completely control, which also suggests a system that was just exceeding the operator's ability to control iwthin satisfaction (he was uncomfortable with the level of control he was maintaining).

The particular difficulties in this transiton stemmed from the following mechanisms:

- Attention Resources
- Operator Decision Making
- Operator Action Guidance

Attention Resources - The attention demand that was required of the pilot during this reversions was extremely high and, had it been any other non-expert user, this would have most likely had a flow down similar to that seen in the TNT Airways accident.

Operator Decision Making - The phase of the human processing which suffered greatest from the attention deficit was the decision making and action guidance block, in the sense that the system required very quick reaction times and precise guidance commands. This maps particularly to the these two blocks. Had the attention drain not been so high, the performance of these blocks might have increased.

Operator Action Guidance - The action guidance was greatly affected as well by the attention deficit, as mentioned previously.

These mechanisms are shown in Figure G.14.

Design Principles and Lessons
The following design lessons can be learned from this reversion case:

- In high workload situations which increase the demands on the attention, employ transions which do not traverse as many LOAs.
- Employ the use of some form of a flight director in such an instance, as this might free up attention resources being used by the perception and interpretation blocks. This attentioned could then be used in the decision making and action guidance blocks.
- Reduce the difficulty of such manual modes to control by improving or augmenting the dynamics. Instead of using a rate control, position control might have reduced the attention resources required to operate the decision and/or the action guidance blocks.

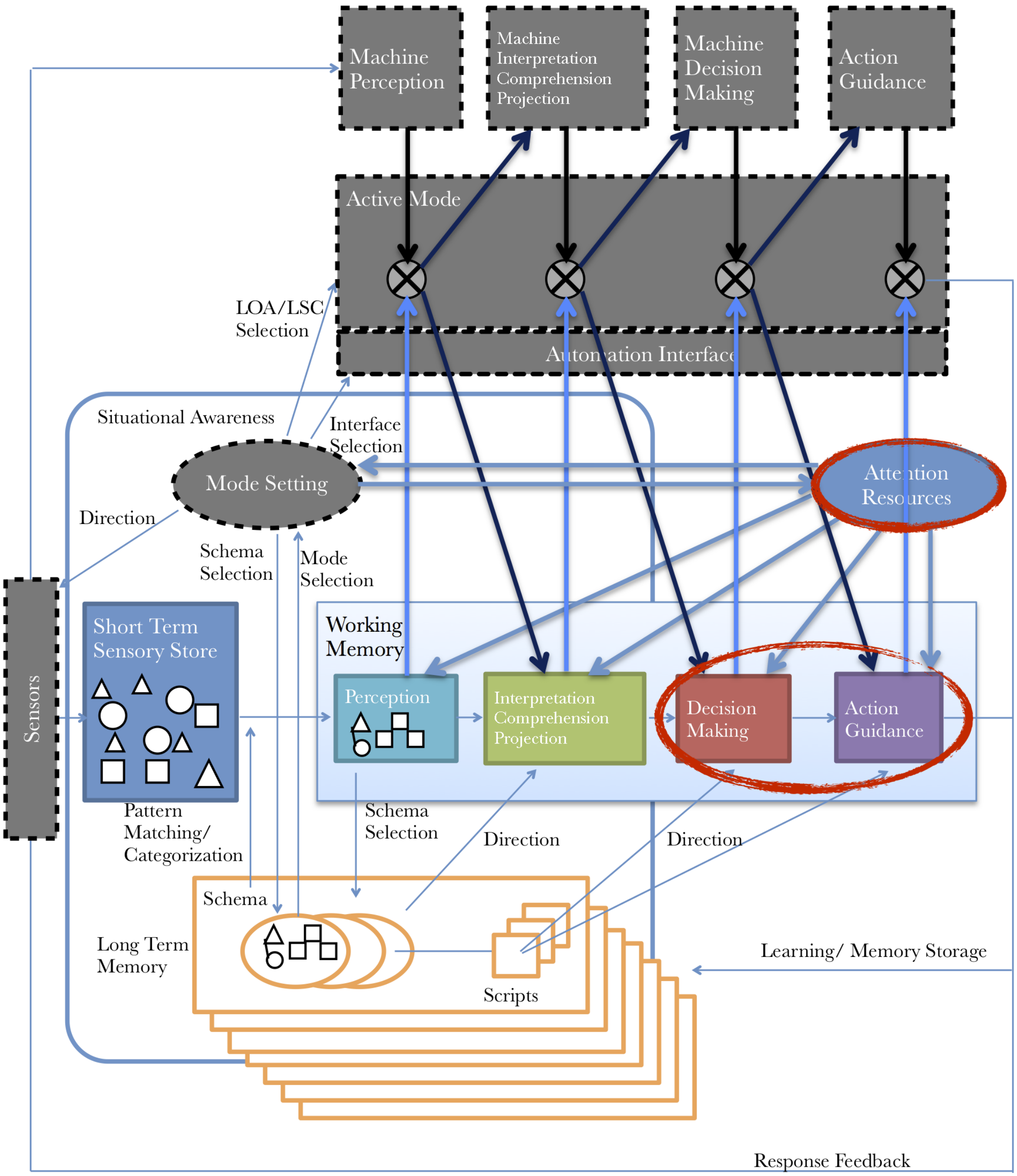

Figure G.14: Mechanisms in Apollo 11 Transition Case 2

- Isolate the operator from other tasks so that attention resources can be completely devoted to dealing with the new mode and the information required by that mode.

Appendix H

Experimental Protocol

Mode Experiment Data Collection Sheet

Experimentalist:___________________________________

Subject No.:________

Date:________

If you find this data sheet, please return to:

C.S. Draper Laboratory
Office 3355A
Cambridge, MA, 02139

Introduction:

Slide 1

Hello, my name is <NAME OF EXPERIMENTALIST> and I'll be conducting the experiment today. Before we begin, I'll start by familiarizing you with our system. This is the Draper fixed-based lunar simulator, and we'll be using it today to simulate a landing on the lunar surface. I'll pause after each slide to give you a chance to read everything. Let me know when you're ready to continue after each slide.

Slide 2

A typical lunar landing has three phases: a braking phase, an approach phase, and a terminal descent phase. You'll be operating within the terminal descent phase today. Let me know when you're ready for the next slide (WAIT TO CONTINUE).

Slide 3

During the terminal descent, the astronaut has to confirm the final selection of a landing location, referred to as the landing aimpoint. In Apollo, these landing aimpoints were identified and confirmed visually. In the future, these landing aimpoints will be recommended by the Autonomous Landing and Hazard Avoidance Technology, or ALHAT, system. However, the astronaut will still need to use his or her own judgment in the final selection of a landing aimpoint. Let me know when you're ready to continue (WAIT TO CONTIUE).

Slide 4

Your task today will be to guide the lander to the lunar surface in a simulated terminal descent. Several displays, both a Primary Flight Display and a Landing Aimpoint Display, will be available to you. Flight director needles will assist you in the flying task at all times. I'll explain the displays a bit later in the training. We'll be doing a total of 48 different runs, including training trials. Let me know when you're ready to continue (WAIT TO CONTINUE).

Slide 5

In addition to these displays, the astronaut will also have access to a variety of different control modes. The uses of these control modes and the way in which an

astronaut switches between these modes is the subject of today's experiment. You'll begin each run in a fully automatic mode, in which the computer will perform all the necessary control inputs for you. At a particular point in the trajectory, the computer will perform a transition to a manual control mode. You'll need to refer to the mode annunciator to see what mode you're in. You'll get a chance to train in these modes before you fly them. During some trials a re-designation will accompany the mode transition. This re-designation will be made by the computer, simulating the real-time rejection of the current landing point. Let me know when you're ready to continue. (WAIT TO CONTINUE)

Slide 6

Your primary goal is to null the error in the flight director in the roll, pitch, and descent axes. You do not need to null the yaw flight director. Try to keep on to the flight director needles within less than 1 degree in roll and pitch, about the width of the attitude indicator pip, and the errors in the descent rate below .5 feet per second. Your secondary task will be to respond to the comm. light which will illuminate at particular points throughout the trajectory. Your response time to this light is being used to measure how much spare attention you have while performing the main flying task, so it is imperative that you don't consider this as a primary task. Never sacrifice the flying task to respond to this light. Remember: aviate, navigate, communicate. I'll explain how you respond to this light a bit later in your training.

I order to save time I'll be cutting the simulation short during the mode transition trials. Let me know when you're ready to continue (WAIT TO CONTINUE).

Slide 7

I'll now take a moment to explain your flight displays. The primary flight display, or PFD, provides information about vehicle states and flight director cues overlaid on a simulated horizon. This is not an out-the-window view. I'll walk you through the elements of this display in just a bit.

The Landing Area Display provides information about hazards and the recommended aimpoints using a top-down view. Again, I'll be taking you through each element of this display shortly. Let me know when you are ready to continue. (WAIT TO CONTINUE)

Slide 8

I'll now explain the primary flight display to you. Don't worry about remembering all of this. You'll have time to practice flying, at which time many of these functions will become much clearer to you.

The PFD is shown here. The first thing you might have noticed is the blue and brown background. These represent a simulated horizon, with the brown indicating the ground and the blue indicating the sky. This is a simulated horizon: it is not an out the window view.

The center of the screen shows a standard attitude indicator (INDICATE PITCH LADDER) right here. This will move up and down and rotate based on the attitude of the space craft. The purple lines here (INDICATE FLIGHT DIRECTOR NEEDLES) represent the guidance cues. These particular lines indicate a fly-to display, which means you need to generate inputs that center the attitude indicator on these lines.

The three numbers labeled "R, P, Y", right here, (INDICATE DIGITAL ATTITUDE INDICATOR) show you digital readouts of your roll, pitch, and yaw angles.

This (INDICATE HEADING INDICATOR) is the heading display. This is a standard heading display, with the degrees representing various compass headings. For example, North is represented by 360, south is shown as 180. You may have noticed the purple indicator on the circumference of the heading display (INDICATE YAW GUIDANCE INDICATOR), right here. This is the yaw guidance value. You do not need to null any errors with respect to this indicator. In the center of the heading display is a small triangle (INDICATE TRIANGLE). A green line extending from this triangle represents your current horizontal velocity vector, both magnitude and direction (INDICATE VECTOR). You'll want this vector to point in the direction of the landing aimpoint "dog house" icon (INDICATE DOG HOUSE ICON). This icon shows you the position of the landing aimpoint in relation to your craft. As you get closer to the landing aimpoint this icon will move from the edge toward the triangle and should ideally enclose the triangle. Below the triangle is a text box (INDICATE BOX). The top number shows you a digital read out of the magnitude of your velocity vector. The bottom number shows you a digital readout of your range from the selected landing aimpoint.

Just to the right of the heading display you'll see three numbers labeled "x dot, y dot, and x bar." " Y dot" is a digital readout of your velocity either left or right. A negative value is a velocity to the left, a positive value is a velocity towards the right. "X dot" is a digital readout of your forward velocity. A positive value

means you're travelling forward, a negative value means you're travelling backwards. "X bar" is the magnitude of your velocity vector in general, so this will read the same as the digital velocity readout in the heading display.

To the left of the attitude indicator you'll see your fuel gauge (INDICATE FUEL GAUGE). Since you'll be operating within the terminal descent phase, you're fuel will be already very low, around 8%. A digital readout below shows the percentage of the maximum fuel capacity. This value is floored, meaning that as soon as your fuel percent goes below 1% it will read 0. You'll still have fuel left, but the meter will turn red to indicate the criticality of your fuel level.

Above the fuel gauge is your "time to go" indicator, right here (INDICATE TGO BOX). This box calculates the remaining time until touchdown based on your range from the target.

To the immediate right of your attitude indicator is your altimeter (INICATE ALTIMETER). A scrolling list will show your altitude as you descend. This is accompanied by a digital read out just below (INDICATE DIGITAL ALTIMETER).

To the right of the altimeter is your vertical speed indicator or VSI (INDICATE VSI). The bar in the center will move to show your current descent rate. The purple indicator, here (INDICATE GUIDANCE TARGET), shows the desired guidance target. Below this meter is a digital readout of your current descent rate. The purple number below this is a digital readout of the desired guidance descent rate. You'll use this if the analog guidance hits the edge of the analog VSI and can't indicate a more extreme value.

Directly above the VSI and the altimeter is the contact light (INDICATE CONTACT LIGHT). This will illuminate to show that your landing sensors have contacted the ground, meaning that you will be completing your landing soon following.

To the left of the contact light is the mode annunciator (INDICATE MODE ANNUNCIATOR). You'll refer to this mode annunciator to determine what mode of operation you're in following the automatic mode transition. You'll know you've changed modes when you hear a beep from the system. The beep only signifies a mode change and nothing else, so you don't need to worry about getting confused about what it means.

You'll be able to tell what mode you're in by consulting each of the boxes under the respective axes. If the box below pitch should read "RCAH", and all the other boxes read "AUTO", then you are manually controlling the pitch rate. If the boxes below "Roll", "Pitch", and "Yaw" all read "RCAH", then you are in complete

control of the spacecraft attitude rate in all three axes. If the box below "Descent" should read "INC" then you have incremental control over the descent rate.

Take a second to review each of these indicators and then let me know when you're ready to continue. (WAIT TO CONTINUE)

Slide 9

The Landing Area Display is shown here with all of its features labeled. The main background shows a topographical map of the moon's surface. Overlaid on this map is a "hazard map" in red, which highlights areas unsuitable for landing. This (INDICATE HAZARD MAP), would be, for example, a hazardous region.

In the center of the screen is a small black icon, outline in white, representing your spacecraft. (INDICATE SPACECRAFT ICON) The rounded line on the top represents the window of the lander so that you can tell what direction you are facing.

Three landing aimpoints are identified by the computer as 1, 2, and 3. Landing aimpoint 1 will always be selected as the default landing aimpoint. The currently selected landing point is highlighted in purple, surrounded by a box, and also presents the range to target just above the landing aimpoint. When the computer re-designates to a new landing aimpoint, this box will move to reflect the change. Additionally, an "X" will be placed over the rejected landing aimpoint.

In the upper right of this screen you'll see that your time-to-go is displayed again (INDICATE TGO CLOCK).

The Comm. light is shown at the bottom right of this screen (INDICATE COMM LIGHT). This will illuminate either green or blue throughout a landing. Press the corresponding button on the joystick to respond to this light. These buttons are labeled with a piece of green or blue tape (INDICATE BLUE AND GREEN BUTTONS), right here. You'll get to practice this during your training. Review these indicators now and then let me know when you're ready to proceed. (WAIT TO CONTINUE)

Slide 10

In Apollo, a Bingo call was used to alert the astronaut to when they only had 20 seconds left to hover before they ran out of fuel. You will receive several Bingo *calls specifying the remaining fuel time you would have if you remained in a vertical hover. These calls will come at 60 seconds and 30 seconds. The fuel time is calculated assuming a fuel burn rate at a vertical attitude hover, and might slightly underestimate the time you have left if you are descending, meaning you have more time than the call-out. However, if you are at high attitude angles it may overestimate your time left, meaning you have less time than the call-out.*

As mentioned before, you will hear a beep when the computer changes mode. You'll need to check the mode annunciator to see what mode you are in. You'll always begin in a fully autonomous state, but the mode to which you'll transition into will be different between different runs. Let me know when you are ready to continue. (WAIT TO CONTINUE)

Slide 11

The comm. light is meant to simulate ground control requesting your attention at various stages throughout the landing. As I mentioned before you'll respond by pressing the button marked with blue tape if it is blue and the button marked with green tape if it is green. If the comm. light is turquoise, then means there are no comm. signals to be attended to. A circle of this constant color is in the center of the comm. light. By comparing the colors you'll be able to determine if the light is illuminated and what the correct response will be. The comm. light will extinguish if you ignore it for long enough. You are not penalized in anyway if this occurs. Be aware that this is only a secondary task and that your primary task is landing. Do not sacrifice the landing task for the comm. task. Let me know when you are ready to continue. (WAIT TO CONTINUE)

Slide 12

As mentioned earlier, a re-designation will be required during some trials. This requirement will be expressed by an "X" appearing over the current landing point. The computer will re-designate for you. In the cases where a re-designation does happen, it will be accompanied by the mode transition, so you'll hear a beep at the same time. Let me know when you are ready to continue. (WAIT TO CONTINUE)

Slide 13

You'll interact with the different modes of operation with two controllers, shown here. Your left hand will interact with the throttle controller and your right hand will interact with the joystick. If you can't comfortably reach these, take some *time now to situate yourself so that you feel comfortable at the controls and then let me know when you're ready to continue. (WAIT TO CONTINUE)*

Slide 14

You'll only need to press a few of the buttons on these controllers. I've already explained the comm. response buttons, so I won't go over those. On the throttle stick you'll notice a button near your index finger (INDICATE ROD BUTTON). When you are given control over your rate of descent you'll use this button to control it. Press up to decrease your rate of descent. Press down to increase your rate of descent. Take a moment to find all of the buttons and familiarize yourself with their functions. Let me know when you're ready to continue. (WAIT TO CONTINUE)

Slide 15

As I mentioned earlier, one of the main things we're interested in is how high you workload is during these runs. You can think of workload as a measure of how much spare attention you have left while attending to your primary task. If your workload is high, you won't have much spare attention. If your workload is low, then you've got a lot of attention left over.

In order to measure your workload, I'll be asking you after every trial to rate yourself using the Modified Bedford scale. The Modified Bedford scale was originally designed for evaluating the workload of test pilots in experimental aircraft, so it fits this application quite nicely. During your training I'll just have you rate your overall workload. During the transition trials I'll have you rate your workload before, during, and after the mode transition. We'll define "after" the transition to be the point at which you have nulled the flight director errors and feel that you are in control of the spacecraft. During the transition means right when you were making the mode transition and the time just following.

During your training I'll ask you to rate yourself with the Modified Bedford scale in order to get you familiar with the system. This scale is relative to the task, so your ratings are not set in stone when you make them: feel free to modify past ratings if you feel that they were not accurate based on more recent flight experiences. You are allowed to make intermediate ratings using decimals. Let me know when you are ready to continue. (WAIT TO CONTINUE)

Slide 16

Here is a diagram of the Modified Bedford Scale. The rating system is based on a decision tree, in which you ask yourself each question and depending on the answer, you will either proceed to the next question or choose from the corresponding ratings for that answer. Here's a reference sheet for you to refer to throughout the test. You are to consider the task as a whole when you are rating your workload, not just the flying task. For example, if you found flying, responding to the comm. task, and making the callouts a piece of cake, then you would rate your workload as a "1".

(PRESENT SUBJECT WITH "SUBJECT REFERENCE MATERIAL" HANDOUT)

Let me know when you're ready to continue.

Slide 17

Your awareness of the situation is an important piece of information in this study. In order to measure this, I'm going to be asking you to make several types of call-outs during the flight. There are three types of callouts: altitude, fuel, and hazard. As we go through the first half of the experiment you'll have a change to get familiar with how to make these callouts and when to make them. These callouts are your last priority and are considered like a "mumble mode" in which you demonstrate an awareness of the different aspects of the system. You are not penalized at all for not making these callouts, but if you do notice the information please make the callout.

I'll ask that you call out the values of the following altitudes in the following manner. Starting at 450 ft, call out every 50 ft until 250 ft. From 250 ft to 150 ft call out every 25 ft. From 150 ft make a callout every 10 ft. Only call out an altitude as you are passing it, if you missed one let it go and wait to callout the next one. For example, if you notice that you've passed 250 ft at 240 ft, wait until 225 ft to make the next altitude callout. In case you forget the callout altitudes, these altitudes are also show on your reference.

I'll also ask you to callout the fuel percent when it changes, for example, from 7% to 6%. Callout when you notice that it has changed. I'll be keeping track to see if you noticed within a reasonable amount of time, which will be approximately 1 second.

Additionally, you'll need to callout when the Lander has been fully enveloped in a new hazard or non-hazard region. For example, if the Lander had been in a red

area, representing hazards, and it is now in a completely grey zone, representing a viable landing region, make some sort of relevant callout, like "grey" or "red". Again, if you see that you noticed this very late, showing that you were not aware of the movement into a hazard zone at the time that it took place just let it go until the next time. Additionally, only make this callout when you have noticed that the entire Lander is within a new region, not just a partial section of the Lander.

You'll get a chance to practice these callouts as we proceed with your training. Try developing a scan pattern to force yourself to continually check these different states, but don't let this task detract from your main flying task or the comm. light task. This is your task of least priority: don't let it interfere with flying. Let me know when you're ready to continue.

Slide 18

This brings us to the end of the training slides. Before we begin I'll give you an idea of today's schedule. In just a few minutes you'll begin flying the simulator without any mode transitions or definitive requirements so that you become comfortable with flying the simulator. After landing you'll see the rating screen pop up, so that you can see how you did. That rating screen is shown here on the right. After you've gotten comfortable flying, we'll start the main experiment. As I mentioned before, you won't be flying the experimental trials to completion.

If you'd like to take a break now before beginning your flight training let me know. Otherwise we'll get started.

Training Session:

Training for Full Automatic Mode (Map T-0)

The first mode is a fully autonomous landing mode. You will start every trial in this mode. This mode is designed to autonomously land the vehicle at any one of the three points designated as primary by the system. By default, landing point 1 will be selected.

I'll demonstrate this mode now. Take this chance to familiarize yourself with the display elements I showed you earlier. If you have any questions about these gauges as the simulation proceeds, feel free to ask. BEGIN DEMONSTRATION OF FULL AUTO MODE.

Begin timing…

Auto:______________

Would you like to rerun this mode? (IF YES, THEN REPEAT. IF NO, THEN CONTINUE)

Training for Manual Pitch Mode (Map T-0)

The next mode is a manual pitch mode, in which you will be given control over the rate of pitch of the spacecraft. You may exercise this control by moving the joystick forward to pitch down and backward to pitch up (INDICATE MOTION). When you return the joystick to center the flight computer will maintain the last commanded pitch angle. Feel free to ask any questions regarding this mode at any time.

I will now give you a chance to fly the spacecraft in manual pitch mode. Please let me know when you feel comfortable with this mode and we'll proceed to the next phase of your training.

Begin timing…

Manual Pitch:______________

Would you like to rerun this mode? (IF YES, THEN REPEAT. IF NO, THEN CONTINUE)

Training for Manual Attitude Mode (Map T-0)

The next mode provides you with full control over the spacecrafts attitude in what's known as Rate-Control-Attitude-Hold. In the same manner as in manual pitch, you will control the rate-of-change in attitude and the flight computer will maintain that attitude when you release the joystick. You will control pitch in the same way that you did in the manual pitch modes. Roll will be control by moving the stick to the right to pitch right and left to pitch left (INDICATE MOTION). Yaw can be controlled as well, although you are not required to maintain any particular value in this axis. I would recommend neglecting yaw control, as it makes the task significantly more difficult.

I will now give you a chance to fly the spacecraft in manual attitude mode. Please let me know when you feel comfortable with this mode and we'll proceed to the next phase of your training.

Begin timing…

Manual Attitude:_______________

Would you like to rerun this mode? (IF YES, THEN REPEAT. IF NO, THEN CONTINUE)

Training for Manual Attitude with ROD Mode (Map T-0)

The next mode again provides you with full attitude control; however, you are also given incremental control over the rate-of-descent of the vehicle. Each time you click the rate-of-descent button, either up or down, you will increase or decrease your rate-of-descent by 1 foot-per-second.

I will now give you a chance to fly the spacecraft in manual attitude mode. Please let me know when you feel comfortable with this mode and we'll proceed to the next phase of your training.

Begin timing…

Manual Attitude and ROD:_______________

Would you like to rerun this mode? (IF YES, THEN REPEAT. IF NO, THEN CONTINUE)

Subject Break 1:

You have now completed all of your familiarization training. If you'd like to take a break before beginning the first set of trials, please let me know. Otherwise, we'll begin.

Trail Set 1:

Welcome back. The next 24 trials will require you to deal with a mode transition I won't be telling you what mode you are transitioning into; you will need to refer to the mode annunciator. You'll begin each run in the full automatic mode and when you hear the mode beep, you'll need to check what mode you are now in.

Run 0

Time:__________

- ✓ ***Map:*** ***M-0***
- ✓ ***Alternative Mode:*** ***PITCH***
- ✓ ***LPR Required:*** ***NO***

We'll begin your first trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

Phase I (1-10):_____ *II:______* *III:_____*

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				Cross 3
	140		5 % Fuel		
	130				
	120				
	110				
	100		4 % Fuel		

If you find this data sheet, please return to:

C.S. Draper Laboratory
Office 3355A
Cambridge, MA, 02139

Run 1

Time:__________

- ✓ ***Map:*** ***M-3***
- ✓ ***Alternative Mode:*** ***2-AXIS***
- ✓ ***LPR Required:*** ***NO***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

Phase I (1-10):_____ *II:______* *III:_____*

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				Cross 3
	140		5 % Fuel		
	130				
	120				
	110				
	100		4 % Fuel		

Run 2

Time:__________

- ✓ ***Map:*** ***M-2***
- ✓ ***Alternative Mode:*** ***2-AXIS+ROD***
- ✓ ***LPR Required:*** ***NO***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

Phase I (1-10):_____ *II:______* *III:_____*

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				Cross 3
	140		5 % Fuel		
	130				
	120				
	110				
	100		4 % Fuel		

If you find this data sheet, please return to:

C.S. Draper Laboratory
Office 3355A
Cambridge, MA, 02139

Run 3

Time:__________

- ✓ ***Map:*** ***M-0L***
- ✓ ***Alternative Mode:*** ***2-AXIS***
- ✓ ***LPR Required:*** ***YES***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

Phase I (1-10):_____ *II:______* *III:_____*

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				
	140		5 % Fuel		Cross 3
	130				
	120				
	110		4 % Fuel		
	100				

Run 4

Time:__________

- ✓ ***Map:*** ***M-2L***
- ✓ ***Alternative Mode:*** ***PITCH***
- ✓ ***LPR Required:*** ***YES***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

Phase I (1-10):_____ *II:______* *III:_____*

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				
	140		5 % Fuel		Cross 3
	130				
	120				
	110		4 % Fuel		
	100				

Run 5

Time:__________

- ✓ ***Map:*** ***M-0L***
- ✓ ***Alternative Mode:*** ***2-AXIS+ROD***
- ✓ ***LPR Required:*** ***YES***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

Phase I (1-10):_____ *II:______* *III:_____*

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				
	140		5 % Fuel		Cross 3
	130				
	120				
	110		4 % Fuel		
	100				

Run 6

Time:__________

- ✓ ***Map:*** ***M-1***
- ✓ ***Alternative Mode:*** ***PITCH***
- ✓ ***LPR Required:*** ***NO***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

Phase I (1-10):_____ *II:______* *III:_____*

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				Cross 3
	140		5 % Fuel		
	130				
	120				
	110				
	100		4 % Fuel		

Run 7

Time:__________

- ✓ ***Map:*** ***M-3***
- ✓ ***Alternative Mode:*** ***2-AXIS+ROD***
- ✓ ***LPR Required:*** ***NO***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

Phase I (1-10):_____ II:______ III:_____

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				Cross 3
	140		5 % Fuel		
	130				
	120				
	110				
	100		4 % Fuel		

Run 8

Time:__________

- ✓ ***Map:*** ***M-3L***
- ✓ ***Alternative Mode:*** ***PITCH***
- ✓ ***LPR Required:*** ***YES***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

Phase I (1-10):_____ II:______ III:_____

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				
	140		5 % Fuel		Cross 3
	130				
	120				
	110		4 % Fuel		
	100				

Run 9

Time:__________

- ✓ ***Map:*** ***M-2***
- ✓ ***Alternative Mode:*** ***2-AXIS***
- ✓ ***LPR Required:*** ***NO***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

Phase I (1-10):_____ *II:______* *III:_____*

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				Cross 3
	140		5 % Fuel		
	130				
	120				
	110				
	100		4 % Fuel		

Run 10

Time:__________

- ✓ ***Map:*** ***M-1L***
- ✓ ***Alternative Mode:*** ***2-AXIS***
- ✓ ***LPR Required:*** ***YES***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

Phase I (1-10):_____ *II:______* *III:_____*

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				
	140		5 % Fuel		Cross 3
	130				
	120				
	110		4 % Fuel		
	100				

Run 11

Time:__________

- ✓ ***Map:*** ***M-1L***
- ✓ ***Alternative Mode:*** ***2-AXIS+ROD***
- ✓ ***LPR Required:*** ***YES***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

Phase I (1-10):_____ II:______ III:_____

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				
	140		5 % Fuel		Cross 3
	130				
	120				
	110		4 % Fuel		
	100				

Run 12

Time:__________

- ✓ ***Map:*** ***M-2***
- ✓ ***Alternative Mode:*** ***PITCH***
- ✓ ***LPR Required:*** ***NO***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

Phase I (1-10):_____ II:______ III:_____

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				Cross 3
	140		5 % Fuel		
	130				
	120				
	110				
	100		4 % Fuel		

Run 13

Time:__________

- ✓ ***Map:*** ***M-1***
- ✓ ***Alternative Mode:*** ***2-AXIS+ROD***
- ✓ ***LPR Required:*** ***NO***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

Phase I (1-10):_____ *II:______* *III:_____*

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				Cross 3
	140		5 % Fuel		
	130				
	120				
	110				
	100		4 % Fuel		

Run 14

Time:__________

- ✓ ***Map:*** ***M-1***
- ✓ ***Alternative Mode:*** ***2-AXIS***
- ✓ ***LPR Required:*** ***NO***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

Phase I (1-10):_____ *II:______* *III:_____*

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				Cross 3
	140		5 % Fuel		
	130				
	120				
	110				
	100		4 % Fuel		

Run 15

Time:__________

- ✓ ***Map:*** ***M-0***
- ✓ ***Alternative Mode:*** ***2-AXIS+ROD***
- ✓ ***LPR Required:*** ***NO***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

Phase I (1-10):_____ II:______ III:_____

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				Cross 3
	140		5 % Fuel		
	130				
	120				
	110				
	100		4 % Fuel		

Run 16

Time:__________

- ✓ ***Map:*** ***M-3L***
- ✓ ***Alternative Mode:*** ***2-AXIS+ROD***
- ✓ ***LPR Required:*** ***YES***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

Phase I (1-10):_____ II:______ III:_____

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				
	140		5 % Fuel		Cross 3
	130				
	120				
	110		4 % Fuel		
	100				

Run 17

Time:__________

- ✓ ***Map:*** ***M-3L***
- ✓ ***Alternative Mode:*** ***2-AXIS***
- ✓ ***LPR Required:*** ***YES***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

Phase I (1-10):_____ *II:______* *III:_____*

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				
	140		5 % Fuel		Cross 3
	130				
	120				
	110		4 % Fuel		
	100				

Run 18

Time:__________

- ✓ ***Map:*** ***M-2L***
- ✓ ***Alternative Mode:*** ***2-AXIS***
- ✓ ***LPR Required:*** ***YES***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

Phase I (1-10):_____ *II:______* *III:_____*

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				
	140		5 % Fuel		Cross 3
	130				
	120				
	110		4 % Fuel		
	100				

Run 19

Time:__________

- ✓ ***Map:*** ***M-1L***
- ✓ ***Alternative Mode:*** ***PITCH***
- ✓ ***LPR Required:*** ***YES***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

Phase I (1-10):_____ *II:______* *III:_____*

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				
	140		5 % Fuel		Cross 3
	130				
	120				
	110		4 % Fuel		
	100				

Run 20

Time:__________

- ✓ ***Map:*** ***M-0***
- ✓ ***Alternative Mode:*** ***2-AXIS***
- ✓ ***LPR Required:*** ***NO***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

Phase I (1-10):_____ *II:______* *III:_____*

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				Cross 3
	140		5 % Fuel		
	130				
	120				
	110				
	100		4 % Fuel		

Run 21

Time:__________

- ✓ ***Map:*** ***M-0L***
- ✓ ***Alternative Mode:*** ***PITCH***
- ✓ ***LPR Required:*** ***YES***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

Phase I (1-10):_____ *II:______* *III:_____*

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				
	140		5 % Fuel		Cross 3
	130				
	120				
	110		4 % Fuel		
	100				

Run 22

Time:__________

- ✓ ***Map:*** ***M-3***
- ✓ ***Alternative Mode:*** ***PITCH***
- ✓ ***LPR Required:*** ***NO***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

Phase I (1-10):_____ *II:______* *III:_____*

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				Cross 3
	140		5 % Fuel		
	130				
	120				
	110				
	100		4 % Fuel		

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Run 23

Time:__________

- ✓ ***Map:*** ***M-2L***
- ✓ ***Alternative Mode:*** ***2-AXIS+ROD***
- ✓ ***LPR Required:*** ***YES***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

Phase I (1-10):_____ II:______ III:_____

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				
	140		5 % Fuel		Cross 3
	130				
	120				
	110		4 % Fuel		
	100				

Mandatory Subject Break

We'll now take a five minute break. Please feel free to get up and stretch, go to the bathroom, or get a drink of water.

Trial Set 2:

Welcome back. We're ready to begin your second set of trails. These trials will be similar to the trials you just completed: you'll need to refer to the mode annunciator to see what more you're operating in, etc.

Run 24

Time:__________

- ✓ ***Map:*** ***M-0***
- ✓ ***Alternative Mode:*** ***PITCH***
- ✓ ***LPR Required:*** ***NO***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

Phase I (1-10):_____ II:______ III:_____

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				Cross 3
	140		5 % Fuel		
	130				
	120				
	110				
	100		4 % Fuel		

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Run 25

Time:__________

- ✓ ***Map:*** ***M-3***
- ✓ ***Alternative Mode:*** ***2-AXIS***
- ✓ ***LPR Required:*** ***NO***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

Phase I (1-10):_____ *II:______* *III:_____*

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				Cross 3
	140		5 % Fuel		
	130				
	120				
	110				
	100		4 % Fuel		

Run 26

Time:__________

- ✓ ***Map:*** ***M-2***
- ✓ ***Alternative Mode:*** ***2-AXIS+ROD***
- ✓ ***LPR Required:*** ***NO***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

Phase I (1-10):_____ *II:______* *III:_____*

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				Cross 3
	140		5 % Fuel		
	130				
	120				
	110				
	100		4 % Fuel		

Run 27

Time:__________

- ✓ ***Map:*** ***M-0L***
- ✓ ***Alternative Mode:*** ***2-AXIS***
- ✓ ***LPR Required:*** ***YES***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

Phase I (1-10):_____ *II:______* *III:_____*

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				
	140		5 % Fuel		Cross 3
	130				
	120				
	110		4 % Fuel		
	100				

Run 28

Time:__________

- ✓ ***Map:*** ***M-2L***
- ✓ ***Alternative Mode:*** ***PITCH***
- ✓ ***LPR Required:*** ***YES***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

Phase I (1-10):_____ *II:______* *III:_____*

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				
	140		5 % Fuel		Cross 3
	130				
	120				
	110		4 % Fuel		
	100				

Run 29

Time:__________

- ✓ ***Map:*** ***M-0L***
- ✓ ***Alternative Mode:*** ***2-AXIS+ROD***
- ✓ ***LPR Required:*** ***YES***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

Phase I (1-10):_____ II:______ III:_____

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				
	140		5 % Fuel		Cross 3
	130				
	120				
	110		4 % Fuel		
	100				

Run 30

Time:__________

- ✓ ***Map:*** ***M-1***
- ✓ ***Alternative Mode:*** ***PITCH***
- ✓ ***LPR Required:*** ***NO***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

Phase I (1-10):_____ II:______ III:_____

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				Cross 3
	140		5 % Fuel		
	130				
	120				
	110				
	100		4 % Fuel		

Run 31

Time:__________

- ✓ ***Map:*** ***M-3***
- ✓ ***Alternative Mode:*** ***2-AXIS+ROD***
- ✓ ***LPR Required:*** ***NO***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

Phase I (1-10):_____ II:______ III:_____

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				Cross 3
	140		5 % Fuel		
	130				
	120				
	110				
	100		4 % Fuel		

Run 32

Time:__________

- ✓ ***Map:*** ***M-3L***
- ✓ ***Alternative Mode:*** ***PITCH***
- ✓ ***LPR Required:*** ***YES***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

Phase I (1-10):_____ II:______ III:_____

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				
	140		5 % Fuel		Cross 3
	130				
	120				
	110		4 % Fuel		
	100				

Run 33

Time:__________

- ✓ ***Map:*** ***M-2***
- ✓ ***Alternative Mode:*** ***2-AXIS***
- ✓ ***LPR Required:*** ***NO***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

Phase I (1-10):_____ *II:______* *III:_____*

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				Cross 3
	140		5 % Fuel		
	130				
	120				
	110				
	100		4 % Fuel		

Run 34

Time:__________

- ✓ ***Map:*** ***M-1L***
- ✓ ***Alternative Mode:*** ***2-AXIS***
- ✓ ***LPR Required:*** ***YES***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

Phase I (1-10):_____ *II:______* *III:_____*

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				
	140		5 % Fuel		Cross 3
	130				
	120				
	110		4 % Fuel		
	100				

Run 35

*Time:*__________

- ✓ ***Map:*** ***M-1L***
- ✓ ***Alternative Mode:*** ***2-AXIS+ROD***
- ✓ ***LPR Required:*** ***YES***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

*Phase I (1-10):*_____ *II:*______ *III:*_____

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				
	140		5 % Fuel		Cross 3
	130				
	120				
	110		4 % Fuel		
	100				

Run 36

*Time:*__________

- ✓ ***Map:*** ***M-2***
- ✓ ***Alternative Mode:*** ***PITCH***
- ✓ ***LPR Required:*** ***NO***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

*Phase I (1-10):*_____ *II:*______ *III:*_____

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				Cross 3
	140		5 % Fuel		
	130				
	120				
	110				
	100		4 % Fuel		

Run 37

Time:__________

- ✓ ***Map:*** ***M-1***
- ✓ ***Alternative Mode:*** ***2-AXIS+ROD***
- ✓ ***LPR Required:*** ***NO***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

Phase I (1-10):_____ II:______ III:_____

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				Cross 3
	140		5 % Fuel		
	130				
	120				
	110				
	100		4 % Fuel		

Run 38

Time:__________

- ✓ ***Map:*** ***M-1***
- ✓ ***Alternative Mode:*** ***2-AXIS***
- ✓ ***LPR Required:*** ***NO***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

Phase I (1-10):_____ II:______ III:_____

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				Cross 3
	140		5 % Fuel		
	130				
	120				
	110				
	100		4 % Fuel		

Run 39

Time:__________

- ✓ ***Map:*** ***M-0***
- ✓ ***Alternative Mode:*** ***2-AXIS+ROD***
- ✓ ***LPR Required:*** ***NO***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

Phase I (1-10):_____ II:______ III:_____

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				Cross 3
	140		5 % Fuel		
	130				
	120				
	110				
	100		4 % Fuel		

Run 40

Time:__________

- ✓ ***Map:*** ***M-3L***
- ✓ ***Alternative Mode:*** ***2-AXIS+ROD***
- ✓ ***LPR Required:*** ***YES***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

Phase I (1-10):_____ II:______ III:_____

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				
	140		5 % Fuel		Cross 3
	130				
	120				
	110		4 % Fuel		
	100				

Run 41

Time:__________

- ✓ ***Map:*** ***M-3L***
- ✓ ***Alternative Mode:*** ***2-AXIS***
- ✓ ***LPR Required:*** ***YES***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

Phase I (1-10):_____ II:______ III:_____

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				
	140		5 % Fuel		Cross 3
	130				
	120				
	110		4 % Fuel		
	100				

Run 42

Time:__________

- ✓ ***Map:*** ***M-2L***
- ✓ ***Alternative Mode:*** ***2-AXIS***
- ✓ ***LPR Required:*** ***YES***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

Phase I (1-10):_____ II:______ III:_____

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				
	140		5 % Fuel		Cross 3
	130				
	120				
	110		4 % Fuel		
	100				

Run 43

Time:__________

- ✓ ***Map:*** ***M-1L***
- ✓ ***Alternative Mode:*** ***PITCH***
- ✓ ***LPR Required:*** ***YES***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

Phase I (1-10):_____ *II:______* *III:_____*

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				
	140		5 % Fuel		Cross 3
	130				
	120				
	110		4 % Fuel		
	100				

Run 44

Time:__________

- ✓ ***Map:*** ***M-0***
- ✓ ***Alternative Mode:*** ***2-AXIS***
- ✓ ***LPR Required:*** ***NO***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

Phase I (1-10):_____ *II:______* *III:_____*

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				Cross 3
	140		5 % Fuel		
	130				
	120				
	110				
	100		4 % Fuel		

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Run 45

Time:__________

- ✓ ***Map:*** ***M-0L***
- ✓ ***Alternative Mode:*** ***PITCH***
- ✓ ***LPR Required:*** ***YES***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

Phase I (1-10):_____ *II:______* *III:_____*

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				
	140		5 % Fuel		Cross 3
	130				
	120				
	110		4 % Fuel		
	100				

Run 46

Time:__________

- ✓ ***Map:*** ***M-3***
- ✓ ***Alternative Mode:*** ***PITCH***
- ✓ ***LPR Required:*** ***NO***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

Phase I (1-10):_____ *II:______* *III:_____*

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				Cross 3
	140		5 % Fuel		
	130				
	120				
	110				
	100		4 % Fuel		

Run 47

Time:__________

- ✓ ***Map:*** ***M-2L***
- ✓ ***Alternative Mode:*** ***2-AXIS+ROD***
- ✓ ***LPR Required:*** ***YES***

We'll begin your next trial now. Are you ready? (WAIT FOR AFFIRMATIVE)

You are flying. (BEGIN TRIAL)

Modified Bedford Rating:

Please rate your workload on the Modified Bedford scale, 1 through 10, before, during, and after the mode transition.

Phase I (1-10):_____ II:______ III:_____

Please confirm the differences between phases.

II-I (0-9):__________ II-III:____________

SA Rating:

	450				
	400				
	350				
	300		7 % Fuel		Cross 1
	250				
	225				
	200		6 % Fuel		Cross 2
	175				
	150				
	140		5 % Fuel		Cross 3
	130				
	120				
	110		4 % Fuel		
	100				

Experiment Conclusion

This completes the experiment today. Before we finish I would like you to take a moment to rate the transitions which you made today from what you would consider most graceful to least graceful. Here is a sheet for you to write these ratings. (PRESENT SUBJECT WITH "DEFINITION AND ORDERING HANDOUT") Above you'll notice a definition of a graceful transition for you to base your ordering on. Once you have finished this you'll have finished the experiment. Thank you for taking the time to participate.

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Appendix I

Subject Forms

Subject Forms

Experimentalist:_____________________________________

Subject No.:_________

Date:_________

Definition of Graceful Transition:

The ability of a complex system to change between levels of automation/ levels of supervisory control (including automation modes) with the operator maintaining control and awareness of the system without excessive workload or sacrificing system performance.

Rating the Transitions:

Please rate the gracefulness of the transitions you experienced, with 1 being the most graceful and 6 being the least graceful. Please note any major factors in the decision you made.

____ Transition Manual RCAH + Incremental ROD with landing point redesignation

Comments:____

____

____

____ Transition Manual RCAH with landing point redesignation

Comments:____

____

____

____ Transition Manual Pitch with landing point redesignation

Comments:____

____

____

____ Transition Manual RCAH + Incremental ROD *without* landing point redesignation

Comments:____

____

____

____ Transition Manual RCAH *without* landing point redesignation

Comments:____

____

____

____ Transition Manual Pitch *without* landing point redesignation

Comments:____

____

____

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Appendix J

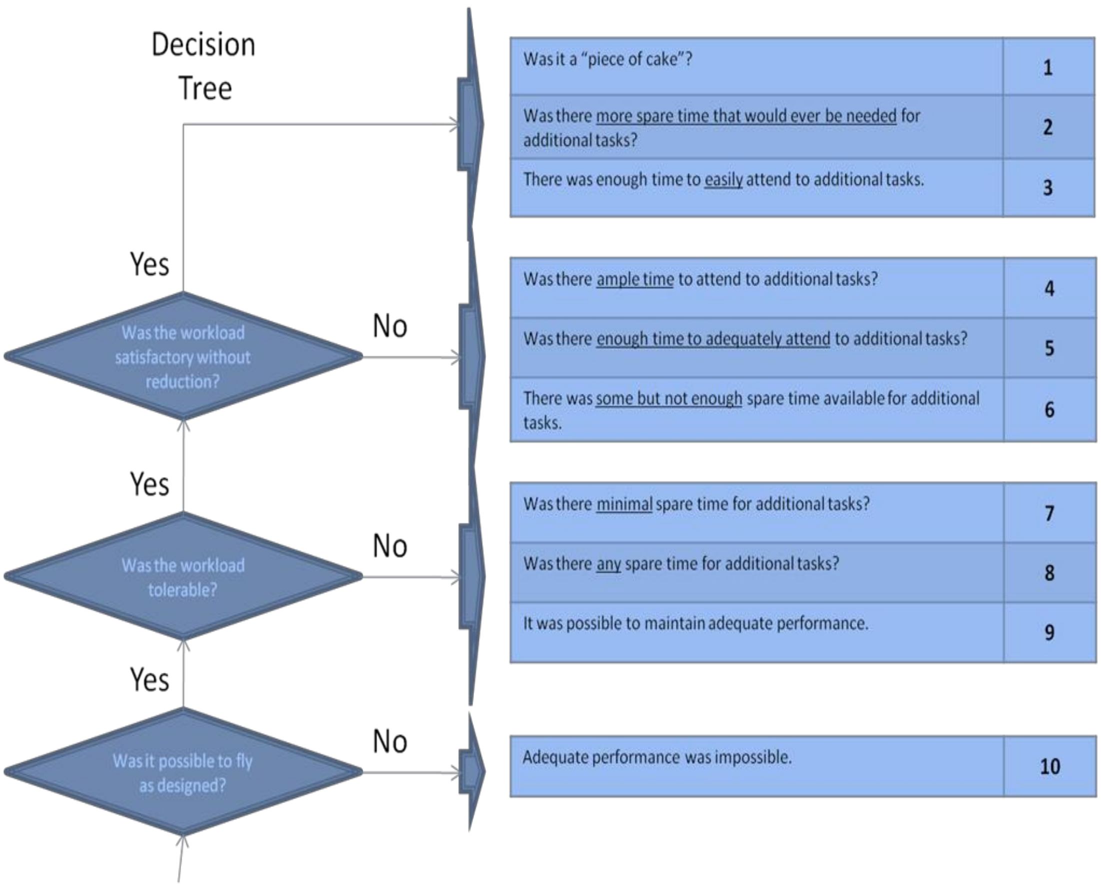
Subject Reference Material

Subject Reference Material

If you find this data sheet, please return to:

C.S. Draper Laboratory
Office 3355A
Cambridge, MA, 02139

Bedford Workload Scale:



ALTITUDE
CALLOUTS

450 ft

400 ft

350 ft

300 ft

250 ft

225 ft

200 ft

175 ft

150 ft

140 ft

130 ft

120 ft

110 ft

100 ft

If you find this data sheet, please return to:

C.S. Draper Laboratory
Office 3355A
Cambridge, MA, 02139

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Appendix K

Subject Demographics Data Sheet

Subject Demographics

Experimentalist:______________________________________

Subject No.:_________

Date:_________

Age:______________________________

Gender: M F

Flying Experience:

- ☐ None
- ☐ Video Games
- ☐ Flight Simulator (Microsoft Flight Sim., etc.)
- ☐ Actual Flight Time
- ☐ Licensed Pilot

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Appendix L

Training Slides

Lunar Landing Simulator Training

CJ Hainley
Kevin Duda
Chuck Oman

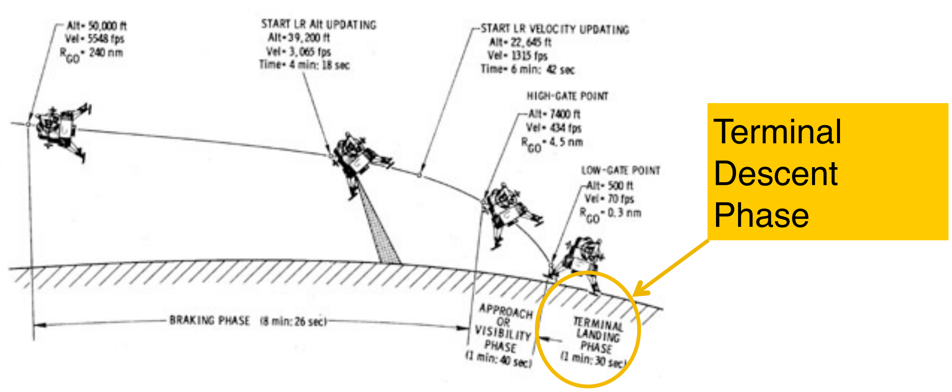
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

DRAPER LABORATORY

9/3/2010

Introduction

- A typical lunar landing trajectory has 3 phases
  - Braking phase (deceleration out of orbit)
  - Approach phase (to establish visual contact with the surface)
  - Terminal descent phase (pilot directs the vehicle down to the surface)
- This experiment focuses on the terminal descent phase of landing



Introduction

- During the terminal descent, the astronaut has to confirm the final selection of a landing location, referred to as the landing aimpoint
- In Apollo, landing aimpoints were typically visually confirmed, and were often changed to different locations by the commander
- For future missions, several landing aimpoints will be recommended to the astronauts by the ALHAT (Autonomous Landing and Hazard Avoidance Technology) system
- The astronaut must use his/her own judgment to select the final landing aimpoint

The Scenario

- You'll be flying a lunar lander in a simulated terminal descent.
- Several displays will be available to assist you, and you will make use of several control modes.
- A flight director will also assist your landing efforts.
- There will be a total of 48 landing simulations (about 2 minutes each).

The Scenario continued…

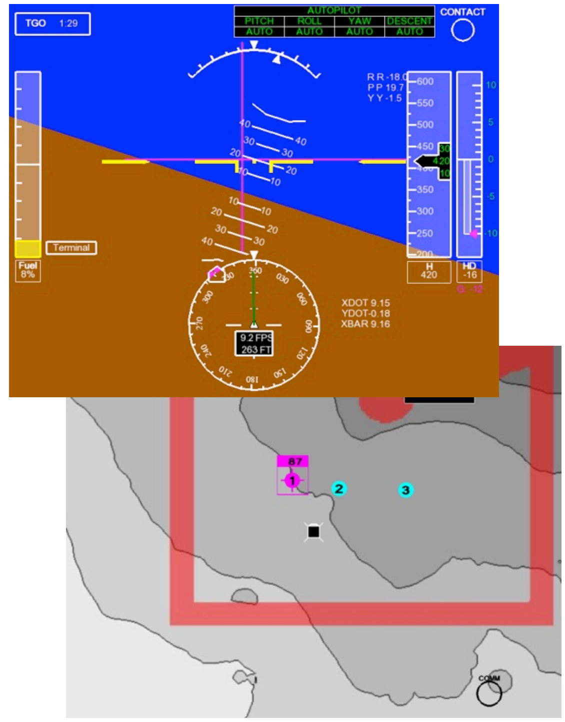
- You will begin in a fully automatic mode, in which the computer will perform all necessary control inputs for you.
- At a particular point in the trajectory, the computer will perform a transition to a manual control mode. You'll need to refer to the mode annunciator to see what mode you're in.
- During some trials a re-designation will accompany the mode transition. This re-designation will be made by the computer, simulating the real-time rejection of the current landing point.

Goals

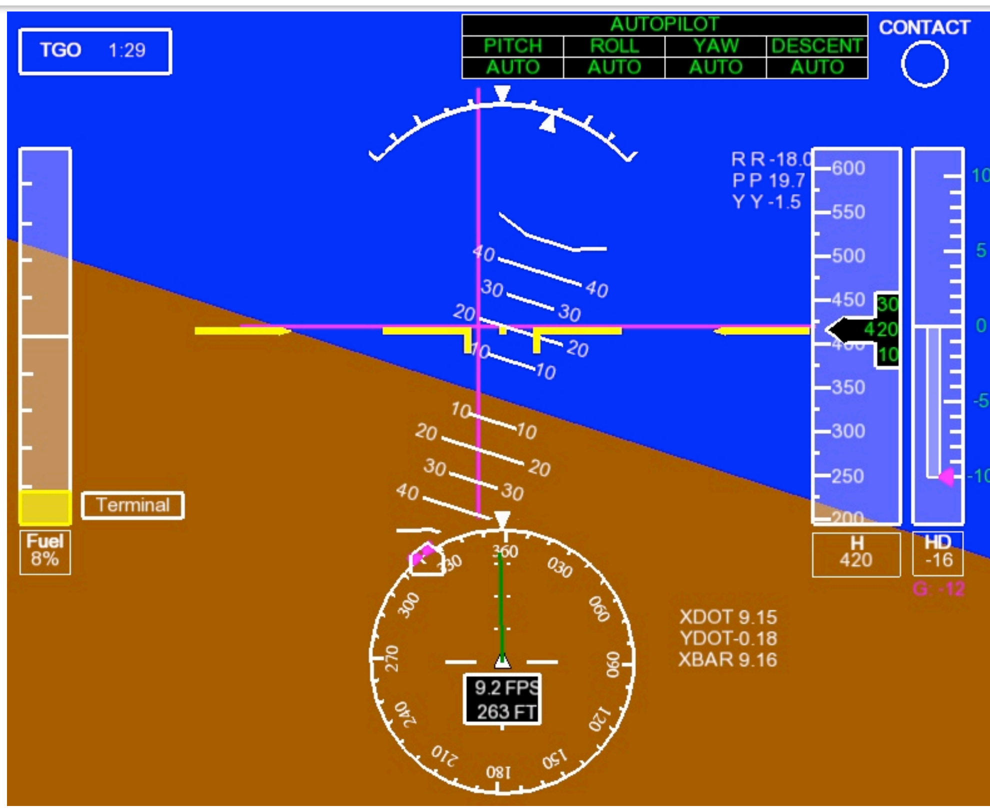
- Your primary goal:
  - Null the guidance errors to ensure an accurate and safe landing.
    - Roll & Pitch within 1 degree
    - Descent Rate: within .5 ft/s
- Your secondary goal:
  - Minimize response time to communication signals
- During the transition trials I'll be cutting the simulation short of landing, meaning that you won't fly to completion.

Displays

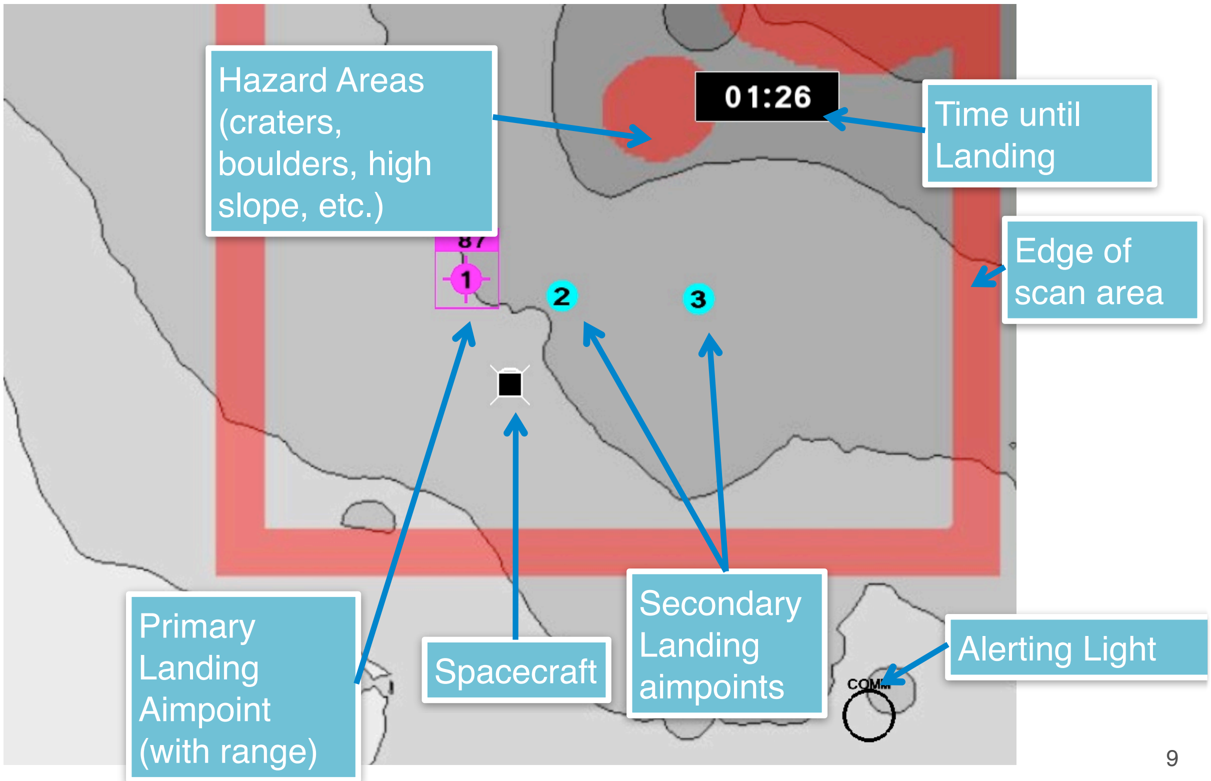
- Two displays will be provided
  - Primary flight display
    - Provides information about vehicle states, such as attitude, altitude, horizontal and vertical velocity
    - Provides flight director cues
    - Uses a simulated horizon; does not show out-the-window information
  - Landing Area display
    - Provides information about hazards and recommended landing aimpoints
    - Top down view of terrain



Displays – Primary Flight Display



Displays – Landing Area Display



Displays – Auditory Display

- The Bingo time represented a measure of remaining fuel, and when reached indicated that you had only 20 seconds to land before you run out of fuel
- You will have an auditory call-out to remind you how long you have until the "Bingo" time.
- You will hear bingo callout at 60 and 30 seconds.
- You will hear a "beep" when the computer switches modes.

Other Communications

- At various intervals, ground control will request your attention (as designated by a lit "Alert" button on the landing area display)
- The "Alert" button will be transparent if you have attended to all requests, and will be either blue or green if your attention is needed
- It is your responsibility to attend to these requests
  - If the light is blue, press the blue button on the top of the joystick
  - If the light is green, press the green button on top of the joystick
  - The light will turn off once you have pressed the appropriate button
- Try to attend to the requests as quickly as you can
- However, do NOT compromise your main task (following the guidance cues to land safely)… only address the comm signal if it will not hinder your flying performance

Redesignation

- In the descent to the lunar surface, a particular landing aimpoint may be judged as unsafe through out-the-window visual views of the lunar surface (out-the-window views are not provided for this experiment)
- However, to represent that possibility, a red "X" will show up over a particular landing site in the Landing Area Display to denote an unsafe landing aimpoint
- If a landing aimpoint is rejected the computer will automatically redesignate to an alternate aimpoint.
- If a re-designation occurs, the mode transition will occur at the same time.

Controllers

- There are two controllers used, a joystick and a throttle

Controllers

THROTTLE

- Press down on the button to increase your descent rate by 1 ft/s
- Press up on the button to decrease your descent rate by 1 ft/s

JOYSTICK

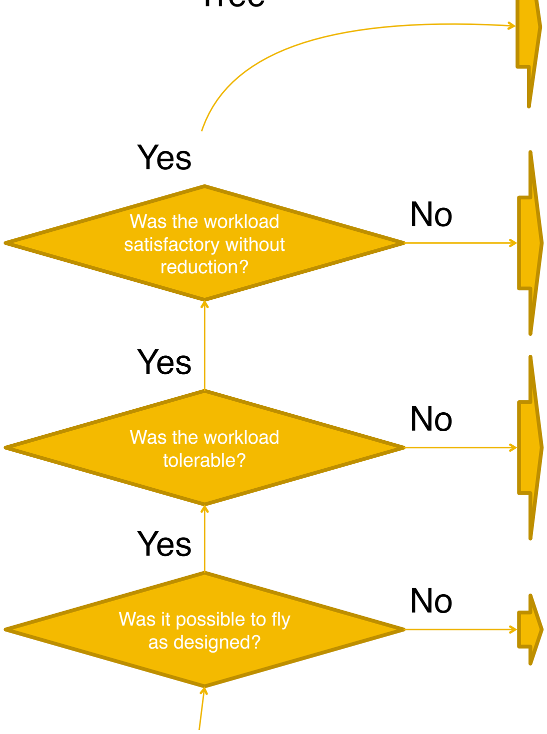
- Fore-aft motion of the stick commands pitch, and left-right motion of the stick controls roll
- Use the trigger to change landing points
- Use the green and blue buttons on top of the joystick to answer alert requests

Bedford Workload Scale

- We're interested in your workload during each trial.
- Workload
  - High = little spare attention for secondary tasks
  - Low = a lot of spare attention for secondary tasks
- You'll rate yourself with the Bedford scale after each run.
- The Bedford scale is a 10 point scale developed for aviation purposes.
- Ratings are not set in stone, feel free to modify past ratings if you feel they don't accurately represent the workload.

Modified Bedford Workload Scale

Decision Tree



Was it a "piece of cake"?	1
Was there more spare time that would ever be needed for additional tasks?	2
There was enough time to easily attend to additional tasks.	3
Was there ample time to attend to additional tasks?	4
Was there enough time to adequately attend to additional tasks?	5
There was some but not enough spare time available for additional tasks.	6
Was there minimal spare time for additional tasks?	7
Was there any spare time for additional tasks?	8
It was possible to maintain adequate performance.	9
Adequate performance was impossible.	10

Situational Awareness

- Three types of callouts:
  - Altitude, Fuel, and Hazard
- Passing Altitude Callout
  - Every 50 ft between 450 ft and 250 ft
  - Every 25 ft between 250 ft and 150 ft
  - Every 10 ft after 150 ft
- Fuel Percent Change Callout
  - When fuel percent switches (e.g. 7% to 6%)
- Entering/Leaving Hazardous Region
  - When the Lander has moved from a hazardous region to a non-hazardous region or vice versa
  - Lander is completely in the new region
- DO NOT SACRIFICE THE FLYING OR COMM TASKS!

Today's Schedule

- Mode familiarization period.
  - Fly-to-completion
- 48 mode transition trials.
  - Possible re-designations
  - Definite mode transitions
  - No fly-to-completion

Landing Performance

	Actual	Desired	Rating
Range	123.8 ft	<10ft	Poor
Fuel	5.4%	>2%	Good
Horiz Vel	0.4 ft/s	<4ft/s	Good
Roll	-2.8 deg	+/-3deg	Good
Pitch	5.0 deg	+/-3deg	Adequate
Descent	7.0 ft/s	<=3ft/s	Poor

Appendix M

MIT COUHES Documentation

MIT Committee On the Use of Humans as Experimental Subjects

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
77 Massachusetts Avenue
Cambridge, Massachusetts 02139
Building E 25-143B
(617) 253-6787

To:	Charles Oman 37-219
From:	Leigh Firn, Chair COUHES
Date:	07/07/2010
Committee Action:	Amendment to Approved Protocol
COUHES Protocol #:	0905003234
Study Title:	Human-Automation Interactions and Performance Analysis of Lunar Lander Supervisory Control: Evaluation of Performance in Mode Transitions
Expiration Date:	06/01/2011

The amendment to the above-referenced protocol has been APPROVED following expedited review by the Committee on the Use of Humans as Experimental Subjects (COUHES).

If the research involves collaboration with another institution then the research cannot commence until COUHES receives written notification of approval from the collaborating institution's IRB.

It is the Principal Investigator's responsibility to obtain review and continued approval before the expiration date. Please allow sufficient time for continued approval. You may not continue any research activity beyond the expiration date without COUHES approval. Failure to receive approval for continuation before the expiration date will result in the automatic suspension of the approval of this protocol. Information collected following suspension is unapproved research and cannot be reported or published as research data. If you do not wish continued approval, please notify the Committee of the study termination.

Adverse Events: Any serious or unexpected adverse event must be reported to COUHES within 48 hours. All other adverse events should be reported in writing within 10 working days.

Amendments: Any changes to the protocol that impact human subjects, including changes in experimental design, equipment, personnel or funding, must be approved by COUHES before they can be initiated.

Prospecitve new study personnel must, where applicable, complete training in human subjects research and in the HIPAA Privacy Rule before participating in the study.

COUHES should be notified when your study is completed. You must maintain a research file for at least 3 years after completion of the study. This file should include all correspondence with COUHES, original signed consent forms, and study data.

CONSENT TO PARTICIPATE IN NON-BIOMEDICAL RESEARCH

Human-Automation Interactions and Performance Analysis of Lunar Lander Supervisory Control: Evaluation of Dynamic Pilot Performance in Mode Transitions

You are asked to participate in a research study conducted by Charles M. Oman, Ph.D. from the Department of Aeronautics and Astronautics Man-Vehicle Laboratory at the Massachusetts Institute of Technology (M.I.T.) and Kevin R. Duda, Ph.D. from The Charles Stark Draper Laboratory, Inc. You were selected as a possible participant in this study because NASA and the National Space Biomedical Research Institute are interested in understanding how to best design the human-machine interface used to control the lunar lander for future lunar missions. You should read the information below, and ask questions about anything you do not understand, before deciding whether or not to participate.

- **PARTICIPATION AND WITHDRAWAL**

Your participation in this study is completely voluntary and you are free to choose whether to be in it or not. If you choose to be in this study, you may subsequently withdraw from it at any time without penalty or consequences of any kind. The investigator may withdraw you from this research if circumstances arise which warrant doing so.

- **PURPOSE OF THE STUDY**

The goal of this experiment is to evaluate your piloting performance with different flight modes and during periods of transition between these modes as you approach the surface of the moon during lunar landing. This experiment is designed to understand pilot awareness given different modes of operation and switches between these modes, as well as the workload associated with piloting the vehicle in the and between these different modes, and the resulting vehicle performance to achieve a safe and precise landing. The results will help determine the recommended pilot-automation task allocation and cockpit information requirements for future lunar landing.

- **PROCEDURES**

If you volunteer to participate in this study, we would ask you to do the following things:

We will evaluate your simulated lunar landing piloting performance, situational awareness, and perceived workload while operating within and between different flight modes (e.g. attitude with rate-of-descent control) using a within-subjects design to compare the control performance across control modes and pilot task allocations. You will be instructed on the task of monitoring and controlling the vehicle trajectory and performance using the primary flight (e.g., attitude indicator, heading indicator, altimeter) and situation awareness displays (e.g., 2-D moving map) during approach and descent during various control modes. Typically, the trials will begin with the lander at a fixed position above the lunar surface with up to 10 minutes of fuel. You will be asked to perform a monitoring and/or controlling task that will require you to scan the instrument panel for information. At a particular time during each trial the active control mode may be switched, and you will be expected to maintain control and awareness of the system. Additionally you will be required to perform a re-designation of the intended landing site. Each trial will run for no more than 10 minutes. We will also ask you about the information presented on other displays (e.g., altitude rate, distance from intended touchdown), have you complete the NASA TLX (Task Load Index), which will help us determine your perceived workload during the trials, and have you complete a SART assessment of your situational awareness. Several practice trials will be available to allow you to familiarize yourself with the procedure before beginning. Be sure to let the experimenter know if you have any questions.

You will participate in an experimental session which is expected to last no more than 3 hours per day over two days. Optional breaks will be provided at least every 30 minutes. The entire session will take place in Draper Laboratory's fixed-base lunar lander cockpit simulator.

- **POTENTIAL RISKS AND DISCOMFORTS**

  - Boredom due to the large number of repetitive trials.
  - Fatigue from operating the joysticks and attending to the displays and tasks
  - Symptoms of simulator sickness due to visual motion in the displays.

You will be given short breaks between trials to reduce the risks of boredom, fatigue and motion sickness. You may request a break at any time during the experiment if you begin to feel any discomfort.

- **POTENTIAL BENEFITS**

There are no benefits to you aside from becoming familiar with the potential human-automation interactions, displays, and tasks associated with future lunar landings.

NASA will benefit from the results of these experiments by being able to design appropriate human-machine interfaces that will mitigate any risks from the human factors issues studied.

- **PAYMENT FOR PARTICIPATION**

You will receive $10 per hour for your participation. Payment is prorated on the basis of time spent if you decide to withdraw.

- **CONFIDENTIALITY**

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission or as required by law.

No personal information will be collected in this experiment. All simulated flight performance data collected in this experiment will be coded to prevent the identification of the data with a specific person. All data reported in journal or conference papers will be group data or de-identified. The data will be archived when the project is completed and papers published (about 2013). No identifying information will be kept with the data

- **IDENTIFICATION OF INVESTIGATORS**

If you have any questions or concerns about the research, please feel free to contact:

Principal Investigator: Charles M. Oman, Ph.D., (617) 253-7508, coman@mit.edu
Co-Investigator: Kevin R. Duda, Ph.D., (617) 258-4385, kduda@draper.com
Research Assistant: Chris J. Hainley, Jr. (617-258-2217., chainley@draper.com

- **EMERGENCY CARE AND COMPENSATION FOR INJURY**

If you feel you have suffered an injury, which may include emotional trauma, as a result of participating in this study, please contact the person in charge of the study as soon as possible.

In the event you suffer such an injury, M.I.T. may provide itself, or arrange for the provision of, emergency transport or medical treatment, including emergency treatment and follow-up care, as needed, or reimbursement for such medical services. M.I.T. does not provide any other form of compensation for injury. In any case, neither the offer to provide medical assistance, nor the actual provision of medical services shall be considered an admission of fault or acceptance of liability. Questions regarding this policy may be directed to MIT's Insurance Office, (617) 253-2823. Your insurance carrier may be billed for the cost of emergency transport or medical treatment, if such services are determined not to be directly related to your participation in this study.

- **RIGHTS OF RESEARCH SUBJECTS**

You are not waiving any legal claims, rights or remedies because of your participation in this research study. If you feel you have been treated unfairly, or you have questions regarding your rights as a research subject, you may contact the Chairman of the Committee on the Use of Humans as Experimental Subjects, M.I.T., Room E25-143B, 77 Massachusetts Ave, Cambridge, MA 02139, phone 1-617-253 6787.

SIGNATURE OF RESEARCH SUBJECT OR LEGAL REPRESENTATIVE

I understand the procedures described above. My questions have been answered to my satisfaction, and I agree to participate in this study. I have been given a copy of this form.

____
Name of Subject

____
Name of Legal Representative (if applicable)

____________________________________ ____________
Signature of Subject or Legal Representative Date

SIGNATURE OF INVESTIGATOR

In my judgment the subject is voluntarily and knowingly giving informed consent and possesses the legal capacity to give informed consent to participate in this research study.

____________________________________ ____________
Signature of Investigator Date

Want to fly a lunar lander simulator?