Divergence between the Human State Assumption and the Actual Aircraft System State

by

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by

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Abstract

Divergence is defined in this thesis as an inconsistency between the human operator's assumption of the system state and the actual state of the system, which is substantial enough to have consequential effects on the outcome of the situation. The purpose of this thesis is to explore the concept of divergence and develop a framework that can be used to identify the consequential causes of divergence in cases involving human-system interaction.

Many recent aircraft accidents involve divergence between the crew state assumption and the actual system state. As aircraft systems and automation become more complex, it's possible that the consequential effects of divergence, illustrated by these accidents, could become more prevalent due to the correspondingly more complex understanding that may be required by the crew to effectively operate the aircraft.

Divergence was explored as a concept by (1) understanding the previous literature related to divergence such as work on human error, human information processing, situation awareness, and mode awareness (2) developing a framework that can be used to understand possible causes of divergence, (3) illustrating use of the framework with accident case studies, and (4) discussing the implications of the findings of the case study analysis of divergence.

Human information processing of divergence was developed using the established human information processing literature including Wickens (1992), Endsley (1995), and Reason (1990). The framework highlighted the inputs to the human and represented human processing of this information in relation to formation of a state assumption. The process model was used to identify potential causes of divergence, which were hypothesized as human information processing failures affecting the human state assumption, and to evaluate the effects of those failures on downstream processes and the human state assumption. Eleven accident case studies involving automation mode confusion were conducted to evaluate divergence using the process model of divergence. Eight of the case studies involved auto-throttle mode confusion and the three remaining cases involved divergence in other automation systems that resulted in controlled flight into terrain. The industry implications of the findings of the case studies were then discussed.

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List of Acronyms

A320	Airbus A320 Aircraft
AA	American Airlines
AC	Advisory Circular
AF	Air France
AMC	Acceptable Means of Compliance
A/P	Autopilot
ATC	Air Traffic Control
A/THR	Auto-throttle
B747	Boeing 747 aircraft
CAST	Commercial Aviation Safety Team
CAA	Civil Aviation Authority
CFIT	Controlled Flight into Terrain
CRM	Crew Resource Management
CVR	Cockpit Voice Recorder
DS	Directed Search
EGPWS	Enhanced Ground Proximity Warning System
GPWS	Ground Proximity Warning System

HFACS	Human Factors Analysis and Classification System
HUD	Heads Up Display
FAA	Federal Aviation Administration
FCU	Flight Control Unit
FDR	Flight Data Recorder
FG	Frequency Gambling
FLR	Flare
FMA	Flight Management Annunciator
FO	First Officer
FPA	Flight Path Angle
Ft	Feet
FSF	Flight Safety Foundation
FWM	Focal Working Memory
KB	Knowledge Base
LOC	Loss of Control
LTM	Long Term Memory
MCP	Mode Control Panel
MSL	Mean Sea Level
NAV	Navigation
PARC	Performance-Based Aviation Rulemaking Committee
PF	Pilot Flying

PM	Pilot Monitoring
PWM	Peripheral Working Memory
QAR	Quick Access Recorder
RA	Radio/Radar Altimeter
RET	Retard
SA	Situation Awareness
SD	Standard Deviation
SPD	Speed
STAMP	Systems-Theoretic Accident Model and Processes
THR	Thrust
TRK	Track
Vref	Reference Airspeed
V/S	Vertical Speed
WM	Working Memory

Chapter 1

Introduction and Motivation

1.1 Introduction and Motivation

Divergence is defined in this thesis as an inconsistency between the human operator's assumption of the system state and the actual state of the system, which is substantial enough to have consequential effects on the outcome of the situation. The Performance-Based Operations Aviation Rulemaking Committee (PARC) and Commercial Aviation Safety Team (CAST) highlighted issues in human-automation interaction in their safety report released in 2013 (Performance Based Aviation Rulemaking Committee & Commercial Aviation Safety Team, 2013). Relevant findings illustrated evidence of continued deficiency of crew understanding of aircraft and automation state as well as the impact of design decisions introducing complexity into the system, further contributing to pilot confusion and errors. This thesis explores the concept of divergence and develops a framework to identify consequential causes of divergence in cases involving human-machine interaction in efforts to ultimately understand causal trends and inform mitigations for divergence. Many recent aircraft accidents have involved divergence between the crew assumption of system state and the actual system state. As aircraft systems and automation become more complex, it is possible that the consequential effects of divergence, likely illustrated by these accidents, could become more prevalent (Woods, 1996).[1]

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[1] AC/AMC 25.1302 discusses complexity as follows: "Complexity of the system design from the flight crew's perspective is an important factor that may also affect means of compliance in this process. Complexity has multiple dimensions. The number of information elements the flight crew has to use (the number of pieces of information on a display, for instance) may be an indication of complexity. The level of system integration may be a measure of complexity of the system from the flight crew's perspective.

This chapter discusses the previous work relating to divergence including literature regarding human error, human information processing, situation awareness, and mode awareness. Following the literature review, this chapter illustrates where divergence would fit within the current literature and proposes a problem statement. Later, the concept of divergence is formally defined and the objectives of the work are presented. Finally, a summary of the thesis organization is provided.

"Pilots mitigate safety and operational risks on a frequent bases, and the aviation system is designed to rely on that mitigation" (Performance Based Aviation Rulemaking Committee & Commercial Aviation Safety Team, 2013). This reliance on the human for robust reaction to abnormal events indicates the importance of ensuring effective human-system interaction. While, automation has contributed to improvements in safety, operational efficiency, and precise flight path management, this technology development has introduced vulnerability into the system at the boundary between the user and the system (Performance Based Aviation Rulemaking Committee & Commercial Aviation Safety Team, 2013). As automation use increases, it becomes more important to address these issues effectively. Figure 1-1 shows the increase in the number of flights with varying generations of aircraft. The trend is toward further use of fly-by-wire systems with higher automation levels, such as envelope protection[2]. The PARC and CAST report also mentions that as the scope of operations, combined with complexity of airspace, procedures, and automated tools on the flight deck has evolved, there is a corresponding increase in the set of required skills and knowledge that pilots need for flight path energy management in today's complex aircraft and airspace. Divergence could occur when this knowledge requirement may either have too high of an expectation for human comprehension, or the skills pilots use, such as supervisory control and observation, become ineffective. In order to provide a basis for the discussion in this thesis, the following description of divergence is provided.

Design of controls can also be complex. An example would be a knob with multiple control modes." (Federal Aviation Administration, 2013)

[2] Envelope protection refers to automation systems that are designed to take control of the aircraft automatically to avoid flight outside of the flight envelope.

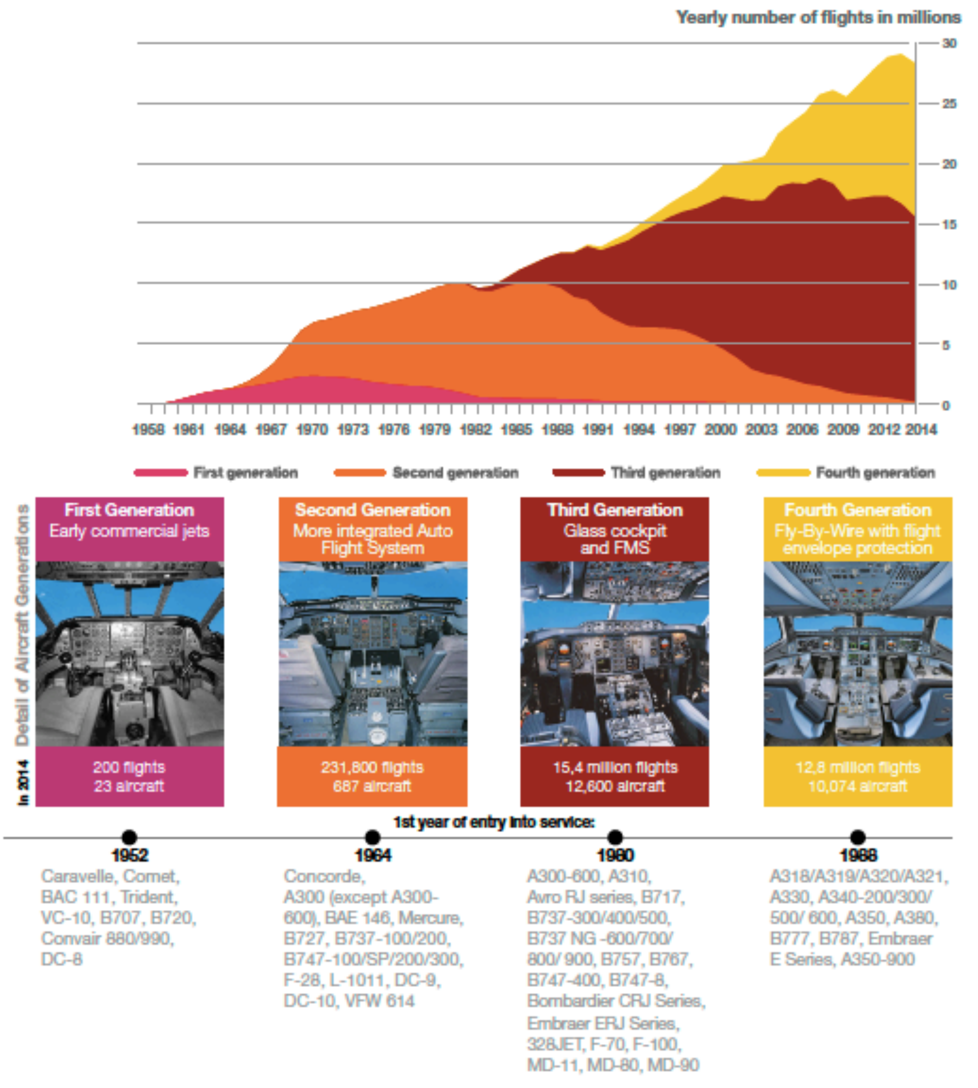

Figure 1-1. Yearly number of flights trend based on generation of aircraft (Airbus Industrie, 2014)

Figure 1-2 illustrates a basic schematic of how the actual system state and human system state are related. As can be seen in the figure, the human state assumption is formed using the human's information processing system transforming the data from actual state into a human state assumption. Thus, at any point in time, the human has a mental representation and assumption of what the actual state of the system is. This human state assumption and the actual system state can be compared to evaluate divergence.

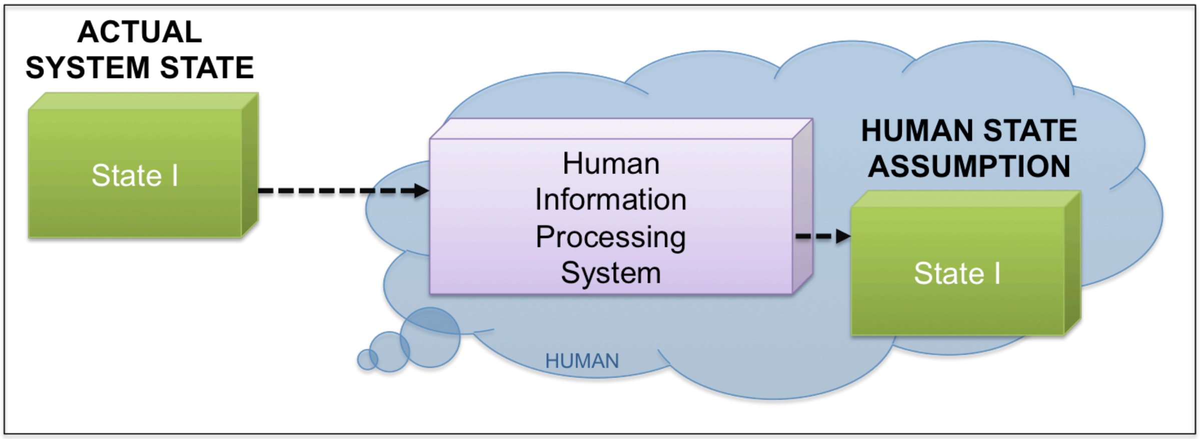

Figure 1-2. Basis for human state assumption

Figure 1-3 illustrates one example of possible divergence in human state assumption. At time t = t_0, both the system state and human assumption of state are consistent. Between time t = t_0 and t = t_1, both the system state and human state transition to State II and remain consistent. However, divergence occurs at time t = t_2, when the actual state transitions back to State I, however the crew believes the system remains in State II. As can be seen by the human state assumption transition from State II to State I at time t = t_3, it is also possible for re-convergence to occur.

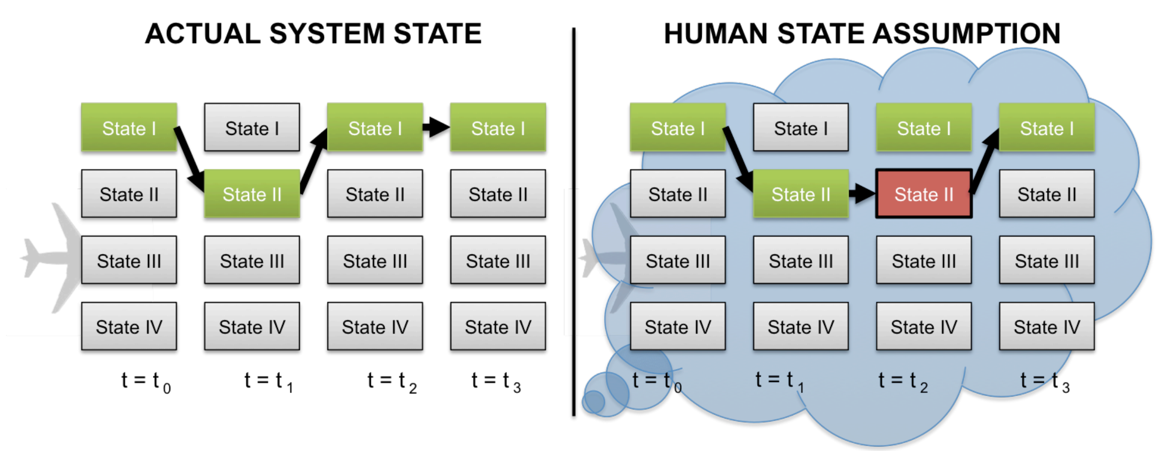

Figure 1-3. Representation of human state assumption and divergence profile through time

This thesis explores how the human state assumption can be formed and the impact of possible divergence on consequences of a situation. While the concept of divergence itself can be used to assess a number of various human-systems issues, this thesis explores divergence in automation systems.

1.2 Previous Work

The concept of divergence appears in many different realms of the previous literature. The topics shown in Figure 1-4 are discussed in this section as they have specific relation to divergence. Divergence is considered to be a subset of human error. Since divergence is determined using the human state assumption, human information processing could be used to understand how the human state assumption is formed. Divergence falls within the concept of situation awareness (SA), discussing specifically the awareness of state. Since mode confusion has been established as a common problem in aviation, divergence in state of automation chosen to illustrate the concept of divergence. Ultimately, this literature review sets the stage for where divergence fits within the current human error and human information processing literature and discusses its applicability to mode awareness issues. The previous literature for these topics is extensive, and this section presents select literature related to the concept of divergence.

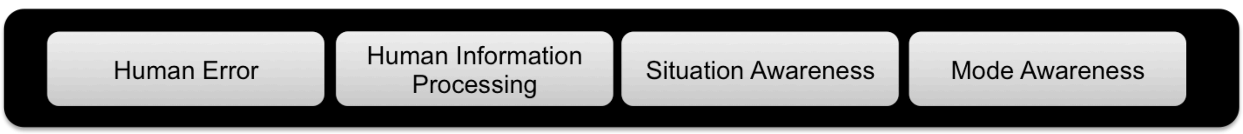

Figure 1-4. Discussed literature related to divergence

1.2.1 Human Error Literature

Human error has been attributed to many high profile accidents in recent history and is not limited to aviation. Some of the current literature views human error and knowledge originating from the same mental processes (Reason, 1990; Ernst, 1905). The same processes that provide humans with a "rapid retrieval system, capable of locating relevant items within a virtually unlimited knowledge base" also make humans susceptible to unintentional actions, information overload, and confirmation bias, which could contribute to the occurrence of divergence. Since the risk associated with divergence is the result of an error in performance, it is relevant to discuss how the concept of human error has been discussed in the past.

Assuming that the human holds a prior intention to achieve a certain goal, errors can be discussed with respect to whether the action was what was intended or not. (Norman 1981,1983,Reason 1982). *Mistakes* refer to cases where the intention itself was not appropriate to achieve the goal. *Slips and lapses* refer to cases where the intention was correct but the action was not what was intended. The difference in these error taxonomies reflect the concept of cognitive levels where mistakes as planning failures may more often be related to divergence, but slips could be less straightforward. Mistakes normally arise from higher-level processes than slips and lapses as execution failures. The details on types of slips and mistakes is further discussed in Section 3.8.

The slips-mistakes dichotomy focused on assessing more inconsequential action slips that occurred through daily life, however Rasmussen developed a skill-rule-knowledge based framework that incorporated planning errors and accounted for more serious errors that could occur when the human holds a supervisory role which is commonly seen in cases of divergence in the cockpit (Rasmussen and Jensen, 1974). Skill-based level of performance refers to task performance that is governed by stored patterns of pre-programmed instructions and is more automatic in nature. The rule-based level of performance refers to tasks, which may be familiar in which solutions are governed by stored rules. The knowledge based level uses conscious analytical processes and stored processes to plan actions to resolve novel situations. Errors in each of these levels manifest differently. Slips and lapses would fall into skill-based errors, however mistakes can be regarded as rule-based mistakes or knowledge-based mistakes depending on what level of cognition is required for the task (Rasmussen, 1985). These distinctions in level of cognition allude to possible other factors affecting cognition, which could contribute to errors in action.

Reason proposed the "Swiss Cheese Model" of error causation to link errors to mishaps (Reason 1990). These failures can be classified as active failures, which have been discussed thus far as errors in action, and latent failures, which are contributory factors, which may lie dormant for a period of time. Shappell and Weigmann expanded on Reason's Swiss cheese model to create the Human Factors Analysis and Classification System (HFACS), defining types of failures and categorized them into Unsafe Acts, Preconditions for Unsafe Actions, Unsafe Supervision, Organizational Influences (Shappell & Wiegmann, 2000). While unsafe actions are active failures, divergence is concerned about the underlying causes of those unsafe actions. The pre-conditions to unsafe acts provide insight into what factors may contribute to divergence. These preconditions could include adverse mental states such as task saturation, physical limitations, as well as crew resource management problems. The causes of these pre-conditions could be linked to unsafe supervision such as poor training practices or lack of guidance from an airline for example. Ultimately this unsafe supervision could be linked to organizational influences such as funding or resource limitations. This framework identifies aspects of how unsafe acts originate and where those underlying preconditions can also originate.

Reason attempted to capture all error with his concept of the "Fallible Machine" model by modeling not only correct performance but also predictable varieties of fallibility (Reason, 1990). Reason's model of a fallible machine incorporates the erroneous, or fallible, behavior of humans (Reason, 1990). The structure of the framework includes a Knowledge Base (KB) and a Working Memory (WM) that is further divided into a Focal Working Memory (FWM) and a Peripheral Working Memory (PWM). According to this model, the PWM is an area of vast capacity that receives information directly from the outside world and the knowledge base. This information is filtered into the FWM, which is an area of limited capacity.

A novel aspect of this model is the description of retrieval mechanisms applied to compare perceived information to the knowledge base content and to select between alternative situations. These include Similarity Matching (SM), Frequency Gambling (FG) and the process of Direct Search (DS). SM refers to a search within the KB for matches to the information perceived from the external word. This search could identify a number of frames that satisfies matching conditions. Thus, it may be necessary to apply FG where the multiple frames are filtered for the frame that is most familiar or most frequently encountered in the past. The literature continues on to suggest that it may be possible for the SM step to be skipped and the FG may be called directly. In some cases, it may be possible that the SM and FG processes may not be able to deliver a "definite" appropriate plan of action. At this point the model describes the method of Directed Search. In DS, the frequent interaction between KB and memory can be used to develop an unfamiliar situation that could explain cues from the environment. This may include searching the environment for further cues or reasoning through the situation to develop a plan of action.

Reason suggests that the prime generators of errors in human behavior are the retrieval mechanisms of SM and FG. Norman (1981) and Reason (1979) suggest that retrieval mechanisms function using an activation-trigger schema, implying that activators can trigger certain schema to search the KB. Two types of activators include specific activators, which use a mental model that is composed of explanations of intended actions and plans, and general activators, which provide contextual and affective background information regardless of intentions. Norman and Reason suggest that errors mostly appear when schemas are appropriately chosen and activated, but are misapplied. This representation of the retrieval mechanisms as an activation-trigger schema system illustrates how the short term memory can handle familiar knowledge with speed and without heavy workloads, but also how error can be introduced into the system as an artifact which could provide insight on origins of divergence. While Reason's fallible machine may be able to encompass the errors in action seen in the human, the generality of the model doesn't detail the individual processes that account behaviors within the feedback loop. Thus, it is relevant to assess models that discuss individual processes and behaviors within the feedback loop captured by previous work on the human information processing system.

1.2.2 Human Information Processing Literature

Human information processing refers to how incoming information is processed through the brain to affect aspects such as decision-making and execution. In order to understand divergence, it’s necessary to understand how human processes information and makes a state assumption. There have been a number of proposals in the literature concerning the manner in which the human information processing functions and the interaction between components of the processing system.

A three-stage model of information processing captures perception of a stimulus, cognition of the information perceived, and action based on cognition ultimately resulting in a response to the input stimulus. (Sperry, 1952; Thelen & Sperling, 1994). Wickens used the fundamentals of the three stage model and developed a representation that is commonly used as a basis for information processing models (Wickens & Hollands, 2000). The Wickens model of information processing is shown in Figure 1-5 (Wickens & Hollands, 2000). It encompasses the aspects such as sensory processing, perception, cognition, response selection and response execution. Wickens illustrates a feedback loop to the environment, and also incorporates the distinct effects of attention, long-term memory and working memory.

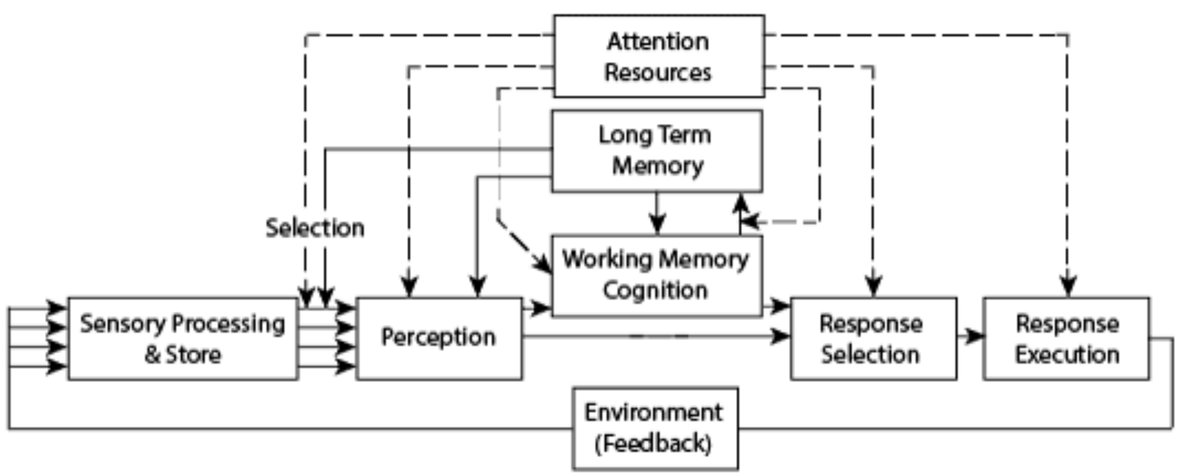

Figure 1-5. Wickens information processing model (Wickens & Hollands, 2000)

Sensory Processing Store and Buffering - Sensory memory refers to the phenomenon of stimuli persisting for a short period after they have been removed from the environment (Standing, Conezio, & Haber, 1970). This is an important aspect of information processing, and relevant to divergence as it affects input into the perceptual stage.

Perception – Perception of the environment is the process by which input of sensory information and outputs filtered sensory information to the processes downstream (Henderson & Hollingworth, 1999). Physiologically, perception occurs through stimulation of the sensory organs and interpretation of those neural signals in the brain (Wolfe et al., 2008). This process can be affected by attention and can occur directly or through an intermediary such as displays or instruments; thus, integrity of perception is also dependent on these intermediary systems (Endsley, 1999). The ways that displays are designed can also influence perception of the information (Nikolic, Orr, & Sarter, 2004). Since perception is the gateway into the human, this stage is very important to understanding where the human state assumption originates.

Working Memory/Cognition – Once the perceptual stage has extracted information from the environment, cognition takes over to ultimately determine the appropriate response to the signal by attaching meaning to that information and forming an understanding of the environment (Schnotz & Kürschner, 2008). Cognition processes could include information retrieval from memory in order to conduct comparisons between signals and frames in memory. Another aspect of cognition is the ability to form an expectation of future states (Herrmann, Buschke, & Gall, 1987).

Working memory or short term memory refers to a store of limited capacity that is used to temporarily represent and retain information for problem-solving and comprehension (Brown, 1958; Peterson & Peterson, 1959).

Long Term Memory - Long term memory (LTM) refers to the store of information that can be recalled for processing in the working memory (Cowan, 2008). Long term stores are recalled often to comprehend system information, determine what action is appropriate, and actually execute the action (Proctor & Van Zandt, 2008). Short-term memory integrates this information and the incoming information from perception and aids with cognition. Sensory stores influence the perception of information. Each of these memory stores is critical to information processing, so limitations associated with all three types of memory could introduce errors into the human information process.

The term mental model generally describes an abstraction researchers use to explain how knowledge and information are represented in the mind (Klimoski & Mohammed, 1994). One theory hypothesizes that the mental model(s) provides a conceptual framework for explaining and predicting future system states (Rouse & Morris, 1985). Examples of mental models in long-term memory are a model of how an aircraft automation system is expected to function, or the dynamics of typical weather patterns encountered. As evidenced, these long term mental models are built from previous experience and training to provide a basis of understanding of the current situation and expected future state of the situation (Cowan, 2008;

Norman, 1983). Norman suggested the concept of "gulfs" of execution and evaluation to describe discrepancies between internal goals and information specifying the state of the world (Norman, 1986). While LTM mental models can contribute a gulf in execution, divergence can be related to the concept of the gulf of evaluation which describes "the degree to which the system/artifact provide representations that can be directly perceived and interpreted in terms of the expectations and intentions of the user" (Norman, 1986). If the degree of similarity in representation is low, it could induce cases of divergence.

Literature discussing influences to the mental model is extensive. It has been found that creating correct mental models by explicit training on underlying causal structures of the system is effective in improving performance on novel tasks (Halasz & Moran, 1983). In addition to explicit training of causal structures, Schnolz and Kurschner discovered that the form of visualization, such as design influences in a display, can affect the structure of mental models ultimately affecting performance on tasks relying purely on the mental model (Schnotz & Kürschner, 2008). In addition to different types of training, degree of experience was also shown to influence mental models. Bellenkes and Wickens showed that more experienced pilots held a better mental model of cross-coupling and predictive behavior between and within axes of the aircraft when flying a simulated pattern (Bellenkes, Wickens, & Kramer, 1997). Although training of actual system structure may not always be practical, the concept of visibility could be used to design a system where the user can immediately determine the state of the system and possibilities for action (Norman, 1988). The literature indicates that the mental model of a system can be dependent both on aspects of the human, such as training, experience, and perception, as well as design of the system. Expectation is dependent on mental models and has been shown to have an effect on human information processing (Deliza & Macfie, 1996; Summerfield & Egner, 2009). Expectation allows tasks to be performed faster and more efficiently and has been found to be a contributor to expert behavior (Bellenkes et al., 1997; Kasarskis, Stehwien, Hickox, Aretz, & Wickens, 2001). However, it can also introduce problems if the expectation or mental models behind the expectation are incorrect. This can cause expectation bias and affect perception of incoming information.

Expectation bias can refer to the manipulation of perceived elements to values consistent with the human's expectation (Bhattacherjee, 2001). This is distinct *confirmation bias,* which describes the cognitive phenomenon of humans seeking confirming evidence in perception supporting their expectations and discounting evidence that disproves their expectation (Nickerson, 1998). For the purpose of this thesis, *expectation bias* is used to describe effects of both confirmation bias and the manipulation of perceived elements to values consistent with expectation. This can be explained using Reason's concept of retrieval mechanisms. While nominal retrieval may conduct similarity matching first and then follow up with frequency gambling to pick a single option, it is possible that FG could occur without SM;

this would be an example of how expectation bias could manifest within Reason's construct. If a state is chosen with only regard to the frequency it occurs or its familiarity, this effectively bypasses the observation and could introduce errors if this occurrence is inappropriate for the situation.

Overall, cognition incorporates processing of information and expectation in order to form an understanding of the situation relevant to a given task at hand. This understanding can include a representation of a human state assumption with which many of the other processes likely interact. The decision making process can be dependent on cognition and if divergence exists, would be directly affected by it. Planning errors based on information from cognition could manifest here.

Response Selection - There are a number of theories relating to decision-making, or response selection. A few examples include the concept of using logic and reasoning, which hypothesizes that when conditions are known, decisions are made logically to determine a result using deduction, induction, or abduction (Harman, 1984). Klein suggests that decisions are not made logically, but are dependent on heuristics representing more naturalistic behavior based on bounded rationality (Klein, 2008; Simon, 1972; Todd & Gigerenzer, 2000). J. Reason suggests that decision making occurs via direct identification, elimination, partial identification, or guessing, which could also exhibit stopping behavior based on heuristics (Reason, 1990). As decision-making is considered a downstream product of the human state assumption, it is discussed as a focus of this thesis. However, it is important to discuss due to the action feedback loop. Once a response is chosen, it feeds into response execution.

Response Execution – Once a decision has been made, if an overt action is required, it is selected, programed, and executed in this action stage (Prinz & Hommel, 2003). Physiologically, the response is translated into a set of neuromuscular commands that control specific limbs or effectors involved in executing the response. Theories of execution are expansive in the literature and include aspects of automatic and conscious control (Fitts, 1964; Rasmussen, 1983). These also incorporate the mechanisms of motor processors (Kieras & Meyer, 1994). However, if upstream processes are corrupt, execution of a corrupt decision may lead to error. This is important to remember as output of the execution process defines performance and correspondingly performance errors.

Attention Resources – Attention can be seen as a limitation input on all processes involved with information processing. These limitations could influence the integrity of the output of the process and contribute to a poor human state assumption and divergence. James defines attention as "the taking possession of the mind, in clear and vivid form, of one out of what may seem several simultaneously possible objects or trains of thoughts…It implies withdrawal from some things in order to deal effectively with others" (James, 1890). There has been much work in different aspects of attention such as focused attention, where it is driven actively in search of information (Hollander, 2000; N. Wood & Cowan, 1995). Attention can also be directed involuntarily, such as toward salient cues for example (Prinzmetal, Ha, & Khani, 2010; Yantis, 2005). Attention has been considered a limiting factor in all stages of human information processing, however there are two main theories regarding the source of this limitation and its effect on selective or divided attention: bottleneck models and resources models (Hogendoorn, Carlson, VanRullen, & Verstraten, 2010; Kahneman, 1973; Lavie, Hirst, de Fockert, & Viding, 2004; Lavie, 1995; Treisman, 1969; Wickens, 2002; N. Wood & Cowan, 1995). Bottleneck models hypothesize that limitations due to attentions are caused by limitations in the information processing sequence where the amount of information to which humans can attend to is limited (Broadbent, 1958; Cherry, 1953; N. Wood & Cowan, 1995). Resource models, on the other hand, hypothesize that limitations due to attention are caused by attentional limitations that arise due to limited capacities available for mental activity (Proctor & Van Zandt, 2008). Unitary-resource models consider attention to be a single limited capacity resource that can be applied to a variety of cognitive processes (Kahneman, 1973). Conversely, multiple resource models suggest that there is not a single pool of resources, but several distinct subsystems of attention that each have their own limited pool of resources (Navon & Gopher, 1979; Wickens, 2002). Despite evidence supporting both of these theories, research indicates that problems in dual-task interference are much more complex then currently understood (Navon & Miller, 1987).

Wickens' model built on the three-stage model of perception, cognition, and action, however Endsley expanded on Wickens' model by incorporating more detail into aspects of situation awareness.

1.2.3 Situation Awareness Literature

Endsley's work focused on how situation awareness fits into human cognition, and she formally defines three stages of situation awareness. She theorizes that situation awareness occurs through perception of the environment, comprehension of those observations, and projection of the current situation into the future. This concept has been well supported in the field (Endsley & Garland, 2000; Endsley, 1996, 1999; Wickens, Mccarley, & Thomas, 2003). Figure 1-6 depicts a model of dynamic decision-making incorporating situation awareness into human information processing. Endsley adds to Wickens' model by explicating the situation awareness elements and introduces how these elements affect each process in the system. Because divergence describes state awareness, a subset of situation awareness, it's important to understand how situation awareness is modeled.

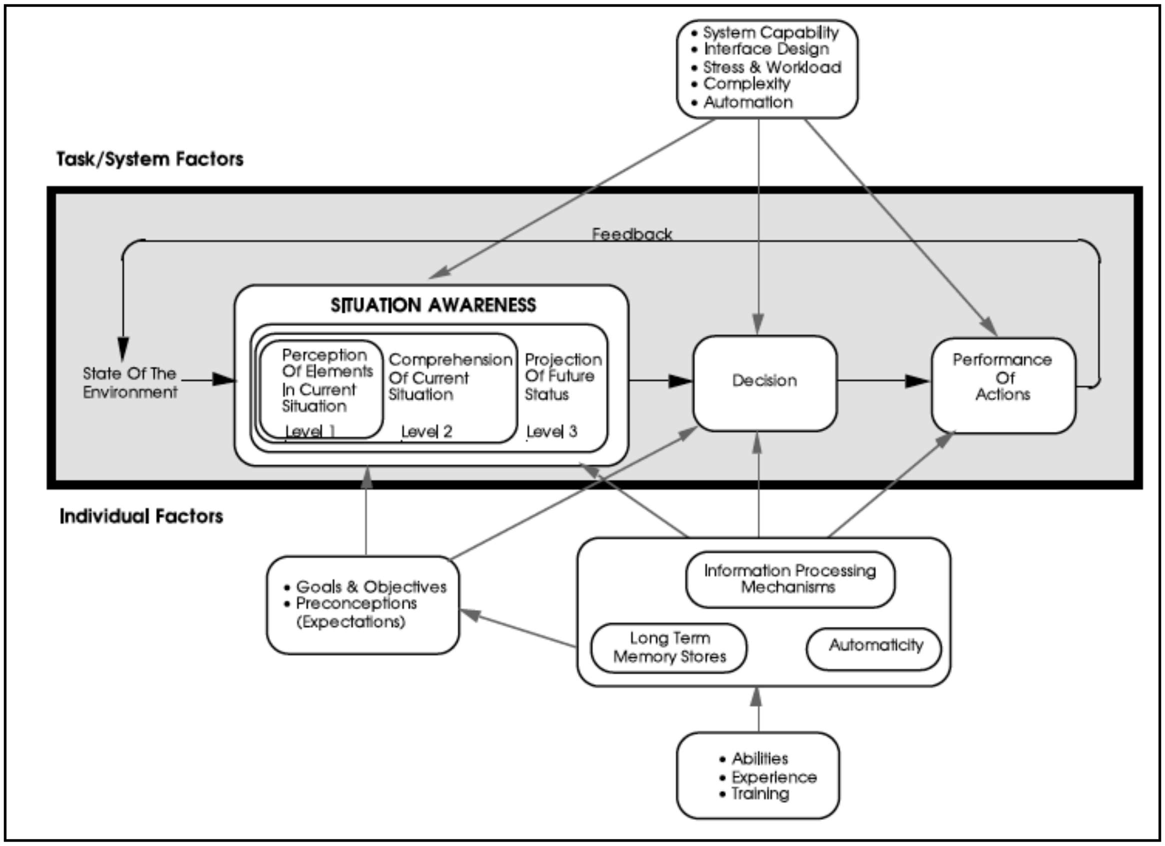

Figure 1-6. Endsley's model of dynamic decision making (Endsley, 1995)

Errors in situation awareness are defined based on which level in the SA taxonomy it originates in (D. Jones & Endsley, 1996). Level 1 errors occur if the human fails "to perceive information or misperceives information." Level 2 errors occur if there is "improper integration or comprehension of information." And Level 3 errors occur if there is "incorrect projection of future actions of the system." During a study conducted using Aviation Safety Reporting System Data, Level 1 errors accounted for 76.3% of SA errors in the events analyzed, followed by Level 2 errors (20.3%) and Level 3 (3.4%) errors. This information illustrates the criticality of Level 1 SA and distinguishes between cognition related to understanding and cognition related to projection.

Situation awareness has been used extensively to evaluate awareness of the mode of automation. The incorporation of automation has increased in reliability, but also introduced complacency into the cockpit (D. Jones & Endsley, 1996), some factors which may contribute to the monitoring (Level 1 SA) failures that have been seen. The following section discusses literature regarding mode confusion and flight path monitoring, possible contributors to divergence.

1.2.4 Mode Awareness Literature

Mode awareness in aviation systems describes the pilot awareness of aircraft configuration and auto-flight system modes (Sarter & Woods, 1995). If awareness is lost, problems such as automation surprise and mode confusion can occur. In addition to issues with understanding of automation, problems in monitoring have been discussed in the literature as a potential cause for mode confusion. The literature presented here relates to both the issues relevant to mode confusion as well as efforts to assess the potential breakdown of pilot monitoring (PM) in the flight deck.

1.2.4.1 Automation Surprise and Mode Confusion

The result of divergence in automation state has been captured in much of the literature on aircraft automation mode confusion, and is a continuing concern for aviation safety. *Automation surprise* occurs when actual behavior of a system departs from that predicted by its operator's mental model (Rushby, 2002). This surprise can affect human response possibly capitalizing human attention following the event (Dehais, Peysakhovich, Scannella, Fongue, & Gateau, 2015; Itti & Baldi, 2009). This attention focus on the automation could also detract from other basic flight control tasks of the crew, possibly evolving to have consequential effects (Dehais et al., 2015). In order to prevent the consequential effects of automation surprise, the causes of surprise were evaluated. McDaniel et. al proposes that surprise can emanate from a lack of sufficient information or knowledge and the basic dynamics of complex adaptive systems (McDaniel, Jordan, & Fleeman, 2003). *Mode confusion* is a specific type of automation surprise that occurs when the system is in a different mode than that assumed by its operator.

PARC and CAST highlighted issues in human-automation interaction in their safety report released in 2013 (Performance Based Aviation Rulemaking Committee & Commercial Aviation Safety Team, 2013). The findings of the PARC and CAST report reinforced previous research on mode confusion and gaps in understanding leading to automation surprise. For example, Sarter, Wickens, and Mumaw explored the concept of automation surprise and probed crew mental models subjectively during a simulator study with a B747-400 (Sarter et al., 2003). The results of this study, as well as a study by the U.K. Civil Aviation Authority (CAA) on flight crew reliance on automation, indicated that pilots had substantial gaps in their understanding of the automation (S. Wood, 2004). This is consistent with findings of Silva and Nicholson's analysis of operational events involving unreliable airspeed, a nonnormal situation that could be difficult to detect by the crew and can occur in various aircraft systems that use airspeed data (Silva & Nicholson, 2012). The analysis used Rasmussen's decision ladder to show that breakdowns in earlier stages in human information processing (detection and understanding), led to more consequential outcomes such as fatal accidents compared to breakdowns that occurred later in human information processing (decision making and execution). In addition to gaps in understanding, it has been suggested that breakdowns in perception can also influence mode awareness (Degani, 1996; Dreyfus & Dreyfus, 1979; McCrobie & Sherry, 1996; Sarter & Woods, 1995; Sarter, 2008).

Dekker suggests that the origins of mode confusion are tied to the interaction between components of the system (Dekker, 2008). In addition, the system safety Systems-Theoretic Accident Model and Processes (STAMP) concept discusses the existence of inconsistencies between the model of the process used by the controller and the actual process state (Leveson, Daouk, Dulac, & Marais, 2003; Leveson, 2011). Since perception and understanding have been shown to be highly influenced by design of displays and systems, and human characteristics such as attention allocation, training, and fatigue, it is important to assess mode awareness from a systems perspective, as opposed to purely a human perspective (Endsley & Kaber, 1999; Hegarty, 2011; Mccauley, 2001).

Because mode confusion can be influenced by feedback of the system, human observation of feedback, as well as understanding of the system, these are discussed in detail throughout the thesis. Pilot monitoring of flight parameters is discussed in the next section.

1.2.4.2 Identified Weakness in Flight Path Monitoring

Both the system and the human can be discussed when assessing flight path monitoring because perception by the human can be directly tied to the feedback the system provides to the human. (M R Endsley & Kaber, 1999; Hegarty, 2011; Mccauley, 2001). Between 2005 and 2014, there were 1706 deaths attributed to inflight loss of control (LOC) and 804 deaths attributed to controlled flight into terrain (CFIT) (The Boeing Company, 2014). Both of these classes of accidents can relate to problems in flight path monitoring (Flight Safety Foundation, 2014). In response, there have been many initiatives focused on enhancing the effectiveness of pilot flight path monitoring (Civil Aviation Authority, 2013; Flight Safety Foundation, 2014; Performance Based Aviation Rulemaking Committee & Commercial Aviation Safety Team, 2013).

The U.K. CAA identified a number of factors involving flight crew monitoring lapses (Civil Aviation Authority, 2013). These are represented in Figure 1-7. The factors involve aspects of the external environment, aircraft, organization, and human performance shaping. The CAA summary accounts for many factors outside the human that also affect monitoring lapses such as system reliability, schedules, and design. The human factors include a number of physiological, psychological, and personal influences.

More detail on the physiological and psychological factors is provided later in Chapter 2 when discussing human information processing and model of divergence.

Figure 1-7. Factors affecting monitoring lapses (Civil Aviation Authority, 2013)

The Flight Safety Foundation (FSF), PARC and CAST proposed various recommendations to address lapses in monitoring of the aircraft (Flight Safety Foundation, 2014; Performance Based Aviation Rulemaking Committee & Commercial Aviation Safety Team, 2013). Some of the specific recommendations in the FSF report included following standard operating procedures, aggressively managing distractions, remaining vigilant, and intervening if flight guidance modes or aircraft actions do not agree with expected actions. This last recommendation directly relates to recovering from divergence, which is discussed in detail throughout this thesis.

1.2.5 Summary of Literature and Research Contribution

1.2.5.1 Summary of Literature

A number of well-established aspects of human information processing exist in the literature. The general structure of the perception, cognition, action and action feedback to the environment is consistent between many of the information processing models (Endsley, 1995; Norman, 1988; Wickens & Hollands, 2000). In addition, it is also generally accepted that this system operates with limited resources. Wickens may consider attentional resources to be limited while Reason may argue that working memory is the limitation (Bellenkes et al., 1997; Reason, 1990; Wickens, 2002). In addition, models also mention how the cognitive system is driven by mental models in long-term memory. These dynamic models show prediction capability and builds on projection or expectation for the human.

Because some problems in mode awareness has been suggest to originate in human understanding, it suggests that development of a model that focuses situation awareness to awareness of state and provides more detail of how this awareness is formed would be beneficial in assessing how these problems could be alleviated.

Divergence can use these common elements established in the literature to develop an understanding of how the human state assumption is formed. Focusing on a state awareness as a specific type of situation awareness, a detailed understanding of the origins of the state assumption and the alignment with actual state could provide the ability to not only evaluate aspects of individual cases, but also identify patterns in groups of cases.

1.2.5.2 Research Contribution

While the previous systems mode confusion literature identifies inconsistencies in pilot understanding of system as a problem, this research puts forth divergence as an inconsistency between the human state assumption and the actual system state, and proposes a framework with which divergence may be better understood.

This thesis presents the concept of divergence (1) as a model that builds on the systems approach of Dekker and Leveson, (2) that incorporates the information processing theories of Wickens, awareness of state by Endsley, and LTM information retrieval modeling of Reason to develop a model of formation of the human state assumption (3) and can be applied to issues of mode confusion in the cockpit. This human information processing model of divergence can illustrate not only how divergence can occur but provide insight into why divergence occurred. Ultimately, this understanding of potential causes of divergence could provide supporting or dissenting evidence of current recommendations for addressing the negative consequences of poor human-automation performance.

1.3 Development of Concept of Divergence

The accident of Asiana 214 in 2013, shown in Figure 1-8 highlights the possible consequences of divergence. In this example, the crew interviews indicated that their assumption during the approach was that the auto-throttle system would capture approach speed, but in actuality the auto-throttle had defaulted to a dormant mode that maintained throttle position, which had been set to idle power (National Transportation and Safety Board, 2013). In this case, there was an apparent divergence between the state of the auto-throttle in actuality (HOLD mode[3]) and the crew's state assumption (likely SPD mode[4]). In this accident, while in HOLD mode and throttles at idle, the speed of the aircraft decayed below the pre-set approach airspeed. The analysis of divergence may explain the delayed crew response to this low speed situation. The crew eventually noticed the low airspeed, however was not able to recover in time to avoid impacting the sea wall short of the runway threshold.

Figure 1-8. Asiana 214 accident in San Francisco, CA in 2013

While it is possible divergence could occur frequently in-flight without resulting in significant safety hazards, accidents such as Asiana 214 reveal the potentially dangerous implications of divergence. This thesis suggests that divergence can play a role in aircraft accidents. If this is true, the understanding of the

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[3] In HOLD mode in the B777, the auto-throttle servos are inhibited and the pilot can set the throttles manually. In HOLD mode, the auto-throttle does not reposition throttle levers (National Transportation and Safety Board, 2013).

[4] In SPD mode in the B777, the auto-throttle maintains the selected speed displayed on the PFD, set by either the MCP or flight management computer (National Transportation and Safety Board, 2013).

mechanisms behind divergence could inform more effective mitigations that can prevent these potentially dangerous situations.

This thesis focuses on divergence in modern commercial aviation where the aircraft includes a complex integration of many sub-systems. It is assumed that pilots use both observation of continuous parameters, such as airspeed and altitude, as well as discrete parameters, such as autopilot (A/P) settings, to build a mental model of the system and control the aircraft. Assuming that control of the aircraft includes controlling continuous parameters as well as discrete parameters, flying can be described as a hybrid control task (Branicky, Borkar, & Mitter, 1998; Lygeros, Tomlin, & Sastry, 1997). The relevant parameters to the crew could change based on aircraft configuration as well as flight situation. When the actual system state transitions through different events, the human state assumption must also transition in order to maintain consistency with the actual system state. These dynamic characteristics of the system could provide more susceptibility to inconsistency between the system and the human in particularly due to these transitions.

The example described in Figure 1-3 illustrates an example of one classification of divergence where the actual state transitions and crew's state assumption is not updated to reflect the transition. Types of divergence are defined below.

- Type D-1: The actual state transitions and crew's state assumption does not update to reflect the transition.
    - Type D-1a: Actual state transitions without input by the crew.
    - Type D-1b: Actual state transitions due to input by the crew.
- Type D-2: The actual state does not transition, however crew's state assumption transitions
- Type D-3: The actual state transitions, and crew's state assumption updates to reflect a different transition.

The different types of divergence can be described by discussing a *divergence trigger*, which refers to the state transition (of the system or human) that initiates divergence. Because the trigger could have been the result of an input by the crew or the system, it is relevant to differentiate the trigger itself from the divergence origin. Divergence origin refers to the origin of the trigger (human or system).[5]

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[5] For example, in Asiana 214, the crew's abnormal use of FLCH along with a manual retardation of the throttles (origin) caused the automation to revert to HOLD mode (trigger).

Divergence can be further sequenced into two levels. The more significant level of divergence is referred to as *unknown divergence* where the crew is unaware that divergence has occurred. When in unknown divergence, the human can be expected to exhibit behavior based on an incorrect state assumption. Depending on the criticality of the situation, significant consequences could occur if this behavior based on incorrect assumptions results in discrepancies in flight path or energy management for example. The other level of divergence is referred to as *known divergence* and occurs when the crew becomes aware that their state assumption is not correct. This thesis assumes that once divergence is identified, the human works to resolve their confusion of the state of the system.

In some cases, the situation can recover from divergence and re-converge. This *re-convergence process* could involve known divergence as a precursor to re-convergence where the human knows that something is wrong, but not exactly what is wrong. The sequence of the entire divergence and re-convergence process is shown in Figure 1-9. If the situation begins with consistency between actual state and human state assumption, when divergence triggers, it is assumed that the human moves into unknown divergence.

The human could potentially move directly into known divergence if immediate awareness of divergence is attained, or the human could remain in unknown divergence for some time. Once the human recognizes an anomaly in the system of interest, she would move into known divergence where she troubleshoots the system to resolve the confusion. Once the confusion is resolved, it is assumed that the human re-converges with the system when their state assumption becomes consistent with the actual system state. It is possible that the re-convergence process first reaches known divergence before fully converging, though these stages could occur in a near simultaneous timeframe, or certain situations could yield re-convergence without the human actually recognizing divergence.

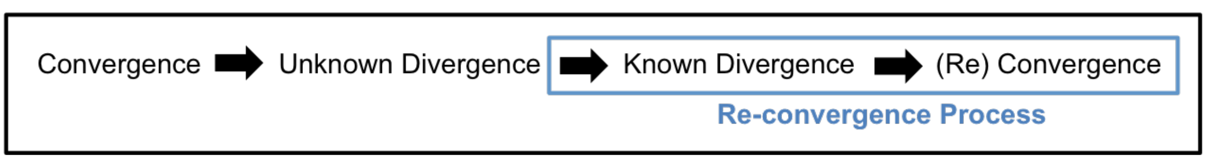

Figure 1-9. Sequence of divergence process

The transition from known divergence to re-convergence could occur in the following ways.

- Type C-1: Aircraft state transitions to meet the human state assumption.
- Type C-2: Human state transitions to meet actual system state.
- Type C-3: Both the aircraft state and human state assumption transition to a new state.

Known divergence does not necessarily involve a state transition, thus in this case trigger for known divergence is defined as the process that apparently recovers to result in known divergence. Similarly to divergence, a *re-convergence trigger* refers to the state transition (of the system of human) that results in re-convergence and the *re-convergence origin* refers to the origin of the re-convergence trigger.[6]

The types of divergence and re-convergence can be used to assess trends in the cases analyzed. Since the mental models inform the human state assumption, errors in mental models could cause errors in the human state assumption as previously discussed, however it may be possible to converge without a full recovery of the mental model. An example of this could be if the human had poor understanding of the automation (i.e. contributing to errors in the expectation process), but decides to disconnect the automation and bring the automation to a state consistent with one they know to be true. This would result in re-convergence type C-3 because the end result is consistency in between actual state and human state assumption. However, would not indicate a recovery of the mental model because, likely, the underlying poor understanding remained after the disconnection of the automation. This distinction between re-convergence and recovery of the mental model is important to remember when discussing mitigations for divergence.

1.4 Research Goals

This research suggests that divergence could be a contributing factor in a number of aviation accidents, particularly those involving automation mode confusion. With a proper understanding of the mechanisms behind divergence, we can be in a better position to understand causality and effectively mitigate these types of accidents. The overall goal of this research is to understand how divergence can manifest in aviation accidents, in order to inform mitigations to alleviate divergence before it occurs and/or promote re-convergence before the situation becomes unrecoverable.

In order to achieve this goal, the following sub-goals were defined:

- Develop a systematic method to identify sources of divergence in human information processing
- Use method to analyze divergence in case studies
- Discuss potential implications of divergence

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[6] For example, the human (origin) decides to disengage the autopilot (trigger) that results in re-convergence.

1.5 Thesis Organization

The remainder of this thesis evaluates the concept of divergence in aircraft operations. Chapter 2 introduces the proposed human information processing model of divergence. This model provides a hypothesis of how the human information process can influence the human state assumption and impact the occurrence of divergence. Chapter 3 explores the impact of failures in processes in the model and the effect of these failures on the occurrence of divergence. Chapter 4 uses the model discussed in Chapters 2 and 3 to evaluate case studies of accidents and incidents involving divergence. Chapter 5 discusses the implications of divergence and how it may inform mitigations to alleviate consequential effects of divergence. Finally, Chapter 6 summarizes the conclusions of this research, the contributions that have been made, and suggestions for future work in this area.

Chapter 2

Development of Human Information Processing Model of Divergence

The human information process of divergence was developed to understand causes of divergence by evaluating how the human state assumption is formed. Using this representation, causes of divergence can be represented in terms of process failures that lead to incorrect state assumptions. This representation can ultimately inform mitigations for divergence, some of which are discussed later in this thesis.

This chapter introduces a representation of human information processing that can be used to explain cases of divergence. Each aspect of the proposed representation is discussed including the indication system that presents feedback to the user regarding the state of the system. Within the human, processes related to the formation of a state assumption are introduced including the observation, association, state selection, expectation, and ambiguity resolution processes.

2.1 Description of Human Information Processing Model

Occurrence of divergence is normally associated with discrete events, such as a change in the actual state or the human state assumption. Within this thesis, an *event* is defined as a change in actual state, human state assumption, expectation, observables, or observation. An *event trigger* is defined as the transition (human or system) that initiates the event. Correspondingly, a *divergence trigger* refers to the event that initiates divergence, a *known divergence trigger* refers to the event that causes the human to transition into known divergence, and a *re-convergence trigger* refers to the event that signals re-convergence.

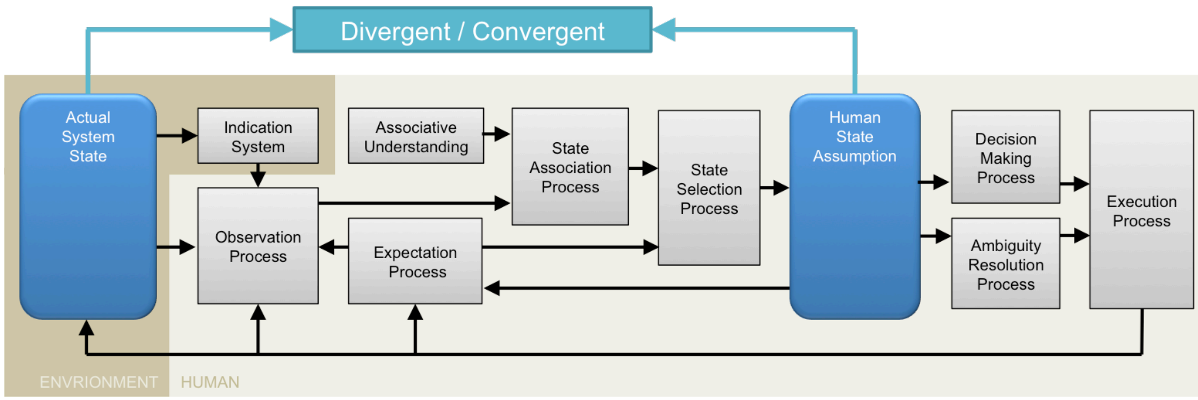

Figure 2-1. Human information processing model of divergence

Information flow through the human information processing system can be described using Figure 2-1. The human state assumption is considered to be formed from a series of processes , which incorporate the set of observations made of the actual system state and aspects of human experience.

If an event occurs due to a trigger such as a change in actual state, this change manifests in the actual system that outputs the actual system state. As seen on the left side of Figure 2-1, the actual system state feeds through an indication system where observables with which the human can make an observation are developed. Observables are perceived in the observation process, and the set of observations is input to the association process where they can be associated with particular states. The states that are consistent with the observation can fed into the state selection process for comparison with the human's expectation of state. The output of the state selection process is the human state assumption, which can be used to make decisions and execute those decisions. If no state assumption can be made, the information can then proceed to the ambiguity resolution process to resolve any confusion in state. It is important to remember that there can be uncertainty sources in each of the individual processes, and various assumptions are built into the model. These assumptions are mentioned in the discussion and also summarized in Appendix C.

The human information processing model of divergence was consistent with current work in the field of human information processing and adapted to incorporate specific attributes for determining human state assumption. The major process components in Wickens' and Endsley's models are included in human information processing model of divergence. Table 2-1 shows a comparison of the processes in each of the models and the corresponding process in human information processing of divergence in which those functions are included. The previous work presented and the model proposed have aspects of perception, comprehension, projection, decision-making, and execution. A difference between divergence and the previous work however, is that the human information processing model of divergence was developed specifically to discuss the awareness of state of a system, a subcomponent of situation awareness. It also introduces a comparator between the human and the environment to evaluate divergence.

Table 2-1. Comparison of common processes between the prior literature and the proposed human information process of divergence

Human information Process of Divergence	Information Processing Model (Wickens, 1992)	Situation Awareness (Endsley, 1995)
Observation Process	Sensory Processing and Store Perception	Perception
Association Process and	Working Memory - Cognition	Comprehension
State Selection Process	Working Memory - Cognition	Comprehension
Expectation Process	Working Memory - Cognition	Projection
Ambiguity Resolution Process	Response Selection	Decision Making
Nominal Decision Making Process	Response Selection	Decision Making
Execution Processes	Response Execution	Performance of Actions
System Understanding	Long Term Memory	Long Term Memory
Associative Understanding	Long Term Memory	Long Term Memory
Attention	Attention	Attention

2.1.1 Indication System

Prior to discussing the aspects of human information processing, it's important to discuss aspects of the environment that relate to system state and can input into human information processing. As mentioned in the example above, the actual system state is output by the actual system. Any change in the actual system state would constitute a triggering event. These could be in the form of mode transitions of automation systems, for example.

The inputs and outputs of the indication system are shown in Figure 2-2. As can be seen in Figure 2-2, the state is then input into an indication system. This system determines how the outside world, as part of the actual state and environment, is indicated to the human. These indications can be direct sensory aspects of the real world or they could be manufactured through a display. Within this thesis, *observables* are defined as indications that provide useful information to the human regarding the state of interest and the situation. In addition to observables relating directly to the state of interest, this process also can include information about the situation to the human. *Situation observables* refer to contextual variables that can be relevant to the situation such as phase of flight, position, aircraft configuration, or air traffic control (ATC) clearances. A change in observables can also trigger an event, as it provides different cues to the human regarding the state of the system.

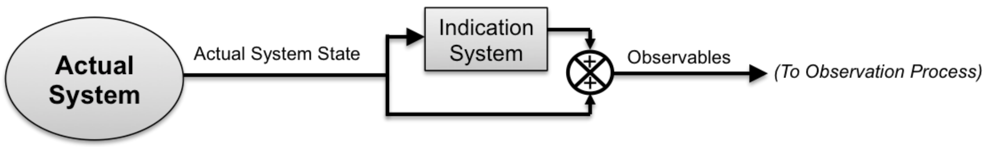

Figure 2-2. Depiction of inputs and outputs of the indication system

There are many characteristics of the indication system. While physical properties such as heat and smell from a fire provide information regarding state, many of these physical variables can be transformed and displayed to the human through displays and automation (Henderson & Hollingworth, 1999). Design of displays and automation as well as implementation of that design can also be important aspects within the indication system. These aspects can influence what observables are available, how they are provided, when they are available, and where observables are located. Design, for example, can impact observability and readability of an observable as well as influence the human's understanding of the system (Endsley, 1999). The observables output by the indication system can also provide varying degrees of discrimination between different states. Due to direct input into human information processing, integrity of the indication system can directly impact the integrity of human information processing. The individual processes are described in detail below, beginning with the observation process as the gateway between the system and the human.

2.1.2 Observation Process

The observation process is the process by which observables can be perceived and how new information enters human information processing system and is a critical basis for the human state assumption.

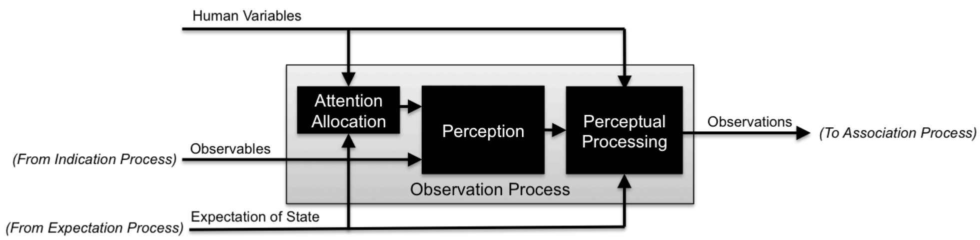

Figure 2-3. Depiction of inputs and outputs of observation process

For the purpose of this thesis, the observation process, shown in Figure 2-3, is considered to have stages of attention allocation, physical perception, and processing of that perceptual information. Attention can act as a filter for what information is actually perceived by the human (Bundesen, 1990; Wickens et al., 2003).[7] This can be a strong component of the observation process and can directly influence input into the other stages of observation. Once attention is allocated, perception can occur. This is a physical process that can use multiple senses. The information that is perceived then goes through a processing stage prior to becoming an observation where meaningful tags can be assigned to the observables (Hollander, 2000).[8] This specific description of stages of observation is specific to visual attention, however it is possible for olfactory signals to be perceived, for example, without attention being allocated, so the process itself can be adapted for the different signals that are input into the human information system.

A change in observation can also trigger an event since the state of the processing system could change based on this added information, possibly resulting in known divergence or re-convergence. On the other hand, its possible that had a mode transition occurred without observation from the crew, the mode transition could be the trigger for divergence. There are a number of reasons why observables are missed by the human, one example could be limits to attention.

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[7] There are a number of theories to how attention is allocated from single resource theory to multiple resource theory. This thesis does not use a specific theory; it only uses attention allocation as an influence into the observation process. Further work can be conducted to adapt this model to incorporate specific attention allocation or perceptual processing theories.

[8] An example of perceptual processing: perception itself may observe the numbers and patterns on an airspeed indicator, however the processing stage morphs that information into a reading on the airspeed indicator.

Attention allocation, a human variable referring to where attention is focused at a given time, is likely a major contributor to whether an observable is actually perceived (Bundesen, 1990; Hollander, 2000; Johnston & Dark, 1986; Summerfield & Egner, 2009). Whether attention is focused on an indication can influence the probability of it being correctly observed. Attention also can play a part in how other human variables influence the observation, such as when the human searches for information. Attention could be allocated to relevant observables if the human is performing a search for information using learned scan strategies, possibly increasing the probability of correct observation (Summerfield & Egner, 2009; Yu, Wang, Li, & Braithwaite, 2014). In addition, involuntary attention allocation could occur for specifically salient signals (Prinzmetal et al., 2010; Prinzmetal, Long, & Leonhardt, 2008; Prinzmetal, Zvinyatskovskiy, Gutierrez, & Dilem, 2009; Yantis, 2005). This illustrates some influences outside of the human, such as design of the system and feedback, on the probability of correct observation. Other human variables can decrease the probability that attention will be focused on the relevant observables. Fatigue could change or slow the scan of information, contributing to a lower probability of all observables being correctly observed (Boksem, Meijman, & Lorist, 2005; Caldwell, 2012; Faber, Maurits, & Lorist, 2012; May & Kline, 1987). While fatigue could affect all observables, workload can influence attention allocation to specific observables if attentional resources are being used in a non-related task. Levels of very high or very low workload may decrease the probability of correct observation of relevant observables (Lohse & Sherwood, 2011; Teigen, 1994). Distraction can operate hand in hand with workload if the human's attention is not focused on the task relevant to the state of interest (Broom, Capek, Carachi, Akeroyd, & Hilditch, 2011; Casner & Schooler, 2015; Dismukes, Young, & Sumwalt, 1998; Dittrich & Stahl, 2012). In addition to human variables, such as fatigue, workload, and distraction affecting the observation, scan strategies can be influenced by the human's expectation of the state of the system.

In some cases, the observation can be influenced by expectation bias possibly affecting the scan strategy of the human or influencing the integrity of values of observables (Jonas, Schulz-Hardt, Frey, & Thelen, 2001; M. Jones & Sugden, 2001; Kassin, Dror, & Kukucka, 2013; Summerfield & Egner, 2009). This could result in bypass of observables, which the human believes is known based on expectation or observables whose values provide conflicting information than is expected. Expectation bias can also influence perceptual processing by contaminating values/trends of observables based on what the human expects to see.

Perceptual processing can also be influenced by human variables such as fatigue or high workload. As the human approaches the limits of her human information bandwidth, fatigue or high workload could slow processing or introduce errors into the observables, possibly decreasing the probability of a correct observation of an observable.

Overall, this model discusses attention as a resource limitation in the information processing system. This is consistent with Wickens' interpretation of attentional limitations (Wickens & Hollands, 2000). Reason also discusses the limited resources in working memory (Reason, 1990). Reason's fallible machine also discusses filtering between the peripheral working memory into the focal working memory. This concept is captured in the model as attention in the perceptual processing stage prior to the transition to the association process. The aspects of attention discussed, introduce the possibility of error occurring in the observation process. Further discussion of these possible "failures" in the observation process is provided in the following chapter. Once the set of observations has been made, it can proceed into the association process and the human becomes one step closer to a human state assumption.

2.1.3 Association Process

Because of the possibly extensive array of observations from the environment and possible states in long term memory, it is considered that there could be an *association process*, which relates the set of observations to a set feasible states. The association process captures one aspect of retrieval of information from long term memory (Anderson, 1974; Khader, Burke, Bien, Ranganath, & Roesler, 2005; Shiffrin & Atkinson, 1969). Based on Reason's model, the association process performs the function of similarity matching of observations to states in long term memory (Reason, 1990).

The inputs and outputs of the association process are depicted in Figure 2-4. This association process, as modeled, inputs the set of observations and correlates those with possible states (built from the human's associative understanding). *Associative understanding* can be formed from prior experience and training and is used to signify the human's understanding of what observables are indicative of each possible state. This associative understanding can be compared to what is actually observed in order to output a list of states that are consistent with the set of observations.

Figure 2-4. Depiction of inputs and outputs of the association process

It may be possible for some observables to provide more distinct information than others. *Definitive observables* are defined in this thesis as observables, which, if correctly observed, provide unambiguous indication of the state of the system. *Indefinitive observables*, on the other hand, could be indicative of multiple possible states. This distinction can become relevant when discussing the observables available to the crew and whether observables were definitive in determining state of the system. Some situations can also lead to ambiguous sets of observables, where only indefinitive observables may get input into the association process.

The human's associative understanding can house the possible states of the system that the human is aware of and the indications associated with each of those possible states. While the knowledge representation of the human's associative understanding is not in the scope of this thesis, there is research that theorizes how knowledge is organized in long term memory (Baader, 1999; Darwiche, 2008; Davis, Shrobe, & Szolovits, 1993; Rasmussen, 1985; Schnotz & Kürschner, 2008). Semantic maps may be one representation that may be particularly relevant to the task of the association process. As a static process of comparing the set of observations to the associative understanding of what states the set of observations can be attributed to. One theory of semantic mapping of a static system suggests that understanding and relationships are organized by characteristics (Lambiotte, Dansereau, Cross, & Reynolds, 1989). This link may be appropriate for representing associative understanding. The indications would be considered as a characteristic of the state. Then these characteristics can be compared to the set of observations in order to determine states that are consistent with the set of observations.[9] The construct of associative understanding can also be represented using a simple deterministic example using Figure 2-5. The matrix illustrates the possible range of observations that would be indicative of each state for each observable. If the observations were tested to fit within the range of observables indicative of each state, this would result in a set of states where the observations were consistent with the associative understanding.

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[9] It may be possible that associative understanding is filtered to possible states only relevant to the state(s) of interest and feasibility given the observed situation. The actual dynamics of the association process are outside the scope of this thesis, but a rich area for further work

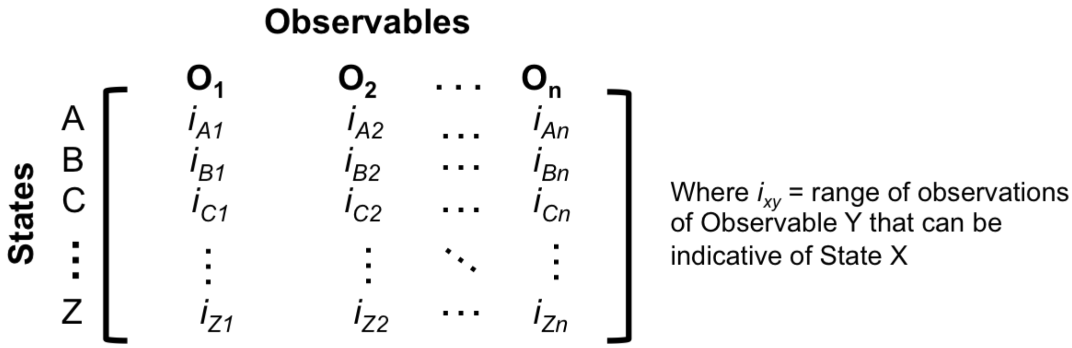

Figure 2-5. Generic form of example associative understanding matrix

The actual selection of possible states may be modeled in a number of different ways. While deterministic comparison of the observations to associative understanding may be a simple method to determine the possible states, this process could also be modeled as a Hidden Markov Process based on probabilities. Because the process is based on prior information (associative understanding) as well as observations, it can be thought of as Bayesian (Itti & Baldi, 2009). Once the association process completes, it outputs a set of states that are consistent with the observations. This is fed into the state selection process for comparison with the human expectation.

2.1.4 State Selection Process

The state selection process is the final process involved in determining the human state assumption. It's purpose is the integrate the information from the association process, expectation process, and possibly ambiguity resolution process in order to determine a human state assumption.[10] This process acts as an executive processor determining which state is assumed by the human using the similarity matching result from the association process and the frequency gambling result from the expectation process (Reason, 1990). It can also detect ambiguity if no result can be gained from either the association or the expectation process resulting in an ambiguous state assumption.

Thus, the state selection process can be modeled using expectation to reduce output of the association process to a single state assumption. In the case that a clear unambiguous state assumption cannot be

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[10] Since the ambiguity resolution process can be called to reconcile confusion if a single human state assumption cannot be determined. This definition is important to understand in the context of the state selection process, however the ambiguity process itself is discussed in detail in a future section.

formed, the process can signal the appropriate processes to resolve the lack of state assumption. Figure 2-6 illustrates the inputs and outputs of the state selection process.

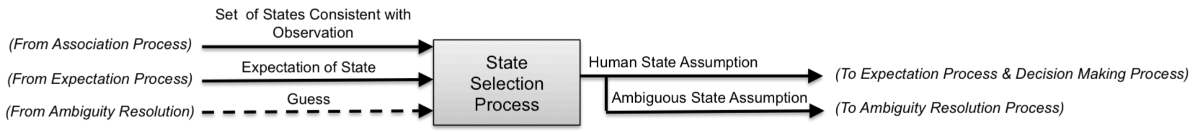
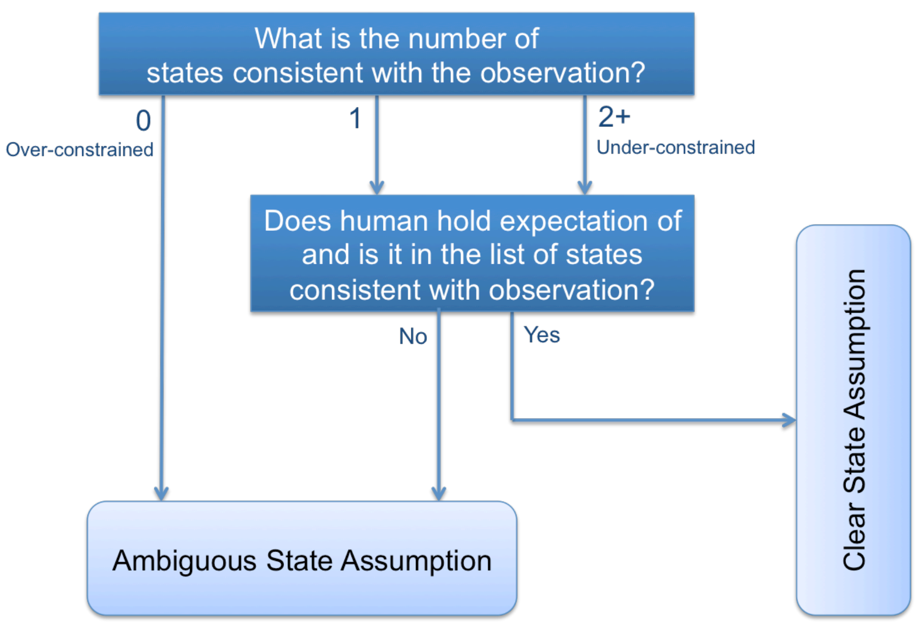


Figure 2-6. Depiction of inputs and outputs of state selection process

Human expectation has been discussed in the literature as a powerful influence on the situation awareness of the human (Deliza & Macfie, 1996). In order to integrate association process information with expectation process information, this thesis models their interaction using a decision tree, shown in Figure 2-7.[11] In particular, Reason's concept of frequency gambling was used here (Reason, 1990). Since similarity matching would have taken place in association, if the output of that process included multiple states, Reason states that frequency gambling would be used to pick between multiple states. If expectation were built on frequency of a particular state, this expectation would have priority in the state selection process. It was for this reason that a decision tree was chosen to illustrate that priority if one or more states were output from the association process.



[11] This thesis treats state selection simply as a deterministic process, however it may be possible in future work to incorporate uncertainty into the process for more realistic dynamics of this process. The decision tree has not been validated for failures in logic.

Figure 2-7. Decision tree of logic of state selection process

The state selection process inputs the states consistent with observation from the association process. The human state assumption can be clear or ambiguous based on how many possible states exist and whether the expectation is consistent with any of those states.

If there are zero states output from the state association process, this can cue the human to a situation that is ambiguous to the human, as the set of observations wouldn't fit within any states in associative understanding.

If there are multiple states output from the association process, this can constitute an under-constrained system. At this point, expectation was modeled to reduce the multiple possible states to a clear state assumption, if expectation were available. If expectation was not available, multiple states would signal an ambiguous state assumption as a clear state assumption cannot be ascertained. However, based on Reason's frequency gambling concept, if expectation is consistent with any of the states consistent with the observation, the expected state is considered to be selected as the clear human state assumption.

This brings up the possibility of the expectation not being consistent with any of the states consistent with the observations. This could cue the human to a discrepancy between their expectation and what she is observing. This could occur if a single state or multiple states are output from state association and can result in an ambiguous state assumption as the human works to figure out whether the observation or the expectation reflects the actual state of the system.

If an ambiguous state assumption exists, it is assumed that the human recognizes that divergence occurs and the situation moves into known divergence. This known divergence can prompt the ambiguity process to attempt to resolve the ambiguity and ultimately re-convergence

Figure 2-6 shows a possible guess input from the ambiguity resolution process into the state selection process. The details of this guess are discussed in the ambiguity resolution process section, however what is relevant for this section is if the result of the state selection process is to guess the state of the system. Within this model, if a guess exists, the decision tree logic in the state selection process is bypassed and the human state assumption is replaced with the guess in this model. This guess is assumed to be conscious and the human is aware of the divergence.

Since the output of the state selection process is the human state assumption, this information is now available for downstream processes. The expectation process also can use the human state assumption to reinforce or refute the current expectation of state.

2.1.5 Expectation Process

Lambiotte et al suggests that knowledge of dynamic systems may be linked through influences, temporal next steps "Next", or causation "Leads to" (Lambiotte et al., 1989). When assessing human's operational knowledge of state, the expectation process functions as a model the human uses to project current state into a future expectation of state. Figure 2-8 shows the inputs and outputs of the expectation of state process. This can be an important component of human information processing and is likely built from previous experience and understanding of the system. This initial expectation can be reinforced, refuted, or replaced based on the human state assumption, ambiguity of that assumption, or a possible action that was taken. (Bhattacherjee, 2001; Deliza & Macfie, 1996).

The dynamics of how expectations are formed, reinforced, or refuted are complex. Because the expectation process uses prior information of expectation and updates that expectation based on new information, it is possible that expectation could be modeled using Bayesian methods which estimates parameters of an underlying distribution based on an observed distribution (López Puga, Krzywinski, & Altman, 2015). It may also be possible to model expectation as frequency based, consistent with Reason's fallible machine. (Reason, 1990). This thesis does not discuss the specifics of how expectation is formed from system understanding. While the dynamics can be complex, for the purpose of this thesis, these dynamics are discussed in relevance to any action taken by the human in addition to ambiguity of the state assumption.

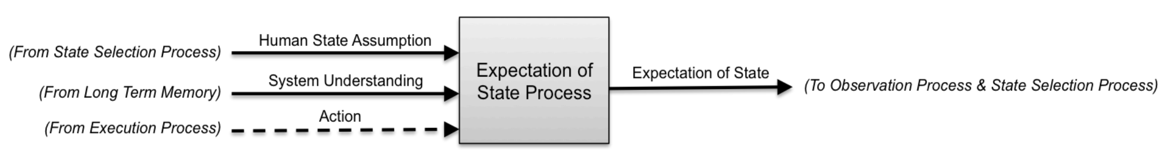


Figure 2-8. Depiction of inputs and outputs of expectation of state process

First, it is assumed that if the human takes an action, her expectation of state is updated to reflect the anticipated result of that action, triggering an event, regardless of whether the action was reflected in the environment or not, such as what could result with a slip.[12] If no action is taken that affects the state of interest where the expectation of state is updated to reflect the anticipated consequences of the action, the

[12] For example, it is assumed that when a pilot depresses the autopilot disengage button, her expectation is updated to reflect the outcome of that action, in this case that the A/P is disengaged, regardless whether the disconnect was actually registered by the system.

expectation process evaluates whether the human state assumption is inconsistent with the current expectation. This inconsistency can indicate to the human that there may be errors in the expectation she previously held and confidence in her expectation could decrease. For this thesis, it is assumed that if an ambiguous state assumption exists, confidence in the state expectation is degraded, and for the next event cycle, the human has no expectation of state.[13]

Finally, if the human has confidence in her state assumption, this state assumption can become the expectation of state for the next cycle of human information processing. If the state assumption equals expectation of state, the expectation of state can be reinforced. The cases without an ambiguous state assumption can appear in cases of re-convergence as well as unknown divergence, while cases with significant ambiguity can only appear in known divergence where the human is working to resolve the divergence. As was mentioned in the previous sections, expectation of state is output from the process and can feed back into the observation process and state selection process for the next event cycle.

In addition to feeding into expectation, if an ambiguous state assumption exists, information also inputs to the ambiguity resolution process, described below.

2.1.6 Ambiguity Resolution Process

The *ambiguity resolution process* occurs when an unambiguous state assumption cannot be output by the state selection process and the human results in known divergence. Figure 2-9 shows the inputs and outputs of the ambiguity resolution process. In addition to ambiguity, the ambiguity resolution process can be influenced by system understanding and attentional limitations. System understanding can provide a basis for a decision to be made, and attentional limitations can also have an effect on what resources can be directed towards the ambiguity resolution process possibly affecting the strategy of resolution and decision.

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[13] As mentioned, the relationship between ambiguity of a signal, reliance of a signal, and confidence in the expectation is a complex process. The relationship assumed in this thesis illustrates how the expectation interacts with the entire cognitive system, but further research can be conducted to evaluate the detailed dynamics of this process.

Figure 2-9. Inputs and outputs of ambiguity resolution process

Contrary to automatic or trained patterns of behavior found in convergent or unknown divergent processing, ambiguity resolution could be more cognitively difficult (Prinzmetal et al., 2009). Considering ambiguity resolution inputs may be atypical, processing could require substantial time or cognitive resources to fully identify the ambiguity (Klapproth, 2008; Wittmann & Paulus, 2008). Thus, the ambiguity resolution process could revert to heuristics in the face of limitations, such as high workload or resource limitations, to make a decision (Klein, 2008; Todd & Gigerenzer, 2000). While heuristics may be effective at solving a problem, it can also introduce error if an incorrect decision is made. This poor decision could propagate through the execution processes and affect expectation and the actual state. Depending on the dynamics, this could possibly reintroduce unknown divergence back into the system. It may also be possible for the human to accept that they cannot (or will not) fully resolve the ambiguity and force the system into a known state forcing re-convergence. This would result in Type C-3 re-convergence where the human may be take action in attempt to force re-convergence to a clear, known state, as opposed to take the time to conduct further observation to determine the actual state of the system.

There is the possibility that the human could revert to guessing the state of the system, as was mentioned in Section 2.1.4. This could occur in the presence of high workload or resource limitations as mentioned in the previous paragraph. Once a guess is made in the ambiguity process, it can be transferred back to the state selection process for direct transition into the human state assumption.[14] There is also the possibility the human chooses to resolve the ambiguity by scanning for more information; in this case, the decision can be fed downstream for execution, ultimately feeding back to the observation process as a search for more information (Reason, 1990). In addition to guessing or scanning, the human could also decide to

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[14] This transfer of the guess through the state selection process into the human state assumption is an artifact of the modeling. It could be modeled differently, such as directly feeding into the human state assumption, however then the assumption would need a process to discern two separate signals. This is why the state selection process and its logic was used to incorporate the guess and output to the human state assumption.

take action to resolve the ambiguity. In this case, the decision can also be fed downstream for execution, but in this case the action feeds back into the system (Endsley, 1995; Wickens & Hollands, 2000). Within the model of divergence, this action expectation also feeds back into the expectation process.

The exact method of ambiguity resolution is not within the scope of this thesis, but is relevant to the output of the process. We use the output of this process to determine further information flow through human information processing, as described above. The ambiguity resolution process can be considered as a problem solving process, however it is not the sole decision making process in human information processing.

While decision making processes and execution processes hold critical function in completing the feedback loop in human cognition, because this thesis focuses on the formation of the human state assumption decision processes (outside of ambiguity resolution) and execution processes are not described in detail. However, the output and feedback of the execution process are relevant inputs into some other human information processes such as expectation and observation, in addition to the possibility of manipulating the actual state of the system.

The result of the execution process could be an action to physically manipulate the system, communicate, or scan for information by manipulating attention allocation. While this output is driven by the decision, it is possible for slips to occur at this phase making the output different from the decision's intention (Norman, 1981). Regardless however of any errors, the output of the execution process can be fed back into the system via the action and communication, and can manipulate human variables such as attention allocation for executing an action or performing a scan, possibly triggering another event through change in actual state, expectation, or observation. These outputs can then be fed back to the respective areas in human information processing and environment. If physical action is taken, this execution can feed back directly into (a) the system possibly changing observables, (b) human variables controlling attention, and (c) the expectation process. If the human communicates, this execution can feed back into the environment providing another observable to the system. Finally, if scanning occurs, the execution process output can manipulate attention to conduct the scan. As can be seen, the effects of execution are widespread in the model. Also, in the context of this model, completion of execution can signify the completion of an event cycle.

2.2 Summary

This chapter introduces a human information processing model of divergence that was developed to evaluate causes of divergence by evaluating inputs to the human state assumption. This model introduces a representation of information processes that can form a human state assumption using a set of observations from the environment and previous experience of the human. This representation can also illustrate how divergence and re-convergence can originate as well as how known divergence can be resolved in the decision making process. This model highlights relationships between processes at a high level. The representation attempts to capture key human information processes influencing the human state assumption and divergence, however does not depict all of the inputs and outputs of each process. A representation of all of the inputs and outputs to each process can be found in Appendix B. Using this human information processing model, the next chapter assesses the impact of failures in individual processes, how these can result in unknown divergence, and how these failures can possibly be contained in other processes.

Chapter 3

Impacts of Process Failures on Divergence

The previous chapter described the basic processes involved with human cognition related to divergence. It may be possible for discrepancies to exist in the inputs and outputs of these processes. If a process produces incorrect or contaminated output, the process can be considered as failed. It is possible that failures could be contained in downstream processes, which, in some cases, could be inconsequential for the human state assumption and result in re-convergence despite a failed process.[15] Containment of process failures discussed in this thesis refers to occurrences where a failure is trapped in a downstream process resulting in either re-convergence or known divergence. Containment of failures when the human is in known divergence is discussed later in this chapter and would in this case refer to trapping of the failure that results in re-convergence only. Containment does not imply mitigation of the process failure or divergence, only that failures could be trapped within human processes to avoid a case of unknown divergence.

As discussed in Chapter 1, human error refers to inappropriate action for a given situation. This thesis suggests that some aspects of human error can be explained by divergence and the human taking action based on a false state assumption. The end of this chapter places divergence within the current frameworks used to describe human error. Assuming that divergence can be caused by failures in one or more of the individual processes described in the previous chapter, the causes of divergence can be evaluated by assessing the impacts of different types of failures on each of the individual processes. Some of these failures may lead to unknown divergence, while others may not. This chapter assesses the potential failures of processes and discusses the impact as well as possibility of containing the failure in downstream human information processes using the human information processing model discussed in

[15] An example of inconsequential failure can be seen in a case when the human observes only that the airspeed value is on target and concludes correctly that the auto-throttle is in SPD mode. Despite a missed observation of the FMA, for example, this observation process failure does not result in divergence.

the previous chapter and reproduced in Figure 3-1. The delineations between environment and human are removed from this figure for simplicity. With the understanding of the impacts of the failures, mitigations can be designed to address them.

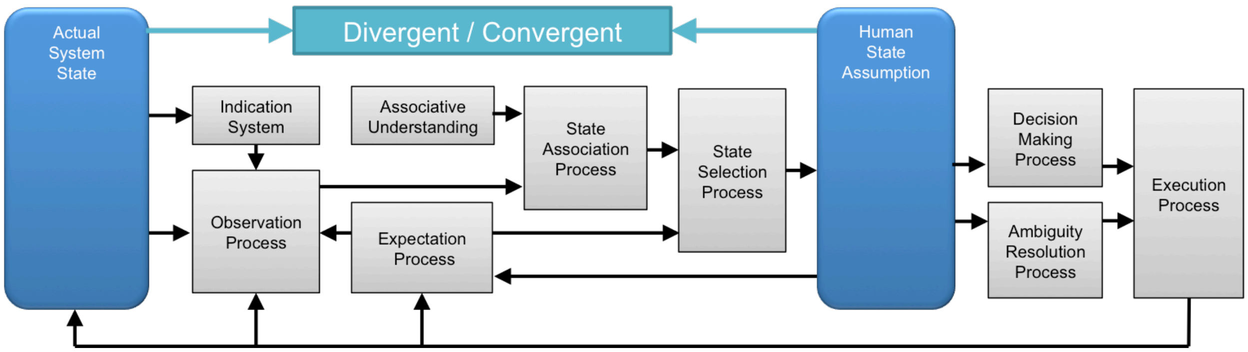
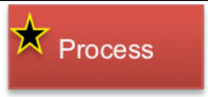
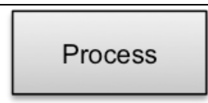
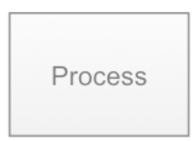


Figure 3-1. Human information processing model of divergence

In order to display propagation of human information process failures, the notation shown in Table 3-1 is used. Upstream and downstream processes are defined relative to the process being discussed. Upstream processes refer to processes that input (directly or indirectly) into the process of consideration. Downstream processes refer to processes that output (directly or indirectly) from the process being discussed. If a failure is apparent in the process it is highlighted in bright red and a star. Since failures can propagate downstream, the process box is highlighted light red if it is affected by a failure upstream, but shows no indication of a failure originating in that process. Finally, if there is a failure upstream, but it is contained in a downstream process, a bar is shown on the right side of the process that contains the failure; a red bar indicates result of known divergence and green bar indicates possible result of re-convergence. In addition to the color of individual process boxes, the human state assumption is also colored based on whether the system indicates re-convergence or divergence. The box is highlighted red if the result is known or unknown divergence, green if the result is re-convergence, and blue if the result could be either re-convergence or divergence.[16]

[16] The result is ambiguous in the context of the discussion of containment of failures because the outcome is dependent on the details of the problem itself. Depending on the states and expectations it could be that in some cases the process can result in known divergence, while in other cases it can result in re-convergence.

Table 3-1. Notation used in human information processing model

Symbol	Meaning
	Failure in process
	Process affected by failures upstream
	Process where a failure may or may not exist
	Process in which an upstream failure is contained and results in re-convergence
	Process in which an upstream failure is contained and could result in known divergence
	Process which is not active during the event
	This block is highlighted red if the human state assumption is corrupted by failures in processes
	This block is highlighted green if the human state assumption is not corrupted by failures in processes
	This block is highlighted blue if the human state assumption could result in re-convergence or divergence

3.1 Failures in the Expectation Process

Figure 3-2 depicts the potential propagation of expectation process failures. As can be seen by the output arrows from the expectation process, failures in the expectation process can influence both the observation process and the state selection process. Failures in previous experience and training could lead to an incorrect mental model of the system with which expectations are formed. It is also possible for the actual system to transition into an abnormal state, triggering an event. In these cases, the human's expectation may be nominal, but the actual system state may be off nominal. Finally, current divergence can also propagate into the expectation process reinforcing an incorrect expectation.

Expectation failures could impact both the observation process and the state selection process and can be difficult to trap because of this characteristic. The feedback to the observation process would likely occur in the form of expectation bias, possibly manipulating the scan strategy or corrupting the values of observations. As can be seen, this failure would propagate into the state association process and the state selection process. Nominally, the observation failure could be trapped in the state selection process if the expectation were correct, however the state selection process is also affected by the incorrect expectation. This characteristic would lead to the inability to contain an expectation failure that corrupts both the observation and state selection processes downstream, which can ultimately result in unknown divergence.

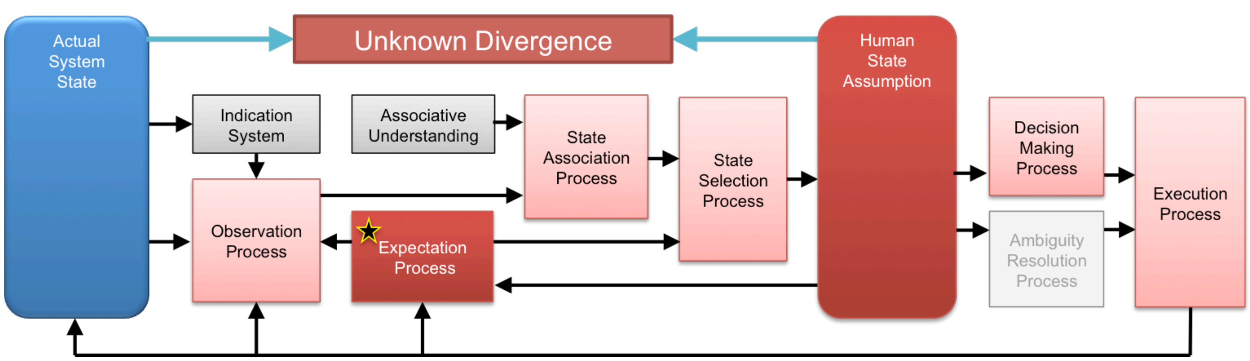


Figure 3-2. Possible propagation of expectation process failure

3.1.1 Containment of Expectation Process Failures

While the negative impact of the expectation process failure on both the observation process and state selection process would lead to unknown divergence, it is possible that if one of those biases can be overcome that the expectation process failure could be effectively contained. The state selection process is dependent on the integrity of both expectation and association (and observation processes upstream). Thus, both inputs to the state selection would be corrupt with an expectation process failure. This characteristic indicates it may not be an effective process to recover to overcome the influence of an expectation failure. The observation process, on the other hand, includes an input from the indication system as well as the expectation process. If the indication system remains unaffected by a failure, it could provide information to the observation process that could overcome the expectation bias. Figure 3-3 illustrates the human information processing model if the observation process recovers triggering an event that results in known divergence. This recovery would feed downstream into the association process and likely provide uncorrupt information to the state association process. Thus, a discrepancy between the states consistent with the set of observations and the expected state would trigger known divergence and the expectation process failure could be contained in the state selection process.

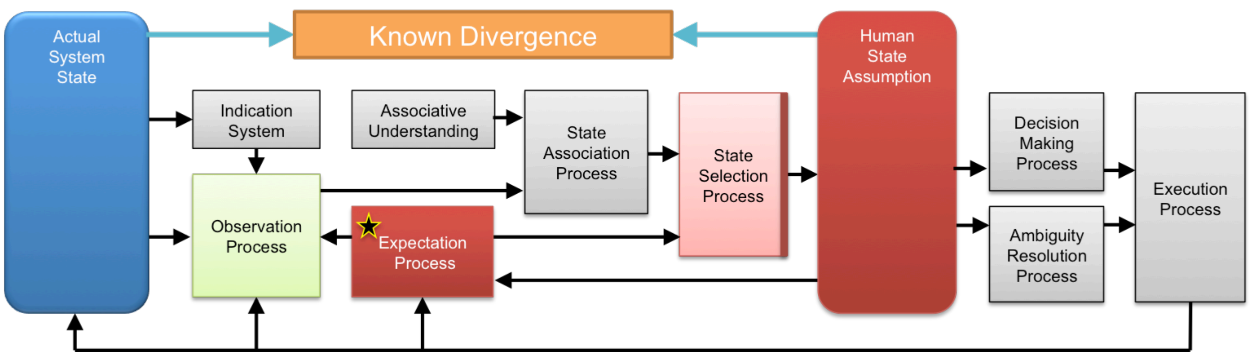


Figure 3-3. Containment of expectation process failure in state selection process

3.2 Failures in the Indication System

As mentioned, the indication system provides another input (alternative to expectation) into the observation process. It is possible however, for the indication system to provide false input to the human, contaminating input into human information processing. Examples of failures of the indication system include the burning out of a landing gear light bulb, a false indication of an error message, or false readings on an instrument. The above examples could originate from component failures, environmental factors, or possibly from design of the system.

Figure 3-4 illustrates the possible propagation of an indication system failure through the human information processing system of the human. If the landing gear light bulb burned out for example, this information, indicating that the landing gear was not deployed when it actually was deployed, would enter human information processing through the observation process.[17] Once it reaches the association process, this observation of no landing gear light annunciation should be associated with the landing gear not being deployed. If the expectation is also incorrect, then this failure would propagate through the state selection process causing unknown divergence. If this indication failure, for example, occurred following takeoff, it may be possible to overspeed the landing gear if the crew did not realize it remained deployed, illustrating the possible consequences of an indication system failure.

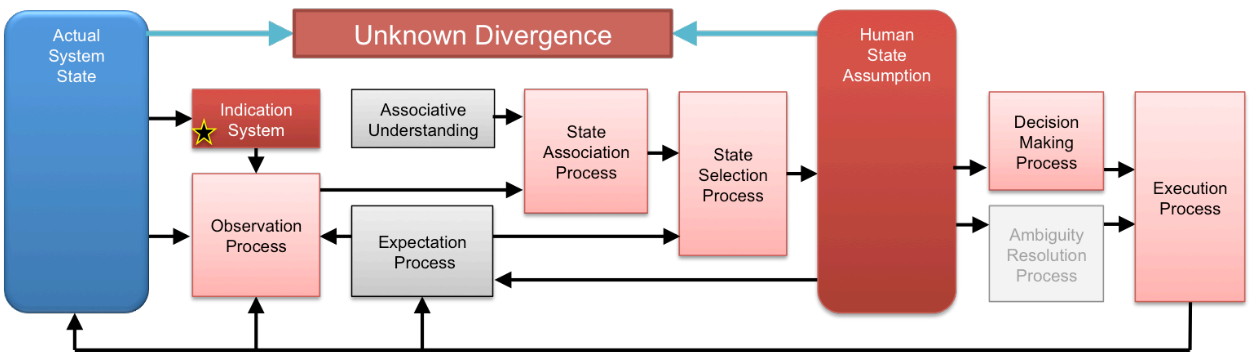


Figure 3-4. Potential propagation of an indication system failure

Section 2.1.3 discussed how observables can be categorized into two groups, definitive and indefinitive, depending on the extent of defining information they provide for the state. The critical aspect in terms of containment of indication failures is not the availability of a specific type of observable, but the availability of any one or more observables unaffected by the failure.

3.2.1 Containment of Failures in the Indication System

When one or more observables exist that are unaffected by the failure in the indication system, this provides the capability to error check the indication. This error checking can occur in the association process when the set of observations is compared with the human's system understanding. Figure 3-5 illustrates the possible containment of the failure in the association process. If the set of observations includes at least one failed observable and at least one correct observable, when compared with an intact associative understanding, a discrepancy should become apparent. It is possible for no states to be

[17] In this example, assume the landing gear annunciation system consists of one light that illuminates when the landing gear is down and locked and extinguishes when the landing gear is not down and locked.

consistent with the opposing set of observations. If no states are consistent with the set of observations, the unknown divergence would be trapped in the association process, known divergence can trigger, and the human can move into the ambiguity resolution process.

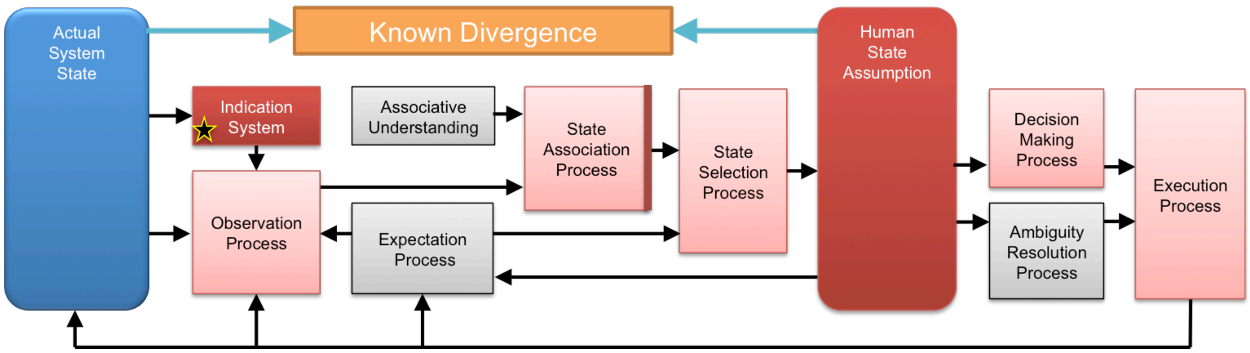


Figure 3-5. Containment of an indication system failure in the association process

If one or more states are consistent with full set of observations, they cannot be trapped in the association process and the next possible place for containment is in the state selection process. This can be seen in Figure 3-6 and would occur if expectation of state is correct.[18] If a correct expectation of state exists, the decision tree logic can identify that the states consistent with the observation conflict with the expectation, triggering an event resulting in known divergence and incorporates ambiguity resolution process. Initial containment of an indication system failure in the association or state selection process can result in known divergence. When in known divergence, the human can work to resolve her ambiguity.

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[18] The logic of the state selection process suggests that it is also possible to trigger known divergence if expectation is incorrect and still not consistent with any of the states output from the association process. For the purpose of addressing divergence however, this thesis places emphasis of having a correct expectation.

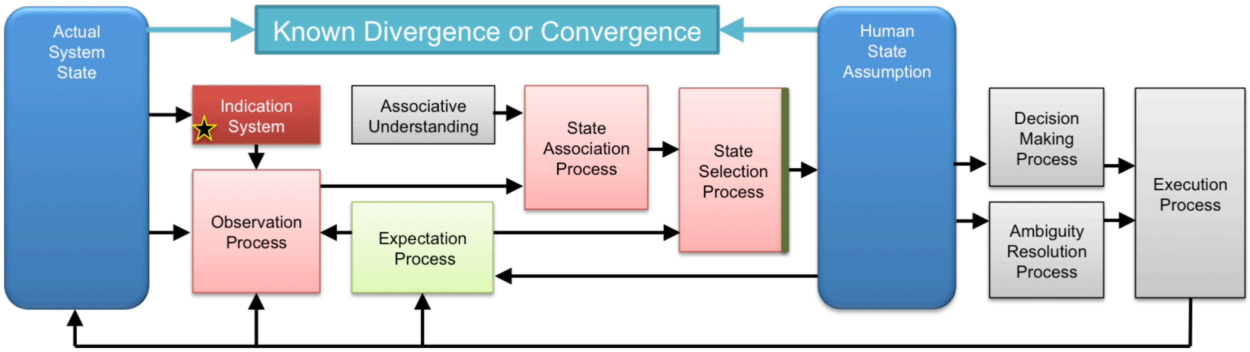

Figure 3-6. Containment of an indication system failure in the state selection process

The case of containment shown in Figure 3-7 is a more trivial case. The indication system failure can be trapped in the observation process if the human makes a correct observation of any correct observable and bypasses the input of the failed observable. This forces only correct information to propagate into the association process and further downstream, and the indication system failure is contained in the observation process. The above containment discussion is dependent on at least one correct observable being available; containment characteristics change if there are no correct observables available to the human.

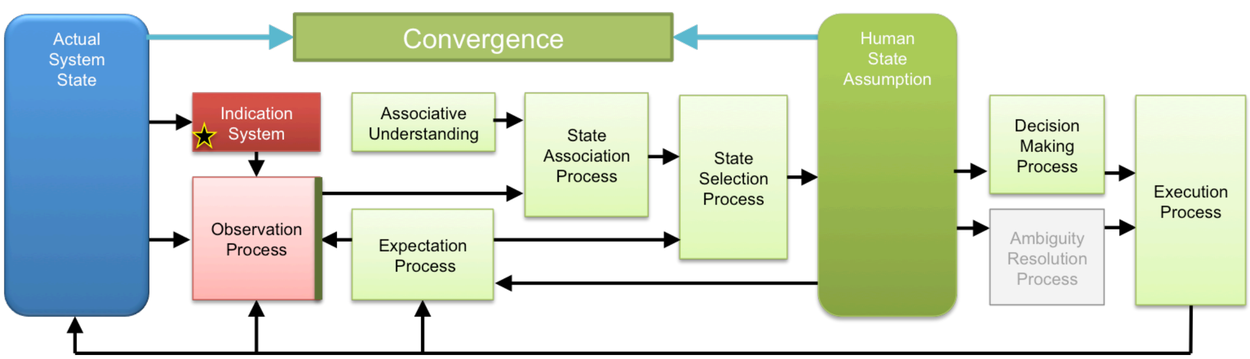

Figure 3-7. Containment of an indication system failure in the observation process

As mentioned, there is the possibility that indication system failures contaminate all observables and no correct observables are available with which to trap the failure. For this case, the failure can propagate through both the observation and association processes downstream. Referring back to Figure 3-6, the model suggests that the only possible containment of this failure would be in the state selection process. The decision tree logic would likely trigger known divergence, since the expectation would be inconsistent with the states consistent with the set of observations. As is suggested by the fewer opportunities for containment, an indication system failure that leaves no observables intact could be more susceptible to unknown divergence.

3.3 Failures in the Observation Process

The previous section discussed possible failures in the indication system. These failures could propagate into the observation process, however the topic of this section discusses failures that originate in the observation process. Even if observations are made, a failure in the observation process can result in some observables being missed or corrupted. Missed observations can be characterized as errors of omission, while corrupt observations characterize errors of commission, since values of observations are perceived incorrectly due to physical or environmental reasons, or expectation bias (Spranca, Minsk, & Baron, 1991; Tversky, Kahneman, & Slovic, 1974). Many aspects can influence how this can be observation made.

The effectiveness and accuracy of the downstream processes can be influenced by the observation process. While aspects of information search and proper scanning can increase the chances for correct observations by appropriately allocating attention, there are a number of human and design aspects that could interfere with correct observation. Salience of a signal can influence attention allocation and influence the probability of an observation being made (Nikolic et al., 2004; Wickens et al., 2003; Yantis, 2005). High salience signals can promote correct observation of the salient signal due to attention capture, however if salience of a signal is low compared to the background noise, such as clutter in the visual mode or engine noise in the aural mode for example, it could possibly decrease the probability of correct observation. This aspect specifically can be a result of design of the indication system, however it can develop as a failure in the observation process since, in the point of view of this model, the result is that the human has a missed observation.

Human variables can also influence failures in the observation process, possibly effecting attention allocation and perceptual processing. Fatigue can affect scan and can decrease probability of correct observation (May & Kline, 1987; Rowland et al., 2005). Workload and distraction can also affect probability of correct observations. Situations with very high or very low workload could be detrimental to making a correct observation (Grier et al., 2003; Teigen, 1994). Distraction from the state of interest can also be detrimental to the chance of making a correct observation likely due to attentional resources being assigned to areas not relevant to the state of interest (Bellenkes et al., 1997; Bundesen, 1990; Hollander, 2000; Yantis, 2005).

Finally, expectation bias can also influence where attention is allocated. If the human is confident in their expectation, they may not scan all observables carefully, possibly relying on expectation to form a state assumption. It is also possible that expectation bias could introduce corruption into perceptual processing of the observations potentially corrupting the value of observables (M. Jones & Sugden, 2001; Klayman, 1995; Lehner, Adelman, Cheikes, & Brown, 2008; Nickerson, 1998). In this case, the confirmation bias aspect of expectation bias is relevant. The confirmation bias, as discussed, can result in the observation process being biased towards selectively processing information that confirms the human's expectation.

These influences are not an exhaustive list of aspects influencing failures in the observation process, however these examples were discussed to illustrate how different aspects could potentially influence the observation process positively or negatively. The potential propagation of an observation process failure can be seen in Figure 3-8. In these cases, we are concerned with the output of the observation process and how failures could potentially propagate through human information processing affecting association and state selection. This failure can eventually reach the human state assumption, possibly resulting in unknown divergence. The next section discusses opportunities to contain an observation process failure.

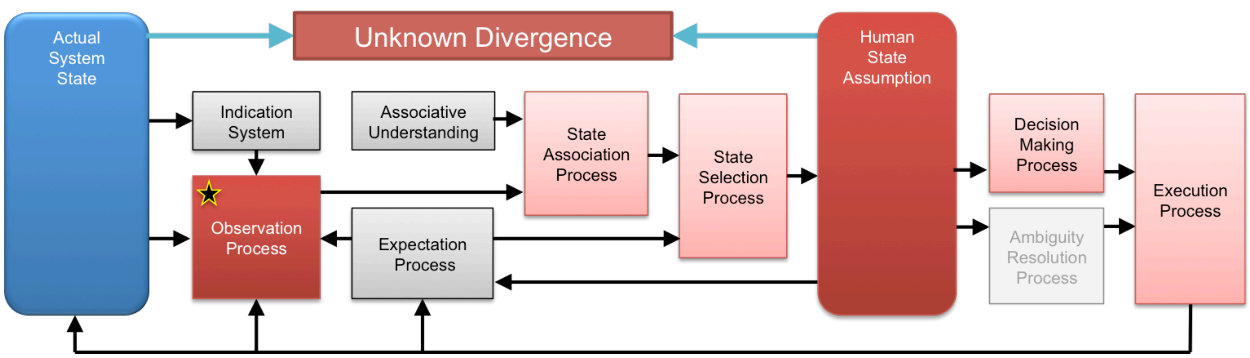

Figure 3-8. Potential propagation of observation process failure

3.3.1 Containment of Failures in the Observation Process

If an event occurs due to change in actual state or change in observables, missed observations or corrupt observations can occur due to failures in the observation process. These could potentially be trapped in the downstream processes. If these observation process failures occur without any failures in the association process, it may be possible to contain if least one definitive observable is observed correctly. Figure 3-9 illustrates the possible containment in the association process if a correct association using that single definitive observable could be made. In this case, the failure of other individual observables would not impact any processes further downstream than the association process as it is contained there resulting in re-convergence. These types of failures likely commonly occur and can be used as a strategy to perform faster processing of information (Reason, 1990).

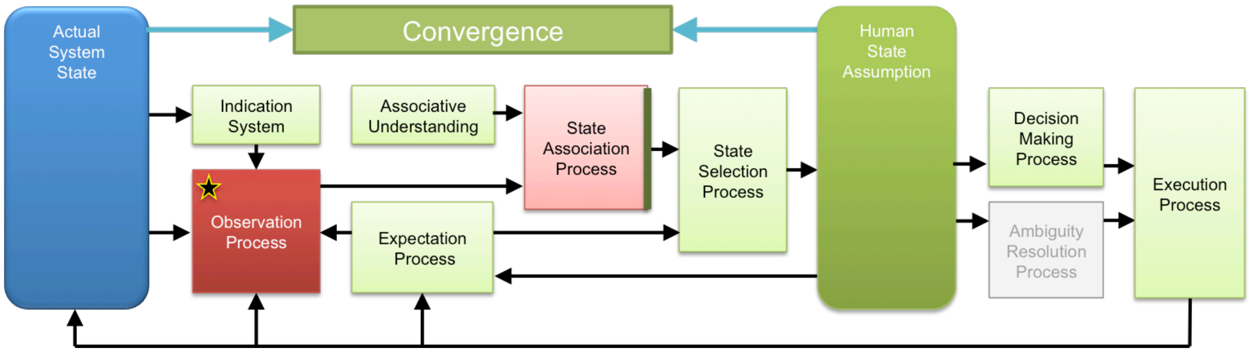

Figure 3-9. Option 1: Containment of observation process failure in the association process

It is possible that failures in misperception, for example, can also be caught if the association process outputs no states that are consistent with the observation.[19] This containment in the association process is shown in Figure 3-10. The result of this containment, is an event caused by a change in the human state assumption to an ambiguous state assumption, and would trigger known divergence ambiguity resolution. If a failure is not contained in the association process, there is a possibility it could be contained in the state selection process.

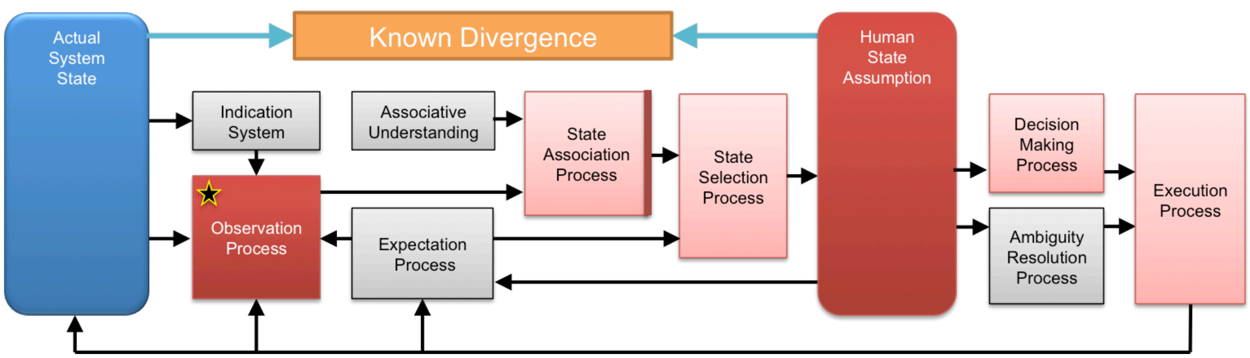

Figure 3-10. Option 2: Containment of observation process failure in the association process

[19] The possibility of containment in the association process due to no states consistent with the output can be a trivial case depending on the failure or combination of failures. In this case, it is possible that the observation process failure is different enough from what would have been observed that no states could be associated. This is a powerful avenue for containment and can possibly avoid the effects of expectation bias.

In the case that one or more states are output from the association process, and includes incorrect states due to failure in the observation process, it may be possible to contain the observation process failure in the state selection process. This containment is shown in Figure 3-11. This again can occur if expectation is correct. The discrepancy between the states consistent with the flawed observation and the expectation of state would likely appear at this stage, forming an ambiguous state assumption and triggering known divergence.[20]

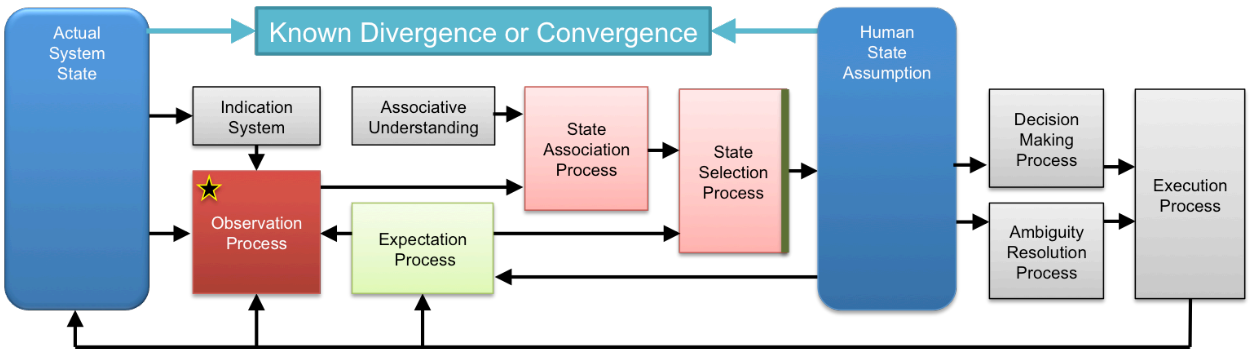

Figure 3-11. Containment of observation process failure in state selection process

3.4 Failures in the Association Process

Failures can originate in the association process due to problems in associative understanding or ambiguity in the set of observations. Each of these failures is discussed below.

3.4.1 Problems in Associative Understanding

Breakdowns in associative understanding are one form of failure of the association process. Figure 3-12 shows the possible propagation of problems in associative understanding. Since the associative understanding is directly used in the association process, problems can propagate directly into the comparison conducted in the association process. The failures discussed below can possibly be attributed to training or experience problems. If a failure in associative understanding occurs, it can occur in a number of different ways.

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[20] It is also possible to trigger known divergence if expectation is incorrect and still not consistent with any of the states output from the association process. For the purpose of addressing divergence however, this thesis places emphasis of having a correct expectation.

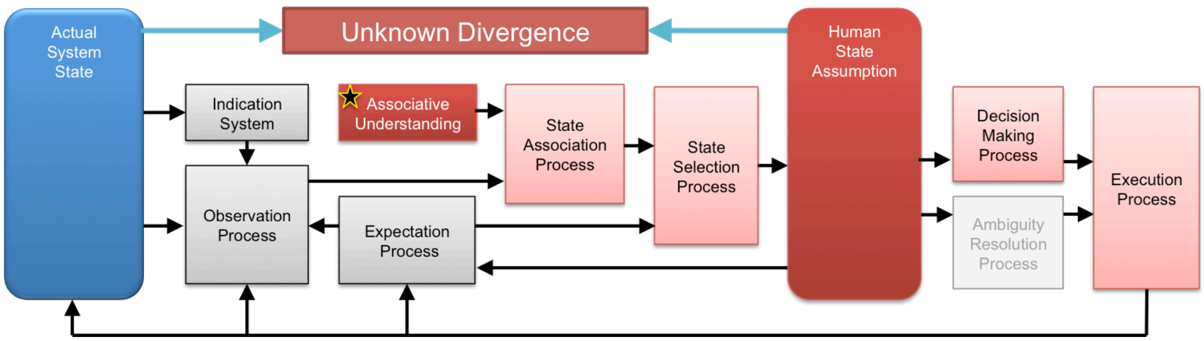

Figure 3-12. Possible propagation of associative understanding and association process failure

The following are examples of failures in associative understanding that would affect the association process.

- Missing knowledge of a state can be caused by lack of exposure to or experience with the state.
- If a state occurs outside of its nominal situation, it's possible that the human may not call that state for comparison.[21]
- Missing association of individual indications of a state could also be attributed to lack of experience associating the indication with the particular state.
- Incorrect understanding of indications for a particular state occurs when the human understands a certain observable is important for determining the state, however the value/trend of that observable is incorrect. This can be caused by possible training deficiency or other experience effects.[22]

As can be seen failures in associative understanding could occur in a number of different ways in the association process. These failures could be compounded if there are situations of high ambiguity that also influence the association process.

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[21] Example: RETARD FLR is a mode on the MCP that is only typically associated with the final approach phase of the flight, so the human may not consider this as a possible state if the situation was in cruise.

[22] Example of incorrect knowledge of indications: This could occur if the human believed that the SPD indication on the MCP was associated with the Retard Mode (when in actuality, SPD would be associated with Speed Mode).

3.4.2 Ambiguity in the Set of Observations

Ambiguity in set of observations refers to cases where individual observations made are exclusively of indefinitive observables. This can disable the association process from identifying a single state that is consistent with the set of observations contributing to the failures. This potential propagation of ambiguity of observables is shown in Figure 3-13. These can then propagate downstream.

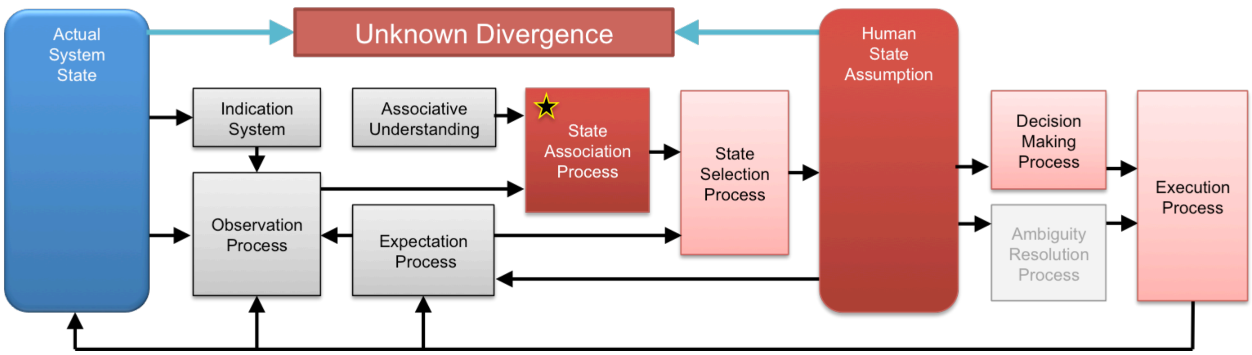

Figure 3-13. Possible propagation of association process failure due to high ambiguity through human information processing

Ambiguity in a set of observables can be a result of the situation, or a result of the design of the system (Sherry, Feary, Polson, & Palmer, 2001).[23] Ambiguity of set of observations and problems with associative understanding can be contained in similar manners that are discussed in the next section.

3.4.3 Containment of Association Process Failures

The state selection process has the potential to trap association process failures caused by both problems in associative understanding and ambiguity in the set of observables.[24] Potential containment of both

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[23] An example of ambiguity due to situation could be the crew initiating a descent with a vertical speed mode, but the automation transitioning into an IDLE mode. In this case, the nominally definitive observables can become indefinitive if they no longer providing distinguishing information regarding state. An example of ambiguity due to system design could be two different modes in the autopilot, which provide no distinguishing information between the two.

[24] Technically, for cases of problems in associative understanding, it is possible to trigger known divergence in the association process if the understanding problems are so severe that no states are

sources of association process failures in the state selection process is shown in Figure 3-14 and Figure 3-15. For problems in associative understanding, if the output of states is incorrect, the failure has the potential to be trapped in the decision tree logic of the state selection process. If expectation of state is correct, these incorrect states would not be consistent with the expectation, likely triggering known divergence. In addition to problems in associative understanding, ambiguity can also be trapped in the state selection process in a similar way if expectation is correct.

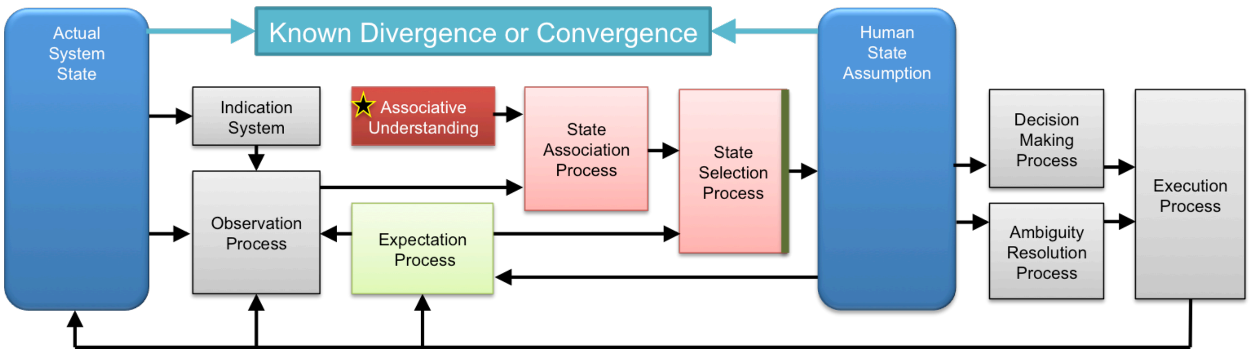

Figure 3-14. Containment of association process failure due to problems in associative understandings in state selection process

As mentioned, ambiguity in the set of observations can result in an under-constrained system, where association process outputs multiple states that are consistent with the observation. The possible containment of the association process failure is shown in Figure 3-15. This failure can be contained in the state selection process if the expectation is correct. The result would be re-convergence if the actual state is in the list of states consistent with the observation, while known divergence would result if the expectation is not included in the list of states consistent with the observation. Containment of association process failures, if not trapped in the state selection process, would not technically be possible in the context of the model, since the state selection process is modeled as the last line of defense between the association process and the human state assumption.

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consistent with the set of observations. However, this is a rather extreme case and less relevant when discussing ways to contain these failures.

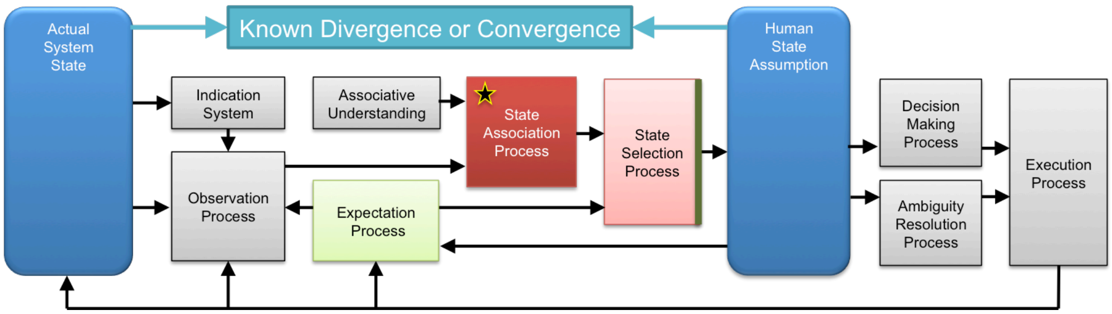

Figure 3-15. Containment of association process failure due to high ambiguity in the state selection process

3.5 Failures in the State Selection Process

A consequence of modeling the state selection process with decision tree logic is that this process becomes purely dependent on upstream input. Considering that failures could not originate here, the state selection process is only discussed as a process that can be influenced by upstream failures or a process where failures could be contained. It should be noted that in this is a simplistic modeling of the state selection process and is purely deterministic. However, with future work this process could be developed to be more realistic of uncertainty in human cognition and test whether internal failures such as within the logic could occur.

3.6 Failures in Processes when in Known Divergence

Known divergence can be signified by an ambiguous state assumption. This ambiguity can influence both the expectation process as well as the ambiguity resolution process. Both processes are described below in the context of containment of process failures.

3.6.1 Impact on the Expectation Process

When the human knows a divergent condition exists, it can be reasonable to assume that confidence in their expectation decreases. For the purpose of this thesis, an assumption was made to negate the influence of expectation in the process if the human does not have confidence in the expectation, shown schematically in the model in Figure 3-16.[25]

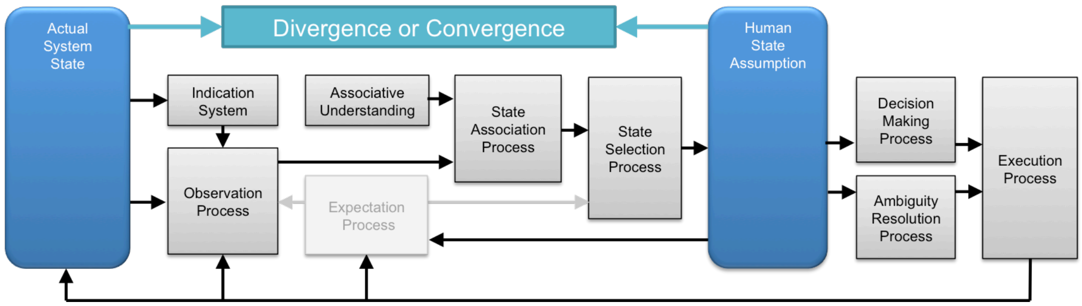

Figure 3-16. Simplified process model of divergence when confidence in expectation is low

Without the expectation process in the model, the only remaining input to the state selection process is through the association process so it becomes impossible for failures to be trapped in the state selection process. On the other hand, in known divergence, humans can look for further information and no longer have a strong expectation bias so efficacy of observation process can increase. Thus, the improved performance of the observation process has the potential to outweigh the loss of possible avenues for containment of failures. The expectation process is not the only process affected by the ambiguity of human state assumption; the ambiguity resolution process is discussed next.

3.6.2 Failure in the Ambiguity Resolution Process

Because the ambiguity resolution process, discussed in Section 2.1.6 could have a number of possible outputs. One of these outputs feeds directly back into the state selection process if the resolution is to guess the state of the system. In this case, it is possible to result in divergence if this state is guessed incorrectly since the decision tree in the state selection process is bypassed if a guess is made. For this failure, it is not likely to be contained until the next cycle of human information processing. If the human is aware that they made a guess at the state however, the significant ambiguity of the human state assumption could input into the expectation process and expectation could be negated from the next cycle through the process model as was discussed in the previous section. With these changes in human

[25] As mentioned earlier, this is a crude representation of influence of low confidence on the expectation process, however this assumption will be used generally to illustrate use of the model. Further work can be conducted to further define the relationship between confidence and the expectation process.

information processing, it may be possible for a poor decision coming from the ambiguity resolution process to be assessed and resolved in a later event.

3.7 Failures in Multiple Processes

The discussion in this chapter until now has focused on single process failures, however in the operational environment, it can be possible for failures in different processes to occur simultaneously. The effects of multiple failures can be very different than single failures. The multiple failures can diminish the containment potential depending on the processes affected. However there are some combinations of failures that do have containment potential based on the model. These combinations of failures involve any combination of indication, observation, and association processes. The possible containment of this combination of failures is shown in Figure 3-17. Failures affecting all three processes can each be contained in the state selection process if expectation is correct.

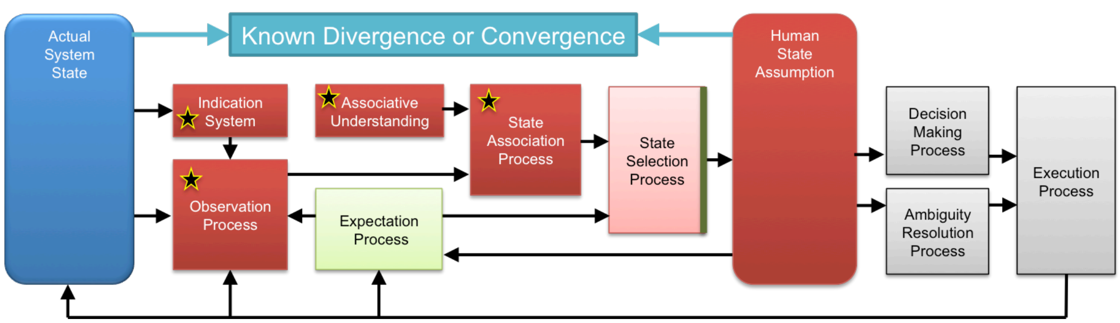

Figure 3-17. Containment of multiple failures involving the indication, observation, associative understanding and association processes only

Since that all permutations of failures with containment potential rely on a correct expectation, more consequential issues can arise as the problems become uncontainable when failures in the expectation process are paired with other processes. This means that the following permutations can have the potential to result in unknown divergence.

- Dual Failures
  - Indication System and Expectation Process
  - Observation Process and Expectation Process
  - Association Process and Expectation Process
- Triple Failures
  - Indication System, Observation Process, and Expectation Process

- Indication System, Association Process, and Expectation Process
- Observation Process, Association Process, and Expectation Process

- Quadruple Failures
    - Indication System, Observation Process, Association Process, and Expectation Process

An example of a lack of possible containment of the quadruple failure is shown in Figure 3-18. For all of these combinations of failures, state selection process can get contaminated along with the other processes. This leaves no uncontaminated avenue available to contain divergence. This provides susceptibility for consequential results if these failures occur simultaneously during critical flight regimes, for example.

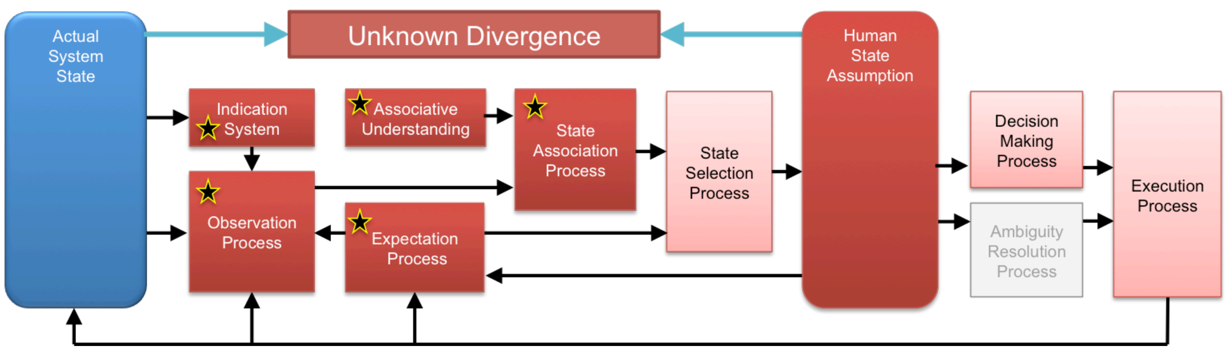

Figure 3-18. Example of lack of containment possibility involving the expectation process

3.8 Model of Divergence in Existing Error Frameworks

Since some impacts of divergence include human error, it's relevant to discuss how divergence may fit into existing error frameworks. For this section, the HFACS error classification and Norman's error classification of slips and mistakes discussed in Section 1.2.1 are used to discuss how divergence may explain the same types of errors. The active errors in the Unsafe Acts causal category in HFACS can be split into decision errors, perceptual errors, and skill based errors. These correspond with mistakes and slips in Norman's framework where mistakes can be further split into rule based mistakes and knowledge based mistakes based on the task (Norman, 1988; Rasmussen, 1985; Shappell & Wiegmann, 2000). Since skill-rule-knowledge based errors are based on the task itself, these are not differentiated in this discussion. Table 3-2 depicts the types of HFACS and Norman's errors and possible corresponding failures in the model of divergence, which could lead to those errors.

Table 3-2. Comparison of existing error frameworks and model of divergence

Class of Error (HFACS)	Class of Error (Norman)	Could be indicative of failures in the following processes in model of divergence					
		Indication	Observation	Expectation	Association	Decision Making and Ambiguity Resolution	Execution
Decision Error	Mistake	x	x	x	x	x	
Perceptual Error	Mistake	x	x	x	x		
Skill Based Error Formation of Intent Description Error	Slip/Lapse						x
Skill Based Error Formation of Intent Mode Error	Slip	x	x	x	x		
Skill Based Error Activation of Schema Unintended Activation Capture Slips	Slip						x
Skill Based Error Activation of Schema Unintended Activation Interference	Slip				x		
Skill Based Error Activation of Schema Loss of Activation Step Skipping/ Post Completion Errors	Lapse						x
Skill Based Error Triggering Wrong Time	Slip						x
Skill Based Error Triggering Not Triggered	Lapse						x
Skill Based Error Triggering Confused Intention with Action	Lapse			x			x
Skill Based Error Triggering Spoonerisms	Slip						x

Decision error in the HFACS framework refers to “intentional behavior that proceeds as intended, yet the plan proves inadequate or inappropriate for the situation” (Shappell & Wiegmann, 2003). This type of mistake can originate from an inconsistent human state assumption, where the decision may be appropriate for the assumption the human holds, however is inappropriate for the actual state. In the model of divergence, this type of mistake could result from a failure in the indication system or any of the processes influencing the human state assumption such as observation, association and expectation. In addition, if any of the decision making processes yield an inappropriate decision, this could also lead to a decision error. Perceptual errors can occur “when one’s perception of the world differs from reality. “This type of error can also originate from an inconsistent human state assumption. It specifies that the corrupt failure process originates from the perceptual path to the state selection process. In this case, failures in the indication system could contribute to an observation failure, failures in the observation process itself, or ambiguity in the observables can be mis-associated or underspecified forcing reliance on an expectation. In this case, because a perceptual error is defined, it may be assumed that failures may propagate into the decision process but may not originate there.

Finally, within the context of slips there are three categories that have been defined. These categories include errors in intention formation, activation of schema, and triggering of schema.

Errors in intention formation further categorize into mode errors, where the situation may be classified improperly, and description errors, where the intent may not be fully specified. Mode errors could originate from divergence and the failures of processes, which can lead to divergence, while description errors can originate due to attentional limitations or problems related to long term memory stores feeding execution.

Errors in activation of schema can be further classified into capture slips, interference, or step skipping. Capture slips and interference refer to an unintended activation where capture may occur due to habitual behavior and interference could occur due to confusion with similar situations. Capture slips may have correct intention, but fail in the execution process, however interference can manifest in the model of divergence as a failure in the association process. Step skipping refers to omission of an action and is classified as a loss of activation, likely corresponding to a failure in the execution process.

Errors in triggering of schema can be further classified into timing errors, confusion of intention with action, and spoonerisms. If a schema is triggered at the wrong time, it may be considered a slip, and if it is not triggered at all, it can be considered a lapse. Both of these timing errors would be captured in the model of divergence as failures in the execution process. Spoonerisms would also be considered as possibly originating in the execution process. Confusion between intention and action however, appears to involve the expectation process in addition to the execution process. An example of this may be an intent to press the auto-pilot disconnect button, but confusion arising because expectation may have updated to reflect the button press even if it had not actually been executed.

Overall, the model of divergence can be used to explain mistakes (decision errors and perceptual errors) and certain types of slips/lapses (skill based errors) including, mode errors, interference, and confusion between intent and action. Slips would not be explained by divergence as they would not be caused by an inconsistent state assumption. This section shows how divergence spans beyond the typical error frameworks and illustrates how errors in current frameworks may be explained by failures in different processes in the model of divergence.

3.9 Summary

Failures in human information processing can have different impacts on the outcome of a situation relating to divergence. These failures range from inconsequential single failures, such as missing observations of indefinitive indications of state, to multiple failures whose occurrence could prevent the possibility of containment anywhere in human information processing. If these failures are not contained prior to reaching a state assumption, it can propagate into decision-making and execution processes leading to errors in human performance. This chapter discussed how failures of individual processes can affect the human state assumption. Problems with understanding of the system can cause failures in the expectation, and association failures. Problems with the indication system and observation process can also affect the human state assumption, possibly resulting in mistakes if not contained.

Major process failures relate to failures and combinations of failures that result in unknown divergence. These have no avenue for containment. Aside from a wrong guess output from the ambiguity resolution process, unknown divergence can also appear for multiple process failures that include an expectation process failure. This chapter discussed influences possibly contributing to failures in human information processes, impact of failures, and possible containment of these process failures. The following chapter uses this information to explore a number of accident case studies.

Chapter 4

Case Studies

The human information processing model of divergence is used in this chapter to evaluate divergence in a set of accident and incident cases. Due to the expansive list of complex automation systems in a modern commercial aircraft, the analysis was scoped to aircraft systems that were complex enough to see the possible occurrence of divergence but with a limited state space such that the system could be easily understood by the reader. This chapter begins with a description of the scope of the analysis and introduces the method used in analyzing data from the accident and incident reports relating to aspects of divergence. The basic results of occurrence of divergence and re-convergence are initially discussed, followed by an evaluation of the dynamics of the divergence timeline. Finally, this chapter closes with a discussion of the factors contributing to divergence and inhibiting re-convergence.

4.1 Cases Analyzed

Table 4-1 lists the accidents and incidents studied.[26] Eleven case studies were conducted. These case studies included the eight accidents involving auto-throttle mode, in addition to three accidents involving other automation systems that resulted in CFIT.

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[26] Some percentage of the following section has been adapted or reconstructed from a previous publication by the author (Silva & Hansman, 2015) that introduced the work.

Table 4-1. List of cases analyzed (Source: Directly (blue) or Indirectly (orange) from FAA Lesson's Learned Database)

		Flight	A/C Model	Accident Year	Description	Result
Auto-throttle mode confusion	Low Energy Cases	Asiana 214[27]	B777	2013	Auto-throttle reverted to a dormant (HOLD) mode during approach and did not capture approach speed	Aerodynamic Stall and Impact
		Turkish Air 1951[28]	B737	2009	Auto-throttle went to RETARD FLARE mode during approach due to previous radar altimeter failure	Aerodynamic Stall and Impact
		Thomsonfly (Incident)[29]	B737	2007	Auto-throttle disengaged during approach and did not capture approach speed	Successful Recovery from Aerodynamic Stall
		American 903 (Incident)[30]	A300	1997	Auto-throttle disengaged during descent and did not capture speed upon level-off	Successful Recovery from Aerodynamic Stall
		Indian Air 605[31]	A320	1990	Auto-throttle in IDLE OP Descent mode and did not capture approach airspeed	Aerodynamic Stall and Impact
	High Energy Cases	Tarom 381 (Incident)[32]	A310	1994	Auto-throttle increased power during transient flap overspeed	Successful Recovery from Aerodynamic Stall
		China Airlines 140[33]	A300	1994	Auto-throttle increased power due to inadvertent crew activation of TOGA button	Aerodynamic Stall and Impact
		Air France 072[34]	B747	1993	Auto-throttle increased power due to end of descent point logic in FMS.	Runway Excursion
CFIT		Air Inter 148[35]	A320	1992	Vertical descent speed set to 3,300 fpm rather than 3.3 degrees FPA	Controlled Flight into Terrain
		American 965[36]	B757	1995	Incorrect waypoint input steered aircraft off-course, coupled with descent into the terminal area resulted in impact with a mountain ridge	Controlled Flight into Terrain
		Eastern 401[37]	L1011	1972	Auto-pilot altitude hold disconnected and aircraft began slow descent. Crew was distracted troubleshooting a landing gear failure	Controlled Flight into Terrain

27 (National Transportation and Safety Board, 2013)

28 (Dutch Safety Board, 2010)

29 (Department for Transport/Air Accidents Investigation Branch, 2009)

30 (National Transportation and Safety Board, 1998)

31 (Ministry of Civil Aviation, 1990)

32 (Bureau d'Enquêtes et d'Analyses, 2000)

33 (Aircraft Accident Investigation Commission - Ministry of Transport, 1996)

34 (Bureau d'Enquêtes et d'Analyses, 1999)

35 (Ministry of Transport, 1993)

36 (Aeronautica Civil of the Republic of Columbia, 1995)

37 (National Transportation and Safety Board, 1973)

In order analyze divergence, a set of similar accidents, which clearly indicated potential for illustrating divergence, was needed. Since the human state assumption within the framework of divergence was tied to human performance, accidents tagged as involving "human error" were investigated initially using the FAA Lessons Learned accident database. The accidents within this set included various systems of interest, thus in order to identify trends, further specification was desired. Since industry initiatives have highlighted mode confusion as a potential threat to safety, the scope of analysis was initially focused on accidents involving auto-flight systems. Another goal in defining scope was to use a system with a simple state space to facilitate understanding of divergence and included a well established actual state of the system. The auto-throttle system within the auto-flight system fit these criteria including a limited set of possible modes and straightforward assessment of actual mode using Flight Data Recorder (FDR) data. Thus, the main analysis focused on cases involving auto-throttle mode confusion.

In order to identify case studies, the FAA Lessons Learned Database was used (Federal Aviation Administration, n.d.). All of the cases within the subcategory "human error" were reviewed and included if they were related to auto-throttle mode confusion. Accidents tagged as "related events" to the accidents involving human error were also reviewed and included if they related to auto-throttle mode confusion. Within the accidents under the subcategory "human error" in the FAA Lessons Learned database, Indian 605, Air France 72, and China 140 were identified directly from the database to involve divergence in auto-throttle state. These are highlighted in blue in Table 4-1. Other accidents were added to this set using the "related events" specified in the database in addition to the investigative reports for those three initiating cases. These are highlighted orange in Table 4-1. The Turkish 1951 accident and Thomsonfly incident were included because it was tagged as a "related event" to Indian 605. The Tarom 381 incident was included as a related to the AF 72 accident. Asiana 214 occurred while this was being conducted and was included based on its relevance to auto-throttle mode confusion.[38]

[38] The American 903 incident was included due to a case of auto-throttle mode confusion where "a factor contributing to the accident was the flight-crew's failure to properly use the auto-throttle" that contributed to an inflight stall. This incident resulted in an inflight aerodynamic stall and exceedance of the rudder load limits. American 903 was tagged for analysis due to its auto-throttle influence. It was tagged as a case similar to AA 587 in which the crew also exceeded rudder load limits. The main accident, AA 587 in this case, did not involve auto-throttle mode confusion and thus, was not included in this analysis.

Auto-throttle and auto-thrust systems both control engines. Despite differences in how auto-throttle and auto-thrust systems function, for the purpose of this thesis these differences were considered negligible and both auto-throttle and auto-thrust systems are referred to auto-throttle systems in this document for simplicity.

Auto-throttle systems are a subcomponent of auto-flight systems and control thrust settings of the engines. Control of the engines however, can occur in multiple different ways based on the mode of the auto-throttle. Examples of auto-throttle modes for the Airbus A320 include Speed (SPD), MACH, Thrust (THR), and Retard (RET) (Airbus Industrie, 1989). Each of these modes uses engine thrust to control different targets. When in SPD or MACH mode for example, the auto-throttle manipulates the engine thrust to maintain a specific speed or Mach number target respectively. While in THR mode on the other hand, the auto-throttle controls the engine thrust to maintain a specific thrust level. Similarly, in RET mode, the auto-throttles reduce thrust to flight idle. The different modes of the auto-throttle can be operated independently of the auto-pilot system or can be coupled to auto-pilot modes. When coupled, the auto-throttle modes can be dependent on the auto-pilot's vertical path control. For example if flying a coupled approach in the A320, when the vertical autopilot mode FLARE is activated, the RET mode on the auto-throttle is automatically selected to accompany the auto-pilot mode transition as the automation assumes the aircraft is in the landing flare (Airbus Industrie, 1989). This capability to couple the auto-pilot and auto-throttle systems illustrates the potential complexity of the system. Also the fact that it can be possible for auto-throttle modes to transition without direct crew input could indicate more susceptibility for cases of auto-throttle divergence if the crew is not in the loop when a transition occurs.

In order to illustrate extensibility of the model beyond auto-throttle mode confusion cases, three further accidents were chosen from the human error list in the Lessons Learned database that did not relate to auto-throttle mode confusion. Since Eastern 401, American 965, and Air Inter 148 were high profile examples of human error, these three were chosen to assess how divergence could be used to understand these accidents. All three of these accidents resulted in controlled flight into terrain (CFIT), a continuing concern for aviation safety (Loomis & Porter, 1982; Shappell & Wiegmann, 2003).

It should be noted that the scope and cases discussed, were chosen to illustrate that divergence could add value as a perspective for evaluating these cases. As accidents can originate from a complex interaction of a number of different factors, this thesis does not claim that divergence is the exclusive contributor to these accidents and incidents, but a possible contributor.

Three accidents, of the eleven, are discussed in detail in this chapter. These accidents, Turkish 1951, Air Inter 148, and Eastern 401, are presented to illustrate the assessment of divergence, while the detailed discussion of all accidents can be found in Appendix D.

4.2 Method

In order to evaluate cases of divergence in accident and incident reports, evidence of divergence was inferred from a number of sources. Different types of data in investigative reports provided different insights into divergence. FDR data for example provided information regarding actual state of the system. This data was supplemented with analysis performed by the investigative team. Cockpit flight recorder (CVR) data, on the other hand, provided insight into the human's assumption of the state of the system. Crew interviews also supplemented CVR data if the crew survived to provide a statement. Other aspects of the human state assumption were inferred from crew actions and behavior. Because these were based on standard operating procedures, appropriate action was possible to infer for different situations. Using these sources of data, the following method was used to evaluate divergence in several accident cases.

Step 1. Determined whether there was evidence indicating unknown divergence, known divergence, and re-convergence.

For the auto-throttle cases, the state of interest analyzed was the mode of the auto-throttle. For the CFIT cases, multiple options were considered and the individual state of interest for each CFIT cases is presented in each discussion.

In order to assess divergence, information regarding the actual state of the system and the human assumption of state was needed.

Actual state information was generally straightforward to infer from the accident or incident reports. Typically, the FDR data included time of mode transition. In auto-throttle cases, the FDR included parameters of auto-throttle engagement and mode of engagement. In some cases the FDR was not recoverable or destroyed by impact, or the data in the FDR would be overwritten if too much time had passed from incident and notification of the incident to authorities. In these cases where FDR data was not available, reports sometimes included Quick Access Recorder (QAR) data that also would have provided mode information.[39] While the list of parameters recorded on the QAR could be less extensive than those recorded by the FDR, it typically includes mode information and flight path vector information. If automation mode information was not available, e.g. in the incident involving American Airlines (AA) 903, the uncertainty in time of mode transition is explicitly noted in the discussion. In these cases, behavior of the engines could have provided insight into the state of the auto-throttle system. For example, in cases of level off, if the auto-throttle was engaged in SPD mode, it is expected that the auto-throttle would have manipulated the engines to maintain SPD upon level off. If the engine manipulation was not apparent in the engine parameters recorded, it was inferred that the auto-throttle was not engaged in SPD mode.

Human state assumption information was more implicit in the investigation reports. In order to make an assessment of the human state assumption, human behavior and verbalization during the case was used. The evidence of behavior was gathered from the FDR/QAR if the action was reflected in the aircraft system. For example, if the auto-pilot was disconnected, the time of disconnect was taken from the FDR. The source of the disconnect (aircraft or human) was inferred based on verbalization of the crew. Verbalization was taken from the cockpit voice recorder if it was available. If the cockpit voice recorder data was not available, behavior was used to make the inference of human state assumption alone. In some cases, the crew survived to provide a statement. The information gathered from these interviews provided further insight into the human state assumption. Typically, in these interviews, the crew explained their expectations at each point in the accident timeline.[40] Thus, the information can be useful in determining divergence. For example the crew in AA903 stated in the interview that they knew the auto-throttle disconnected sometime during the descent, but didn't recognize it until level off and the speed was below their target airspeed. Thus, the human state assumption until that airspeed was reached can be inferred as the last known expectation by the crew, which in AA903 was likely when they began

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[39] QAR was a recording device installed to record engine performance. Operationally, this information can be used by mechanics to troubleshoot engine problems. However, since the device records other aircraft information, it is a useful tool for accident investigators to validate FDR data or replace it if the FDR is not available.

[40] Typical cues in the report could include verbiage such as "the crew was not aware of _____," or "the crew did not realize that ____." In CVR or interview transcripts, verbiage such as "I didn't know that ____," or "I was confused ___"

the descent (they reported that the auto-throttle behaved as expected reducing thrust to idle for the descent).

Unknown divergence was inferred if there was evidence that the crew's state assumption was inconsistent with the actual system state. Re-convergence was inferred if there was evidence that the crew's state assumption was consistent with the actual system state. Known Divergence was inferred if there was evidence that the crew recognized errors in their state assumption. This could be in the form of verbalization such as "what's going on?" indicating confusion. This information was also gained from crew interviews if available.

Step 2: Recorded times of critical events

Critical events in this thesis were considered as the events related to loss of control, recovery, point of unrecoverability (if available) and impact. A record was needed of time of imminent loss of control and the time of impact for assessment of dynamics of divergence. Time of imminent loss of control was defined for these specific cases as the time of stall warning, overspeed warning, aerodynamic stall, aircraft overspeed, annunciation of EGPWS or impact with the ground, whichever occurred first.[41] Initiation of recovery was recorded as the time of crew input of the appropriate recovery action for the situation. Completion of recovery was recorded as the time following recovery when flight parameters returned to a stabilized configuration consistent with nominal controlled flight. Point of unrecoverability was occasionally provided in the accident report, and if it was available, it was included in this analysis. Finally, time of impact was defined as first contact with the ground outside of the runway environment. These critical events were used to understand the overall timeline of divergence and effects there of.

Step 3. Identified events of interest

Events of interest constituted events that were relevant to the divergence timeline. They may or may not have included critical events identified above. From the report, it was determined when divergence most likely occurred. From that point on, an event would constitute a change in actual state of the system, human state assumption, observables or observation. All events of interest were listed. The description of the event and time of the event were also recorded.

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[41] While this definition was sufficient for the autothrottle and CFIT cases analyzed, the definition of imminent loss of control can be adapted to include other parameters such as extreme attitude for other cases where that may have constituted a loss of control.

Step 4. For each event, possible observables present were identified and assessed about whether they provided definitive or indefinitive information about the actual aircraft state

Using the report and sometimes information from an accident aircraft manual to supplement the report, possible observables available to the crew at each event were identified. Based on the situation, an assessment was made about whether the observable was an unambiguous indication of the actual state (definitive observable) or whether it could be an indication of more than one state (indefinitive observable).

Step 5. For each event, the impact of the event on each individual process (indication system, expectation process, observation process, and association process) was assessed.

Indication System Failures

- Was there evidence of a component failure in the indication system, which provided false cues to the crew regarding the value of an observable? [Yes ,No]
  - If Yes, then consider as evidence of indication system failure
  - If No, then consider as no evidence of indication system failure

Expectation Process Failures

- Was crew's behavior and verbalization consistent with behavior if they had <u>noticed the actual state</u> or behavior if they <u>assumed the nominal state</u>? [Actual, Nominal]
  - If consistent with nominal state, then consider as evidence of expectation process failure
  - If consistent with actual state, then consider as no evidence of expectation process failure

Evidence of Poor System Understanding

- Was actual state or human state assumption changed?
  - If action was taken, was behavior consistent with the knowledge of the <u>actual state transition</u> or consistent with the knowledge of a <u>different state transition</u>? [Actual, Different]
    - If consistent with different state transition, then consider as evidence of poor system understanding
    - If consistent with actual state transition, then consider as no evidence of poor system understanding

Evidence of Perpetuation of Divergence

- Does unknown divergence exist? [Yes, No]
  - If Yes, then consider as evidence of perpetuation of divergence
  - If No, then consider as no evidence of perpetuation of divergence

Observation Process Failures

Evidence of Expectation Bias

- Was expectation incorrect? [Yes, No]
- If Yes, could it have affected the observation of observables? [Yes, No]
  - If Yes, then consider as evidence of expectation bias
  - If No, then consider as no evidence of expectation bias

Evidence of Distraction

- Were there other activities the crew was attending to at the time of divergence and once divergence had occurred that may have interfered with scanning of observables? [Yes, No]
  - If Yes, then consider as evidence of distraction
  - If No, then consider as no evidence of distraction

Evidence of Workload Issues

- Was the crew performing extra tasks or fewer tasks outside of nominal workload during the period of divergence? [Extra, Fewer, Nominal]
  - If Extra, then consider as evidence of high workload
  - If Fewer, then consider as evidence of low workload
  - If Nominal, then consider as no evidence of workload issues

Evidence of Fatigue

- Did the report conclude that fatigue was a factor in the accident? [Yes, No]
  - If Yes, then consider as evidence of fatigue
  - If No, then consider as no evidence of fatigue

Association Process Failures

Evidence of Poor Associative Understanding

- Was there evidence of observation of a definitive observable (from verbalization or behavior*)*? [Yes, No]
- If Yes, was there evidence of a different response than what was expected if this observation had actually been made? [Yes, No]
    - o If Yes, then consider as evidence of failure in associative understanding
    - o If No, then consider as no evidence of failure in associative understanding

Evidence of Ambiguity of Observables

- Was a definitive observable observed? [Yes, No]
- If No, was there evidence of observables whose presence could have been indicative of multiple different states concerning the state of interest? [Yes, No]
    - o If yes – then consider as evidence for ambiguity of observables
    - o If no – then consider as no evidence for ambiguity of observables

The outcome of execution for that event was also inferred from the accident report if action was taken or communication occurred in response to that event.

Step 6. Repeated Steps 4 and 5 for each event in the divergence case

When there was enough time for divergence to evolve, there were typically multiple events that were analyzed for a given case. Thus, steps 5 and 6 were repeated for each event involving divergence.

4.3 Example Case Studies

4.3.1 Case Study 1: Turkish Airlines Flight 1951

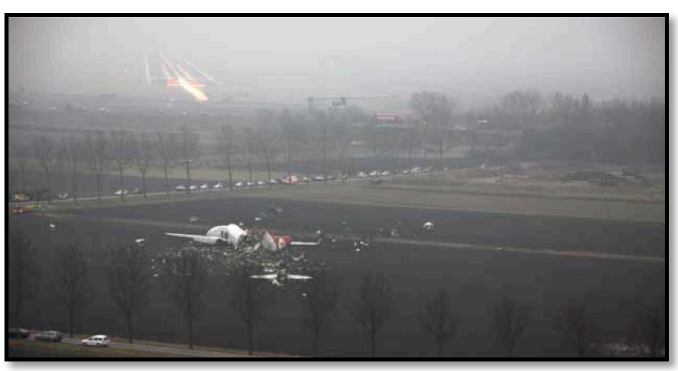

Figure 4-1. Wreckage of Turkish Flight 1951 (Dutch Safety Board, 2010)

The accident of Turkish Airlines Flight 1951, shown in Figure 4-1, occurred on February 25, 2009 in Amsterdam, Netherlands (Dutch Safety Board, 2010). In this accident a previous radar altimeter (RA) component failure had apparently caused the auto-throttle to transition to an abnormal flight mode at the top of the final approach descent.[42] This abnormal mode caused the throttles to retard and remain in idle position. This mode change apparently went unnoticed by the crew, which appears to be a case of an observation process failure. However, while the crew was intercepting the glide path there were few definitive observables available to the crew regarding this abnormal mode, as most of the available indications were showing behavior that was consistent with behavior typically shown by the nominal mode in this situation. This illustrates the possibility of an association process failure if there were only indefinitive observations input into the association process and expectation process failure if the crew expected the nominal mode to be active during this time. As the airspeed dropped below reference airspeed, more observables appeared to become definitive, however there was no evidence that the crew recognized this abnormal mode until the stall warning system had activated close to 500 feet of altitude. The crew attempted to recover, however the aircraft impacted the ground short of the runway (Dutch Safety Board, 2010).

The flight profile and inferred divergence history for this accident is provided in Figure 4-2. The state of interest was the auto-throttle mode. Key events related to the apparent divergence and the implication of this divergence were identified and discussed in this analysis. The observables available to the crew throughout the timeline are presented at the end of this section in Figure 4-10.

In this case, the abnormal auto-throttle transition to the abnormal mode of Retard Flare (Event E1) was considered to be the trigger for divergence in auto-throttle mode.

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[42] The crew action to perform a coupled approach with a radar altimeter failure indicates a system understanding failure influencing their expectation likely not incorporating this abnormal mode transition as an effect of flying a coupled approach with a radar altimeter failure.

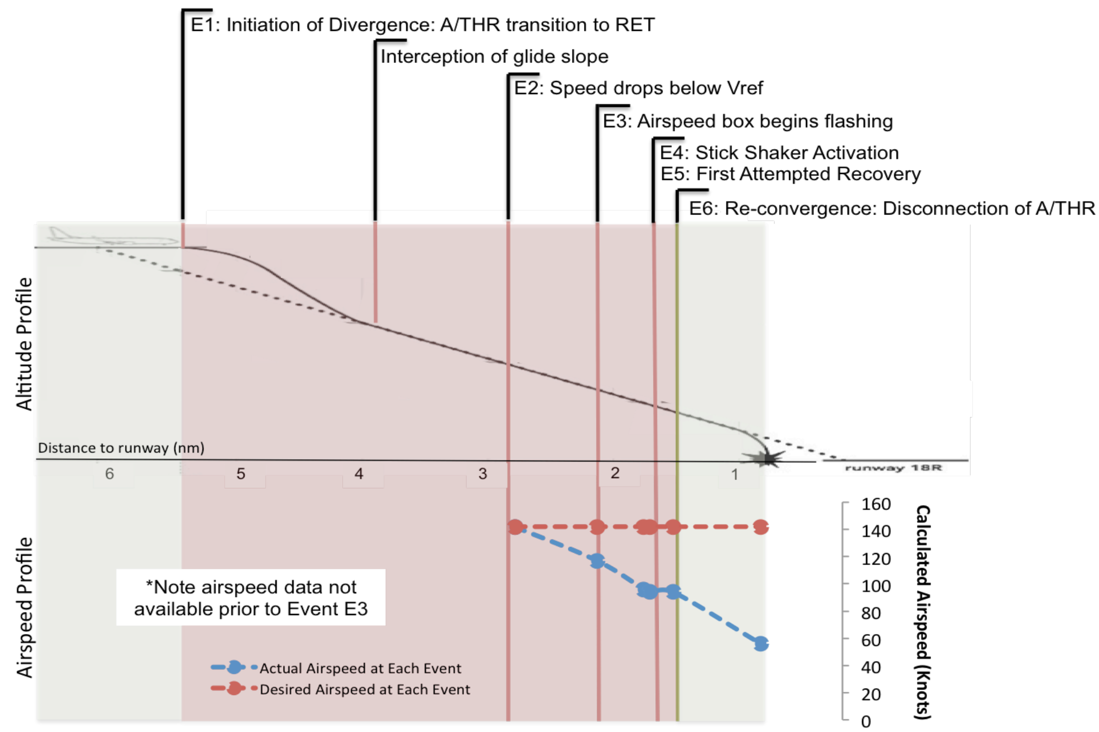

Figure 4-2. Vertical flight profile and approximate airspeed profile for Turkish 1951 relative to overlaid inferred divergence history (Dutch Safety Board, 2010)

4.3.1.1 Event E1: Initiation of Divergence

Time	Impact – 01m 39s
Actual State	Auto-throttle mode: Retard Flare (RETARD FLR)
Situation	Descending to intercept glide slope from above
Event Trigger	Change in actual state
Divergence Type	D-1a: Actual state transitions without input by the crew

At Event E1, the apparent divergence in auto-throttle state was considered to be triggered by an abnormal transition to Retard Flare at the top of descent, which was not realized by the crew, who possibly defaulted their expectation to the nominal transition into SPD mode. This abnormal transition was attributed to a faulty radar altimeter reading. Without this failure, the auto-throttle should have transitioned nominally to SPD mode, which included speed hold capability.[43] If a failure in the expectation process had occurred, it is possible that it influenced the observation process, possibly contributing to a missed observation of the RETARD on the flight management annunciation (FMA), which was a definitive observable. There was also the possibility of an association process failure if exclusively indefinitive observables were observed. As introduced, at the initiation of divergence, failures in the observation, association, and expectation processes could have occurred. These are discussed in detail below.

The observables available to the crew included one definitive observable of the "RETARD" shown on the FMA depicted at the top of Figure 4-3. In addition to this single definitive observable, a number of indefinitive observables were also apparently available to the crew such as values and trends of airspeed, pitch attitude, engine parameters, and throttle position. These observables were indefinitive because the aircraft was initiating its descent at this point in the timeline, and idle power (and all indications consistent with idle power) were indicative of not only the RETARD mode, but also the nominal SPD mode which the crew likely expected the aircraft to be in given their previous experience. This means that if the single definitive observable was missed in the observation process, discrimination between RETARD and SPD mode would not be possible in the association process.

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[43] The abnormal transition was the result of a component failure. Not only was the radar altimeter providing false data, but this false data coming into the automation was not flagged as failed; thus, the automation failed to prevent activation of the autopilot which would have nominally occurred if a fail flag was received by the automation (Dutch Safety Board, 2010).

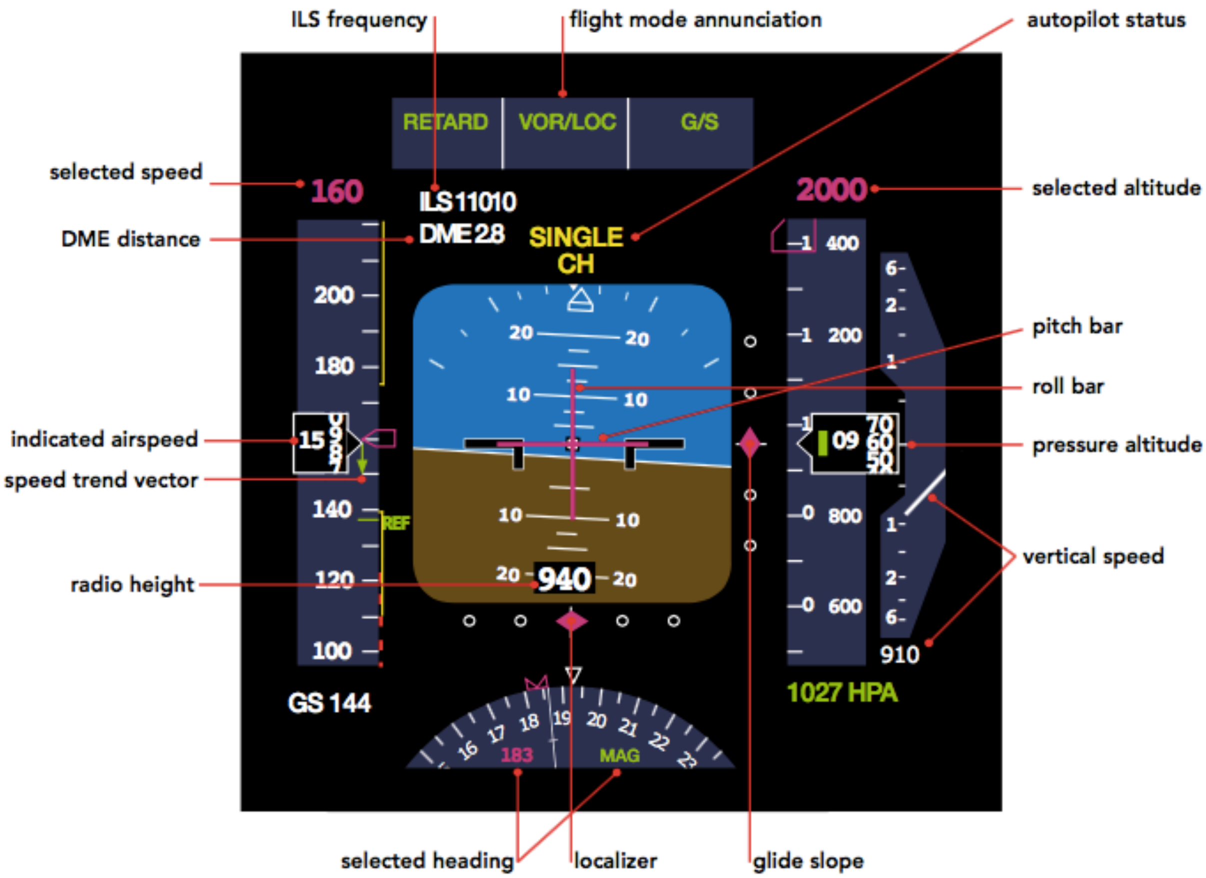

Figure 4-3. Example primary flight display in the B777 (Dutch Safety Board, 2010)

The data suggested the crew likely missed the definitive observable of RETARD on the FMA[44]. In order to understand this observation process failure it was necessary to evaluate the environment and tasks the crew was attending to at Event E1. While intercepting the glide slope from above is not an uncommon procedure, nominal interception of the glide slope typically occurs from below. It may be possible that this non-standard vertical profile could have increased workload for the crew and introduced a distraction

[44] CVR transcript and FDR shows behavior consistent with an expectation that the aircraft was in SPD mode. The assumption made here was that the data would have showed different behavior if the crew had observed the RETARD. Because the behavior was consistent with behavior expected in SPD, the evidence suggests that RETARD was not observed. Here, the lack of verbalization about the abnormal mode of RETARD on the FMA followed by the downstream surprise apparent in the "speed!" were supporting evidence that the RETARD was not observed.

from maintaining awareness of the auto-throttle mode.[45] In addition to the situational influences of workload and distraction, it was important to investigate the system influences involved with the crew not noticing the transition. The single definitive observable available to the crew, the FMA, was purely a visual indication on the primary flight display. Due to this characteristic, the crew's attention was likely required to be directed in the vicinity of the PFD in order to detect the transition. Thus, if the crew's visual attentional resources were focused elsewhere due to a prioritized task it is possible that the FMA indication could have been missed. The investigation also concluded that fatigue was not a likely factor in the accident due to sleep in the previous days as well as a lack of behavior consistent with serious fatigue (Dutch Safety Board, 2010).

Finally, as previously mentioned, it was likely that the crew held expectation of SPD mode formed from the numerous other times they had flown an ILS approach. It is also possible that this could have introduced expectation bias into the observation process contributing to the apparent missed observation of the FMA. System influences, situational influences, and expectation bias could all have played a part in this apparent observation failure.

If the only definitive observable, the FMA, was missed, then only indefinitive observations would be input into the association process. This, by definition, would have likely resulted in the association processes outputting multiple states consistent with observation. These states would need to be filtered in the expectation process, where the correct state would result if the expectation was also correct. However, as discussed already, the crew likely had an incorrect expectation.

Another influence on the association process can be traced back to system design. Because of a possibly ambiguous design, even if the RETARD indication was observed, the RETARD shown on the FMA could have indicated the RETARD Flare mode or the RETARD Descent mode, a mode that is commonly seen inflight. While RETARD Flare is not typically seen at the top of approach descent, this ambiguity could have potentially occurred in the association process if the RETARD had been observed. Also related to the situation, is the possibility that the crew did not believe RETARD could occur at the top of descent effectively removing it from the association process comparison. If this occurred, the RETARD mode option would not even make it into the state selection process. As can be seen, there were a number of potential sources of failures in the association process.

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[45] CVR transcript shows discussion about the vertical profile as divergence initiated through interception of the glide path

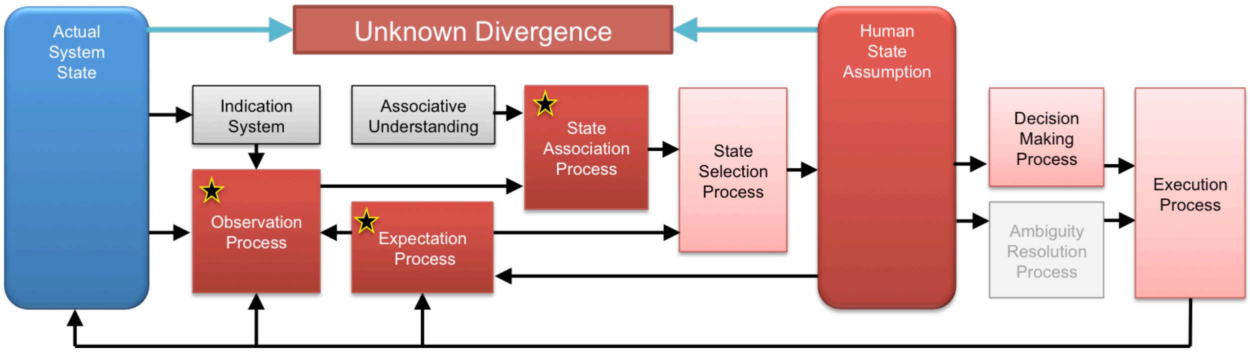

Figure 4-4. Human information processing model of divergence for Turkish 1951: Events E1 and E2

The possible expectation process failure, coupled with possible association process and observation process failures, likely resulted in unknown divergence. Figure 4-4 shows the containment possibility of this situation and suggests that containment of this combination of failures would have been difficult. This set of failures continue through the interception of glide path, until the airspeed decays below the reference airspeed set on the mode control panel, which brings us to Event E2.

4.3.1.2 Event E2: Speed Decay below Vref

Time	Impact – 00m 39s
Actual State	Auto-throttle mode: Retard Flare (RETARD FLR)
Situation	Airspeed decay below reference airspeed
Event Trigger	Change in observables

As airspeed decayed below Vref, some indefinitive observables would have become definitive. Airspeed, engine noise, throttle location, and pitch attitude became definitive observables as these indications would not reflect the values output if the auto-throttle were in SPD mode. These extra definitive observables could have reduced the dependency on the crew observation of the RETARD on the FMA. Yet, the observation process failure appeared to continue.[46]

The association process, however, could have recovered due to the change of observables. If any of the added definitive observables were observed, they had the possibility to be associated with the correct

[46] There was no evidence in the report of verbalization of new information or a change in behavior reflecting an observation being made.

state. In addition, the Retard Flare/Descent ambiguity, while it still existed, could have been diluted by the availability of other definitive observables. The FMA no longer appeared to be the sole variable the crew had to rely on. While failures originating in the association process were alleviating, the association process was still affected by the failure in the observation process. Again, this failure could have been trapped in the state selection process if expectation was correct, however the expectation process failure still appeared to exist. This combination of failures is represented in Figure 4-5. While more definitive information was available to the crew, this was not sufficient to overcome the expectation bias that likely prevailed. 15 seconds after the speed dropped below reference, the airspeed box on the PFD began flashing, providing yet another definitive observable to the crew regarding the state of the auto-throttle.

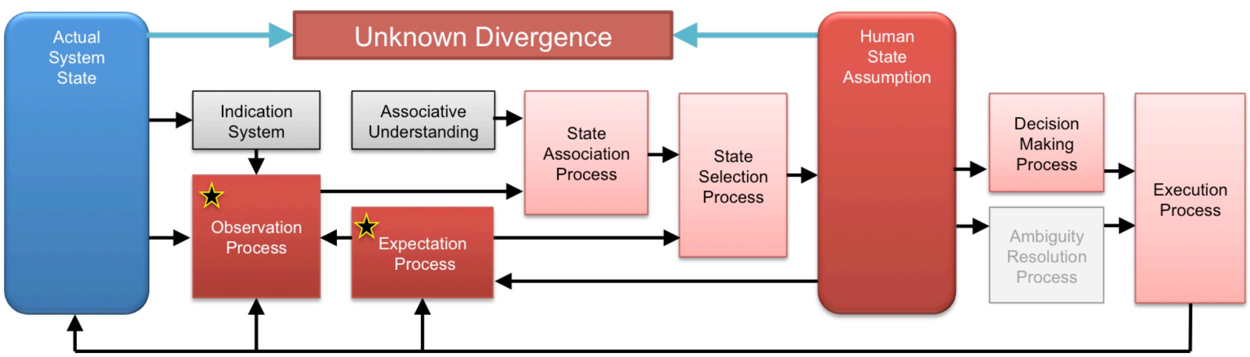

Figure 4-5. Human information processing model of divergence for Turkish 1951: Events E2 and E3

4.3.1.3 Event E3: Airspeed Box Begins Flashing on PFD

Time	Impact – 00m 24s
Actual State	Auto-throttle mode: Retard Flare (RETARD FLR)
Situation	Airspeed approaching stall regime
Event Trigger	Change in observables

The next event involved the airspeed box on the PFD beginning to flash. This was designed as a low speed alert (Dutch Safety Board, 2010). In this case, the indication was a visual indication on the primary flight display. This indication had the same limitations discussed for the FMA. Presumably attention would need to be focused in the vicinity of the PFD in order to perceive the signal; thus, if the crew had their attention on the PFD, it was possible that the flashing could have captured their attention. However, the crew's lack of response indicated that they did not observe this definitive observable either. The observation process failure and expectation process failure persisted, and as is still consistent with Figure

4-4, the crew remained in unknown divergence despite the added definitive observable. A highly salient cue from the system was used to break the expectation bias and indicate divergence to the crew.

Figure 4-6. Example of flashing airspeed box on a B737 PFD [adapted from (pmFlight, 2014)**]**

4.3.1.4 Event E4: Stick Shaker Activation

Time	Impact – 00m 15s
Actual State	Auto-throttle mode: Retard Flare (RET FLR)
Situation	Stall warning activation
Event Trigger	Change in observables

As the airspeed decreased, the autopilot attempted to hold glide slope by increasing the angle of attack of the aircraft. Once the angle of attack exceeded a critical value, 15 seconds prior to impact, the stall warning system activated the stick shaker, warning the crew of impending aerodynamic stall. This stick shaker was a salient, definitive indication for low airspeed. The low speed could then provide definitive insight into the auto-throttle state in this case. Evidence from the cockpit voice recorder indicated that this observable was apparently noted by the crew, highlighting recovery of the observation process.[47] The only failure remaining when the stick shaker activated was the expectation process failure.

Thus, because the expectation process failure appeared to be the only remaining process failure at this point, it became possible to contain in the state selection process when comparison was made between states consistent with observation and expectation of state. If the expectation was the SPD mode, the stick shaker observation would not be indicative of SPD mode because speed is protected, by definition in this mode. This discrepancy likely trapped the expectation process failure in the state selection process, apparently triggering known divergence. This containment is depicted in Figure 4-7,

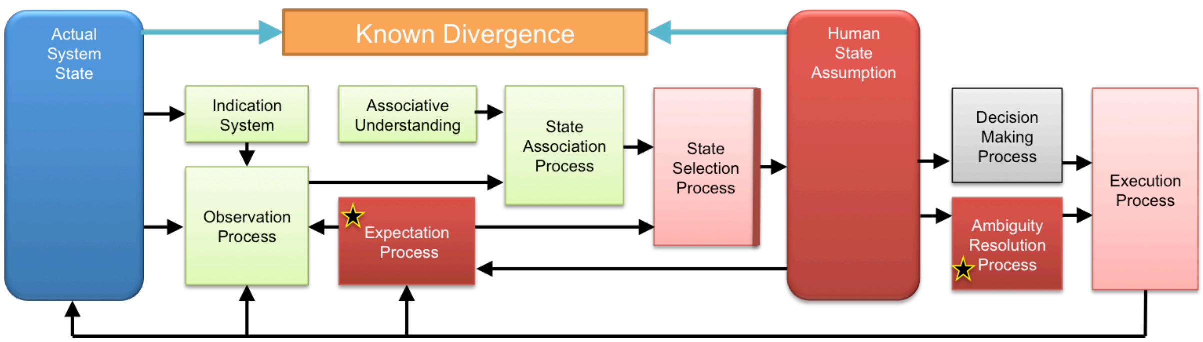

Figure 4-7. Human information processing model of divergence for Turkish 1951: Event E4

The onset of known divergence would have triggered the ambiguity resolution process. The crew verbalized concern with the airspeed, indicating that the ambiguity resolution process could have resulted in a scan for more information and communication of the observation made. Following this communication, the crew apparently took action to recover by pushing the throttles forward.

4.3.1.5 Event E5: First Attempted Recovery – Auto-throttle retards during recovery

Time	Impact – 00m 15s
Actual State	Auto-throttle mode: Retard Flare (RETARD FLR)
Situation	First attempt at recovery, however auto-throttle retards during recovery
Event Trigger	Change in human state assumption

47 10:25:47: Stickshaker On, followed by an immediate application of power by the first officer (Dutch Safety Board, 2010). This immediate reaction was consistent with what was expected if the stick shaker signal was observed.

The action taken to push the throttles forward was taken immediately following stick shaker activation, however this was not effective without disconnecting the auto-throttle system, uncovering another failure in the expectation process. The pilot flying (PF) could have expected that by pushing the throttles forward, they would remain there (or disconnect the auto-throttle), while in actuality since the auto-throttle remained in RETARD mode. The auto-throttle reverted the levers back to idle once the pilot's hand was removed from the throttle (to hand over control of the aircraft to the captain). Even though expectation was called into question in the previous event, the action taken updated the expectation of state to the result of that action during this event. The crew immediately noticed the throttles retarding and this observation was likely inconsistent with their expectation as demonstrated by their disconnection of the auto-throttles once the captain took control of the aircraft. Figure 4-8 depicts human information processing for this combination of process failures. As can be seen, the divergence was again trapped in the state selection process due to the pilots' likely observation of indications that were inconsistent with the state they expected the auto-throttle to be in. The result was, again, apparently known divergence.

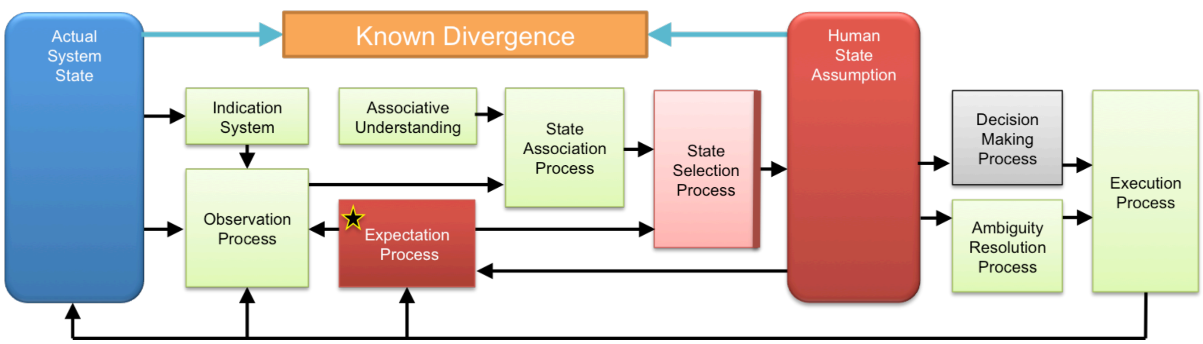

Figure 4-8. Human information processing model of divergence for Turkish 1951: Event E5

Again, known divergence would have triggered the ambiguity resolution process. Since the next action taken by the crew was to disconnect the auto-throttle, there are two possible paths in human information processing that could have resulted in this action.

a) Option A. The crew decided in the ambiguity resolution process to disconnect the auto-throttle when any question existed to the state of the system. In this option, re-convergence would occur once the auto-throttle was disconnected.

b) Option B: The crew decided in the ambiguity resolution process to search the observables again, however in the next cycle through the model, since an expectation was not involved, the state selection process possibly output RETARD as the human state assumption. In this option, re-convergence would have occurred in the current cycle through human information processing and only became apparent once the auto-throttle was disconnected.

However, based on the information in the accident report, it is not possible to ascertain when exactly re-convergence occurred. Since there is no explicit evidence of Option A or B, Option A was used as a conservative estimate of the timing of re-convergence.

4.3.1.6 Event E6: Re-convergence

Time	Impact – 00m 12s
Actual State	Auto-throttle mode: OFF
Situation	Disconnection of auto-throttle
Event Trigger	Change in actual state
Re-convergence Type	C-3 – Human state assumption and actual state transition to alternate state

The action of disconnecting the autopilot would have presumably updated the actual state of the auto-throttle as well as the human expectation of auto-throttle state. Figure 4-9 depicts human information processing in the next cycle through the process. The set of observations would likely be consistent with expectation resulting in a human state assumption of the auto-throttle being OFF. The timing of re-convergence however did not apparently leave enough time to complete the recovery prior to impact.

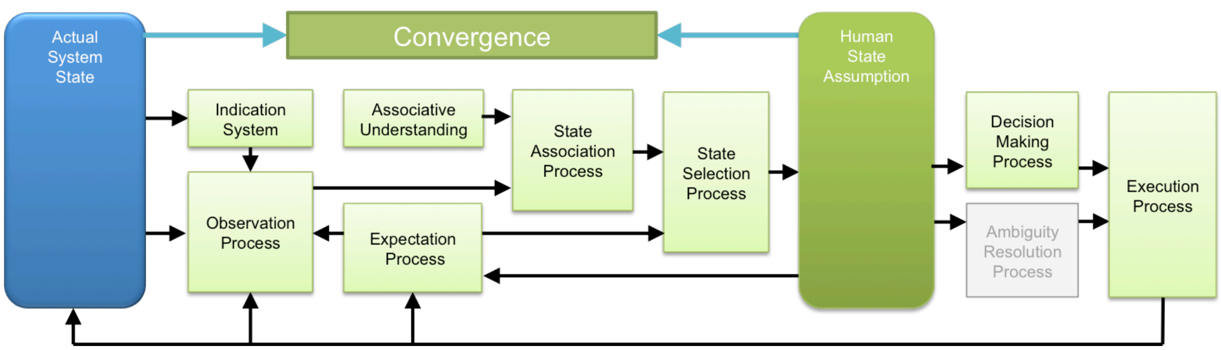

Figure 4-9. Human information processing model of divergence for Turkish 1951: Event E6

Despite recovery actions initiated 6 seconds later, impact occurred 12 seconds after auto-throttle disconnection. Aircraft documentation from the manufacturer stated that at least 500 feet of altitude was needed to recover from a full stall (Dutch Safety Board, 2010). The report also stated that if the crew had followed stabilized approach procedures, they would have been required to execute a missed approach at 1000 feet altitude, which would have prevented the accident.

4.3.1.7 Summary of Turkish Air 1951

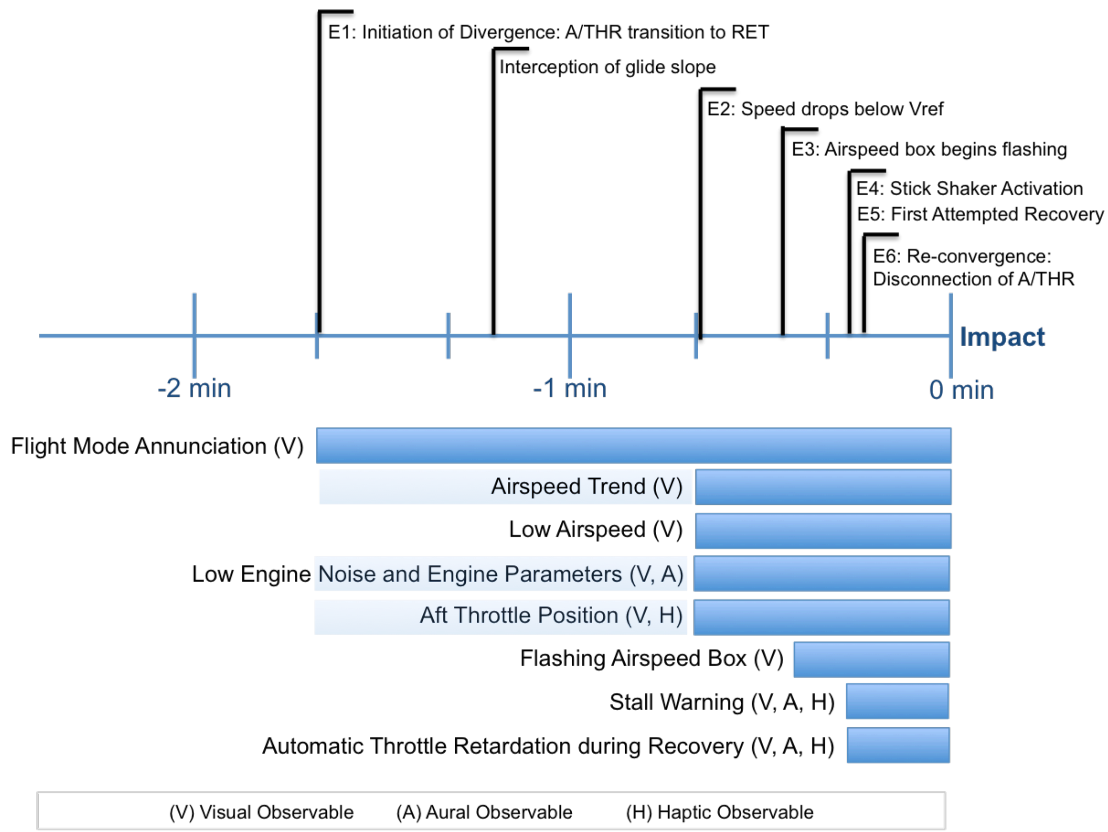

Figure 4-10. Definitive observables for Turkish 1951 and timeline they were available to the crew

The accident of Turkish Air 1951 illustrated a full process of unknown divergence to known divergence to re-convergence. In this case, there were a number of factors influencing the observation process such as expectation bias, distraction and workload from the vertical profile and glide slope interception from above, and possible design influence of the insufficient salience of the FMA indication to capture the crew's attention. In terms of the association process, there was no evidence of failures in associative understanding however there was likely a period of ambiguity of observables due to the descent masking many of the nominally definitive variables to the crew. Finally, expectation process failures were seen and possibly influenced by issues with system understanding of the effect of a radar altimeter failure on a coupled approach resulting in an abnormal transition, in addition to once divergence occurred it fed back into expectation essentially perpetuating the false expectation.

Table 4-2. Summary of process failures for Turkish Air 1951

Case \ Failure	Occurrence of Observation Process Failure					Occurrence of Association Process Failure		Occurrence of Expectation Process Failure		
	Expect-ation Bias	Dist-raction	Work -load	Fatigue	Design Influences	Associative Under-standing	Ambiguity of Observables	Abnormal Transition	System Under-standing	Perpetuation of Divergence
Turkish Air 1951	x	x	x (high)		x		x	x	x	x

As in any case where divergence could play a part in the accident, it is generally a piece of a greater picture. In this case, a previous radar altimeter failure combined with a failure of the error checking code apparently caused the auto-throttle to revert to an abnormal mode on approach. Ultimately, it was the timeline of the divergence compared to recovery potential of the situation that likely led to the consequential impacts of this accident. The divergence however can be assessed in the greater accident context when illustrating causal factors. Turkish Air 1951 highlighted the impact of divergence in auto-throttle state, however divergence in other automation states can also result in accidents. This is illustrated by the next case study, Air Inter Flight 148.

4.3.2 Case Study 2: Air Inter Flight 148

The accident of Air Inter 148 occurred on January 20, 1992 near Strasbourg, France, the wreckage of which is shown in Figure 4-11. This accident occurred as the crew flew an abnormal approach into the airport. During the initiation of final approach descent, the crew apparently inadvertently input a descent rate of -3,300 fpm into their Flight Control Unit (FCU) when likely intending to set a -3.3 degree flight path angle (FPA). The vertical flight profile of divergence for this accident is provided in Figure 4-12, and the observables available to the crew throughout the divergence timeline is provided in Figure 4-18. The crew apparently did not recognize their mistake and the aircraft eventually impacted a mountain short of the runway. There were a number of likely human information process failures involved in this accident including missed observations, incorrect expectation, many non-definitive observables affecting the discriminability of state in the association process, and a possible associative understanding failure of the observables appropriate for a -3.3 degree glide path. The process model of divergence was used to identify the impacts of different failures in individual processes relating to the divergence in vertical flight path value (V/S or FPA).

Figure 4-11. Wreckage of Air Inter Flight 148 (Ministry of Transport, 1993)

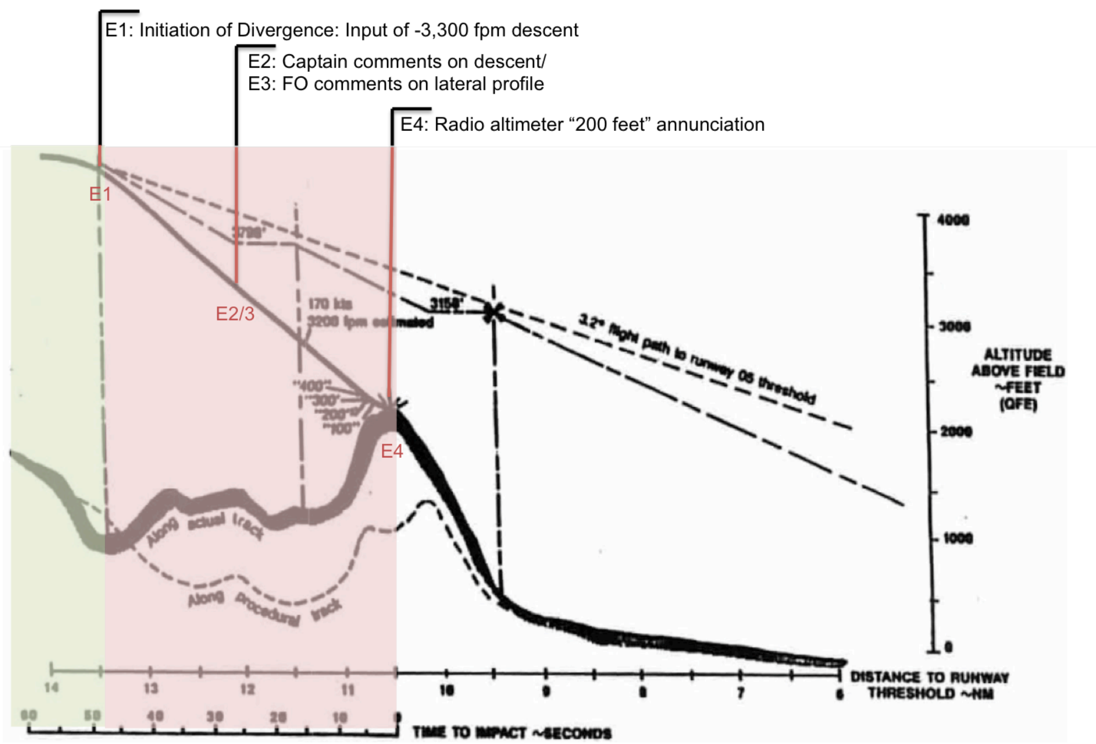

Figure 4-12. Altitude profile of Air Inter Flight 148 with divergence overlay (Bateman, 1991)

4.3.2.1 Event E1: Initiation of Divergence

Time	Impact – 00m 57s
Actual State	Vertical Rate Target: -3,300 fpm
Situation	Initiation of descent on final approach
Event Trigger	Change in actual state
Divergence Type	D-1b: Actual state transitions due to upstream input by the crew

Table 4-3. Difference in flight path angle and vertical speed vertical flight path values (Ministry of Transport, 1993)

Vertical Flight Path Value	FCU Annunciation	Target Descent Rate
Flight Path Angle		**- 3.3 degree glide path descent** (approximately -1000 feet per minute)
Vertical Speed		**- 3,300 feet per minute descent** (approximately -10 degree glide path)

In this accident, divergence was considered triggered when the crew apparently inadvertently set -3,300 fpm into the FCU while likely intending to set -3.3 degrees flight path angle (FPA). This section discusses how the crew could have failed to observe the correct vertical flight path value, could have held an incorrect expectation, and how indefinitive observations could have contributed to an inability of the association process to output a single definitive possible state that was consistent with the set of observations. At the initiation of divergence, failures in observation, association and expectation processes were apparent based on the crew's behavior.

Initially, it is relevant to discuss the observables available to the crew to discriminate the vertical flight path value. The single definitive observable available to the crew at this point was the text label ("V/S" or "FPA") and decimal, shown in Table 4-3 on the FCU, as the two discriminating characteristics between the V/S and FPA modes (Ministry of Transport, 1993). The FCU was located on the forward panel of the cockpit between the two pilots, which could effect readability of the values on the panel. Typically the automation mode was also depicted on the FMA, however in this case, the A320 had not provided information on vertical path value on the PFD because these modes were linked to different lateral modes. Instead of providing indication on the FMA, the designers elected to provide subtle cues on the navigation

(NAV) display to differentiate vertical path value (Ministry of Transport, 1993). "The only differences in presentation between the two reference modes from the point of view of the method of displaying values concern, in fact, on the one hand the brightness and length of the yellow heading indicator, which are not as great in Track (TRK) TRK-FPA mode, and on the other the appearance of the navigation display horizontal marker in TRK mode for the selected magnetic track. However, there is also a vertical indicator (cyan-coloured) similar to the one used everywhere else as a heading indicator" (Ministry of Transport, 1993).

While these observables may technically have been definitive observables, the report highlighted discriminability issues and that these observables which the crew was probably not trained to look for (Ministry of Transport, 1993). Thus, these observables would have been expected to exist in the pilot's associative understanding of the flight path value modes. In addition to these definitive observables, there was the initiation of descent, which illustrates a change in altitude and vertical speed. These two observables were indefinitive because they could have potentially signified either the V/S or FPA mode until the descent was established. The observables discussed in this paragraph were the only indications available to the crew on the state of the system during the divergence timeline. We can use the human information processing model of divergence to assess how the crew responded to the unexpected mode transition with the above-mentioned observables.

Because a descent was probably expected in the FPA mode the crew attempted to set, it is reasonable to assume that they observed the descent, but did not associate the initiation of descent with the correct mode. This failure in the association process is discussed later in this section, however because the non-definitive observables were probably observed, the likely failure in the observation process probably involved missed observations of the definitive observables displayed on the FCU and navigation display. This failure could have strong ties to system design, since the strongest apparent indication the crew had into the vertical flight path value was the annunciation on the FCU. This indication however, was not actually very strong considering it was outside the normal field of view of the crew and in small font. The readability of the FCU was not the only display issue. There were the subtle indications on the navigation display. These distinctions relied on the crew identifying subtle differences in brightness and discriminating similar symbols that nominally referred to heading. Using brightness to discriminate modes posed a concern due to the environment in the cockpit such as varying ambient lighting causing contrast differences. Perceived brightness changes would not likely be expected to provide sufficiently discriminating indication between states. The final design consideration discussed is the possible use of the heads up display (HUD) during this accident. It's possible that use of the HUD could have influenced the observation strategy of the captain.[48] If the HUD was used, this could have contributed to possible focus on the HUD, which did not have the flight path value depicted. As can be seen, there were a number of possible design aspects to the lack of observation of the vertical flight path value.

In addition to design issues affecting observation of the definitive observables, the crew was also apparently busy performing a non-standard approach to the runway. This, coupled with confusion on lateral profile and confusion with air traffic control (ATC), could have resulted in high workload and distraction from nominal scan patterns, including the scan of parameters related to the vertical flight profile.[49] In addition to the distraction, expectation bias could also have influenced the observation process since their expectation had likely updated to reflect their intended action of inputting -3.3 degrees FPA into the FCU. In addition if the crew had not understood the implication of not switching the vertical flight path value, this could indicate the presence of a systems understanding issue affecting expectation. There were many influences to the observation process, however failures in the association process were also possible at this stage.

A possible association process failure could have occurred if observation of only indefinitive observables had been made. In addition, the lack of training (in addition to the readability issues) of the subtle cues on the NAV display likely resulted in a failure of associative understanding. The initiation of descent provided indefinitive observables, like altitude and vertical speed, which could have been attributed to both FPA and V/S. The transition apparently resulted in observables that, while nominally may be definitive, became indefinite for some period of time. This lack of definition would likely have dissipated once the descent rate was established which was three times more than the descent rate should have been for a -3.3 degree glide path (Ministry of Transport, 1993). The failures in the observation process and association process could have been trapped in the state selection process if the expectation was correct, however, as discussed, the expectation process at this point in the timeline was likely also failed. Figure 4-13 illustrates the effect of the failures on human information processing. The combination of all of these three apparent failures that could have led to unknown divergence of vertical flight path value; there would not have been a possible way to contain all of these all of these simultaneous failures in the context

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[48] While the data did indicate that the HUD was turned on, there was not data recorded on whether the HUD was actually deployed from its stowed position. Thus, its not possible to ascertain whether the crew was using the HUD during the approach.

[49] There was no evidence in the report to indicate that fatigue was a factor in this accident

of the model. While observation process failures were apparently a strong contributor to this divergence, there was a brief alleviation of the observation process failure 26 seconds prior to impact.

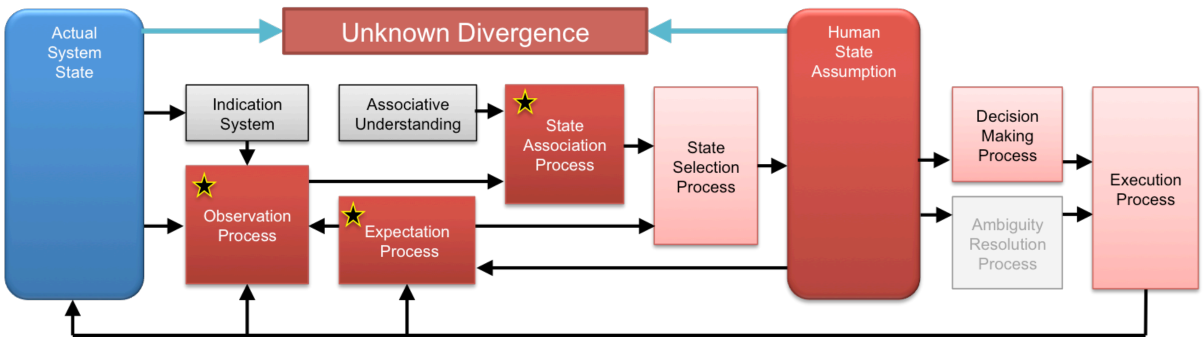

Figure 4-13. Human information processing model of divergence for Air Inter 148: Event E1

4.3.2.2 Event E2: Captain (PF) comments on descent

At 26 seconds prior to impact, the pilot flying commented on the descent. Translated from French he declared, "We'll have to watch it doesn't descend" (Ministry of Transport, 1993).[50] Since the captain had made observations independent of the first officer (FO), there was likely a difference in human information processing between them; thus, they were analyzed separately for this part of the divergence timeline. We'll start with the captain as he had held pilot flying duties.

4.3.2.2.1 Pilot Flying (Captain)

Time	Impact – 00m 26s
Actual State	Vertical Rate Target: -3,300 fpm
Situation	On final approach descent for runway
Event Trigger	Change in observation

At this point in the timeline, the descent rate had become a definitive variable as it likely provided discriminating information between FPA and V/S. This was approximately three times the normal descent

[50] It was not clear from the evidence how the crew observed the descent (i.e. via display, out the window, or HUD). The accident occurred at night one night following a full moon, however reports indicated a stratocumulus layer of clouds at 2000m. It was not determined whether the crew was IMC at any point in the descent. (Ministry of Transport, 1993)

rate for a -3.3 degree glide path, should have provided discrimination between FPA and V/S. However, this added observation did not appear to alleviate the divergence apparently, because while the observation process failure had possibly recovered, an underlying failure in associative understanding appeared to emerged.

This possible failure in associative understanding was indicated by the captain not considering the descent rate as abnormal. It was expected that had the captain recognized the gravity of a -3,300 fpm descent that he would have prioritized taking action to arrest the descent. Because no action was taken, it is possible he did not have a clear mental model of the dynamics of the aircraft in different modes with which to base his associative understanding on. As mentioned, while this apparent associative understanding failure was uncovered, the association process failure due to the solely indefinitive set of observations feeding to the process, was likely alleviated once the descent rate was established at 3,300 fpm providing an added definitive observable that made it to the association process. Figure 4-14 shows the effect of the newly uncovered associative understanding failure. Despite the possibility that a definitive observable reached the association process, the combination of the emergence of a possible failure in associative understanding and the alleviation of the failure in the association process, resulted in a similar contamination of human information processing likely contributing to continued unknown divergence for the captain.

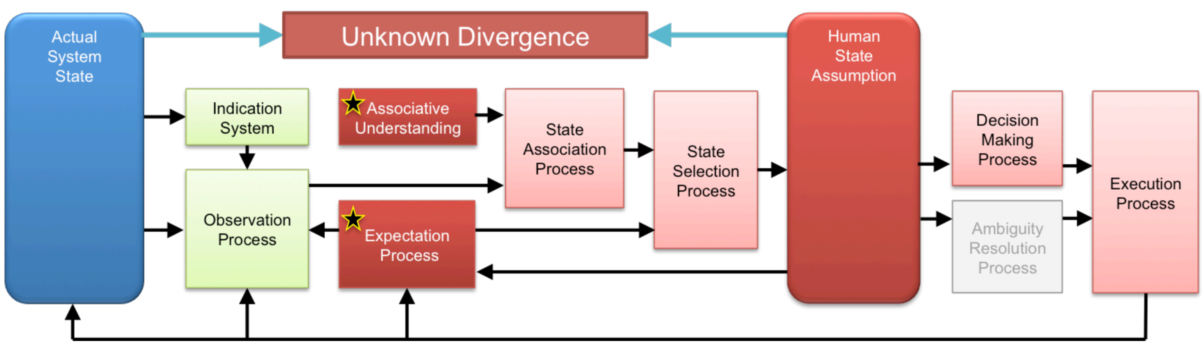

Figure 4-14. Human information processing model of divergence for Air Inter 148: Event E2 (captain)

4.3.2.2.2 Pilot Not Flying (First Officer)

Time	Impact – 00m 26s
Actual State	Vertical Rate Target: -3,300 fpm
Situation	On final approach descent for runway
Event Trigger	Change in observable

The first officer on the other hand, likely held a different interpretation of the system. Because the captain commented on the descent rate, a new observable was available to the first officer. Normally, this should trigger attention to be directed to the vertical speed indicator, however the first officer simultaneously commented on the lateral profile. Because there was no evidence that the captain's comment was heard, this likely indicated no change in his human information process, thus indicating continued observation process and expectation process failures for the first officer. This combination of failures is shown in Figure 4-15, illustrating that unknown divergence apparently continued for the first officer, despite the captain's comment. The simultaneous comment made by the first officer is discussed in the next section, as it likely introduced another distraction from managing the vertical profile of the aircraft.

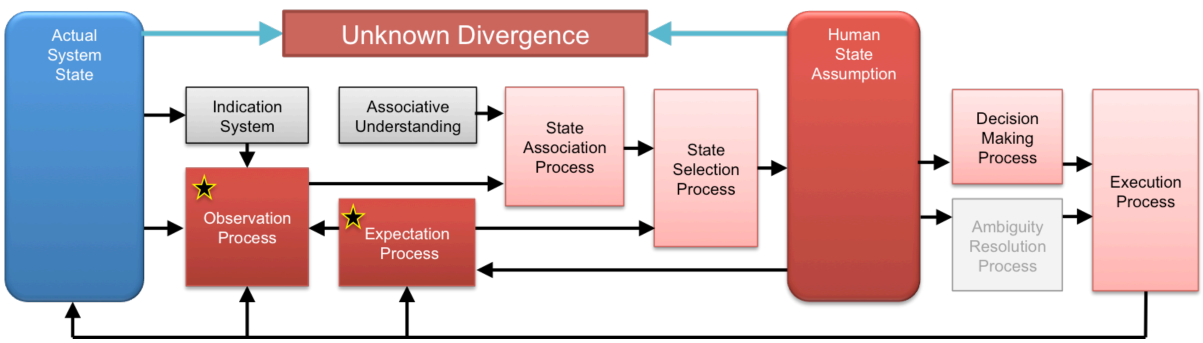

Figure 4-15. Human information processing model of divergence for Air Inter 148: Event E2 (first officer)

4.3.2.3 Event E3: First officer (PNF) comments on lateral profile

Time	Impact – 00m 26s
Actual State	Vertical Rate Target: -3,300 fpm
Situation	On final approach descent for runway
Event Trigger	Change in observation

At the same time the captain commented on the descent rate, the first officer commented on the lateral profile that the crew had shown confusion with earlier. This distraction possibly caused the captain to refer his attention to the lateral profile possibly compromising the observation of descent rate, reintroducing the observation process failure.[51] In addition, the expectation process failure likely

[51] Simultaneously to the PF comment on descent, the PNF states "On centerline… Half a dot from centerline. There it is, it had been at sixty, it's good, you see here" (Ministry of Transport, 1993). In

continued, and the captain's possible failure of associative understanding, revealed in Event 2, also likely continued, since that understanding was formed from prior experience and not likely to be easily updated in real time. Figure 4-16 depicts this combination of failures and the effect on human information processing. If the observation process failure was re-introduced, no containment would have been possible for the combination of observation, association, and expectation process failures. Thus, despite the recovery in observation the captain possibly experienced in the previous event, the comment made by the first officer likely re-compromised the observation process and unknown divergence appeared to continue to prevail. [52]

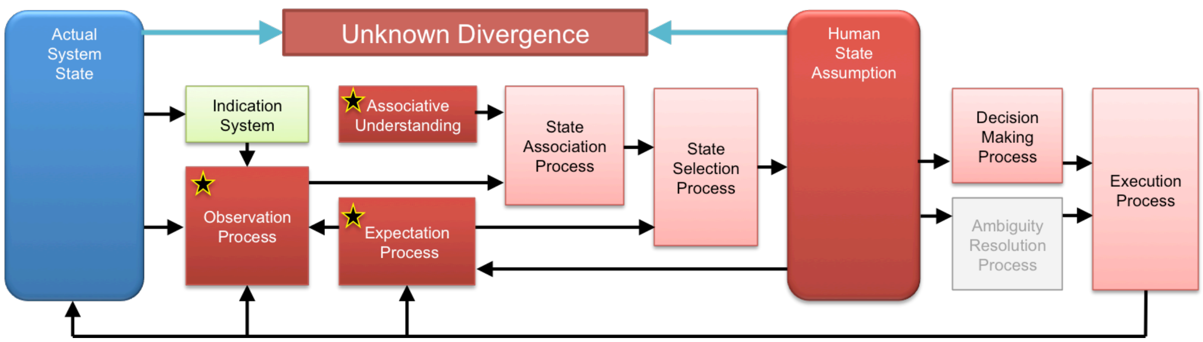

Figure 4-16. Human information processing model of divergence for Air Inter 148: Event E3

4.3.2.4 Event E4: "Two Hundred" radio altimeter call out

Time	Impact – 00m 01s
Actual State	Vertical Rate Target: -3,300 fpm
Situation	Immediately prior to impact
Event Trigger	Change in observables

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addition, if the crew had indeed observed the descent rate or any other definitive observable, it would be expected that they would have taken action immediately given the criticality of the situation. Since no action was taken, it was inferred that the observation process failed.

[52] The accident report indicated that the crew had missed numerous procedural callouts from the operations manual during the approach (Ministry of Transport, 1993). If conducted, these may have been sufficient to cue the crew to the abnormally high descent rate. No details about which callouts were missed were presented in the report.

Unknown divergence likely continued until the radio altimeter made an altitude call out. One second prior to impact, the radio altimeter issued a “Two Hundred” aural call out. Since this signal was likely salient, it is possible that the crew observed this signal. Because the signal occurred 1 second before impact, there was no time for the crew to respond verbally or manually, so there was no evidence of whether the crew observed or did not observe the signal. If they did not observe the call out, unknown divergence likely continued until impact.

If the call out was observed and associated correctly, this observation would have provided the association process a definitive observation to associate with possible states. This possible recovery of the observation process and its effect on human information processing is shown in Figure 4-17.

This, in theory, would have output state(s) that were inconsistent with the incorrect expectation. The failure in the expectation process would have been trapped in the state selection process provided that the set of observations were actually associated with a state inconsistent with the expectation. This would have resulted in known divergence. However, due to the criticality of the situation, the crew would not have had enough time to recover even if they had recognized divergence at this point.[53]

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[53] Simulated behavior of the aircraft during final approach demonstrated that it takes 7 seconds to arrest the vertical speed “when break-off is initiated in auto-pilot (load factor approximately 1.25g). This is reduced to about 5 seconds if the break-off is initiated in manual mode and the control column is pulled fully back (load factor is then limited to 2g). In both cases, reaction to the alarm would have enabled the aircraft to avoid hitting Mont La Bloss. According to the manufacturer, flight tests would have shown that the average reaction time needed for the crew to take avoiding action is 5 to 6 seconds after the alarm sounds for the Mark II and III, and with pilots trained to use the GPWS in the simulator. A simple arithmetical calculation (6+7=13 is less than 18) therefore seems to confirm that a GPWS would have saved the aircraft, even for a flight path where the break-off was in auto-pilot. In fact, such confirmation, based on an order of magnitude whose significance is purely statistical (average reaction time), would be totally simplistic if it were to be applied to a particular event, because crew reaction time to a given alarm signal is not a deterministic process” (Ministry of Transport, 1993).

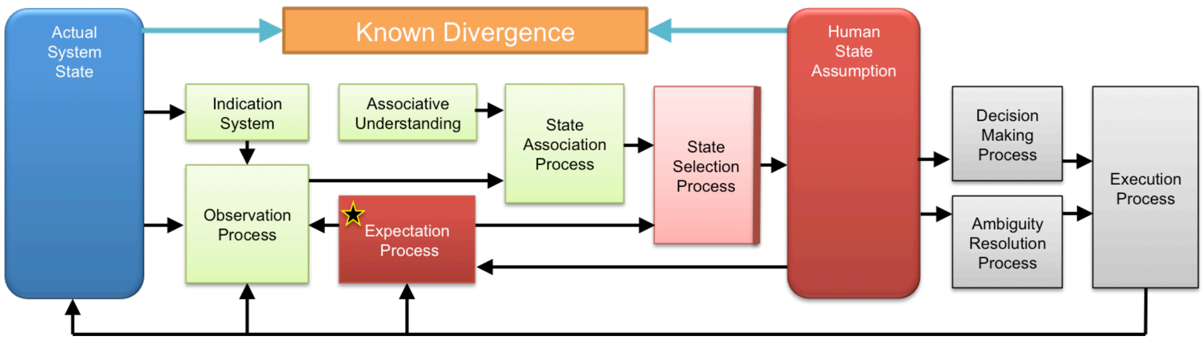

Figure 4-17. Human information processing model of divergence for Air Inter 148: Event E4

4.3.2.5 Summary of Air Inter 148

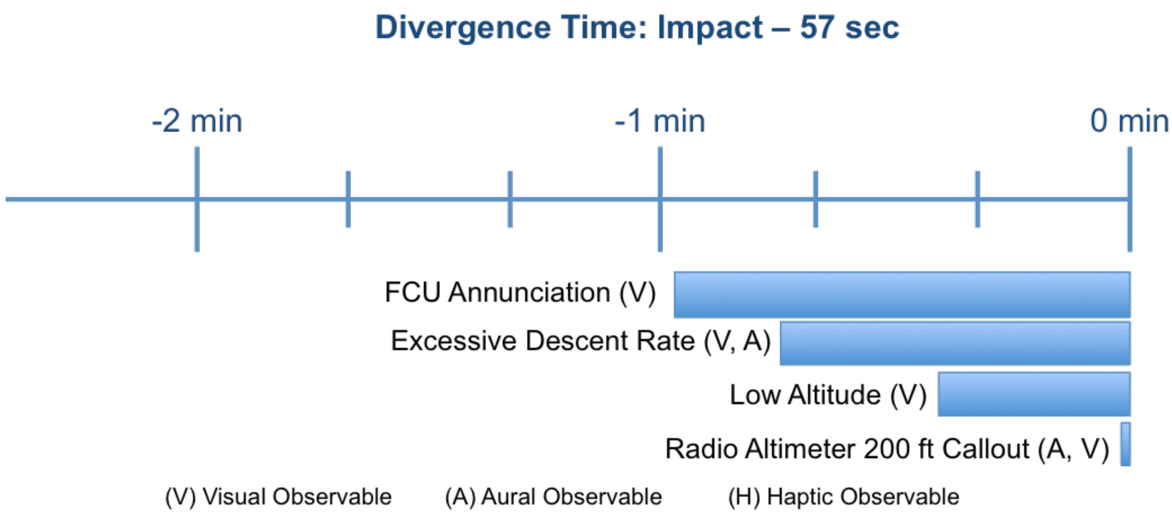

Figure 4-18. Definitive observables apparent in Air Inter 148 and the timeline when available to the crew

The assessment of divergence, in this case involved the automation vertical rate target as the state of interest. Failures in the observation, association, and expectation processes could have played a part in this accident. Expectation bias, distraction and high workload due to abnormal lateral profile, and possible design influences of the indications of state could have all influenced the observation process failure. Since the captain may not have associated the excessive descent rate with the V/S mode, this would have indicated an associative understanding failure. There was also a period of ambiguity of observables when the descent was initiated. In terms of expectation problems, it is possible that if the crew did not understand the implication of the incorrect selection of the vertical flight path value, an abnormal transition, that this would indicate a problem in system understanding. It was apparent that divergence could have propagated this expectation failure as well.

Table 4-4. Summary of process failures for Air Inter 148

Failure / Case	Occurrence of Observation Process Failure					Occurrence of Association Process Failure		Occurrence of Expectation Process Failure		
	Expect-ation Bias	Dist-raction	Work -load	Fatigue	Design Influences	Associative Under-standing	Ambiguity of Observables	Abnormal Transition	System Under-standing	Perpetuation of Divergence
Air Inter 148	x	x	x (high)	no data	x	x	x	x	x	x

It is important to recognize where this assessment fit in terms of the greater situation awareness picture. The crew also had lapses in position awareness over terrain. Another aspect of this accident involves the use of the ground warning proximity system (GWPS), which the airline had elected not to equipped their fleet with at the time of the accident (Ministry of Transport, 1993). This GWPS could have given the crew a salient indication of upcoming terrain, indirectly giving them information regarding descent rate. These organizational issues combined with the systems and human factors involved with divergence in vertical flight path value likely contributed to the consequential effects of this case of divergence.

4.3.3 Case Study 3: Eastern Airlines Flight 401

The accident of Eastern Airlines Flight 401 occurred on December 29, 1972 in the Florida Everglades, shown in Figure 4-19 (National Transportation and Safety Board, 1973). In this accident, the crew established the aircraft in a holding pattern using an auto-pilot altitude hold mode while the crew troubleshot a landing gear failure. While troubleshooting, the autopilot altitude hold disconnected and the aircraft began a slow descent, apparently unbeknownst to the crew. This descent is illustrated in Figure 4-20 and the definitive observables available to the crew throughout the descent is shown in Figure 4-25. The crew's verbalization indicated that they recognized the altitude deviation just prior to impact (National Transportation and Safety Board, 1973). This accident illustrated failure in the observation process, likely attributed to distraction while troubleshooting the gear failure, and could have been compounded by a failure in the expectation process introducing expectation bias. The detailed events of the apparent divergence in this accident are described below.

Figure 4-19. Wreckage of Eastern Airlines 401 (Markowitz, 1972)

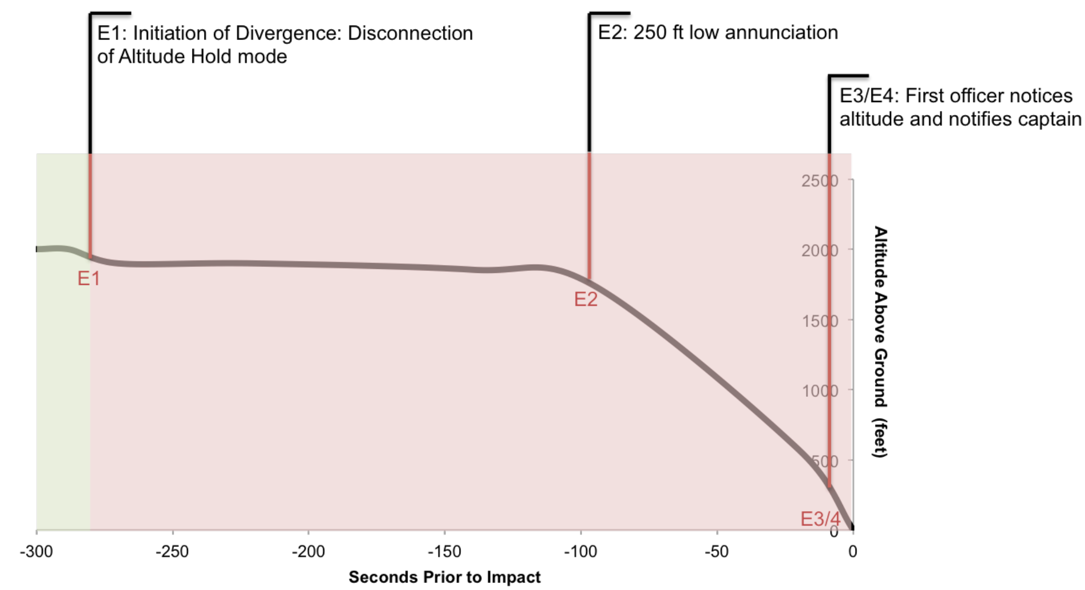

Figure 4-20. Approximate altitude profile for Eastern Airlines Flight 401 accident with divergence overlay (National Transportation and Safety Board, 1973)

4.3.3.1 Event E1: Initiation of Divergence

Time	Impact – 04m 48s
Actual State	Auto-pilot vertical mode: OFF
Situation	In holding pattern at 2000 feet
Event Trigger	Change in actual state
Divergence Type	D-1b: Actual state transitions due to upstream input by the crew.

Event E1 presumably triggered the divergence when while diagnosing the landing gear failure, the autopilot altitude hold disengaged, and the aircraft began a slow descent. At this point in the timeline there was evidence of an observation process failure as the crew showed no behavioral evidence of recognizing the disconnect, as well as an expectation process failure as the crew had manually set the altitude hold mode prior to beginning troubleshooting; Thus, without observing new information, they likely had no reason to believe that this state had changed. The details of these failures are described below.

While no conclusive cause of the disconnect was found, the reigning hypothesis was that a moderate force applied to the yoke caused the automation to disconnect (National Transportation and Safety Board, 1973).[54] The automation was not designed to aurally annunciate with a disconnection. Because the

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[54] The accident report describes that when the altitude hold is established in control wheel steering mode, which it was for this accident,"… pilot-applied pitch forces on the control wheel [of 20 lbs. or greater] will cause disengagement of the altitude hold function, reverting the autopilot pitch channel to attitude stabilization sensitive to control wheel inputs. … It is possible, therefore, to disengage altitude hold without an accompanying "CMD DISC" warning appearing on the captain or first officer annunciator panels. The normal indications of such an occurrence would be only the extinguishing of the altitude mode select light on the glare shield and the disappearance of the "ALT" annunciation on both annunciator panels." (National Transportation and Safety Board, 1973)

Provided the above logic in the automation, the following was hypothesized to have occurred by the investigative team. "At approximately 2337, some 288 seconds prior to impact, the DFDR readout indicates a vertical acceleration transient of 0. 04 g causing a 200-fpm. rate of descent. For a pilot to induce such a transient, he would have to intentionally or inadvertently disengage the altitude hold function. It is conceivable that such a transient could have been produced by an inadvertent action on the automation disconnected without aural annunciation, the only observables available to the crew are depicted in Figure 4-21 and included (1) a visual change in both the captain's (shown) and first officer's (not shown) annunciation panel, and (2) the extinguishing of the altitude mode select light on the autopilot control panel.[55] These both classify as definitive observables, along with any deviation of altitude from their 2000-foot target. Despite the availability of multiple definitive observables available to the crew, the crew appeared to have resulted in unknown divergence. The report did not include data on fatigue effects on the crew.

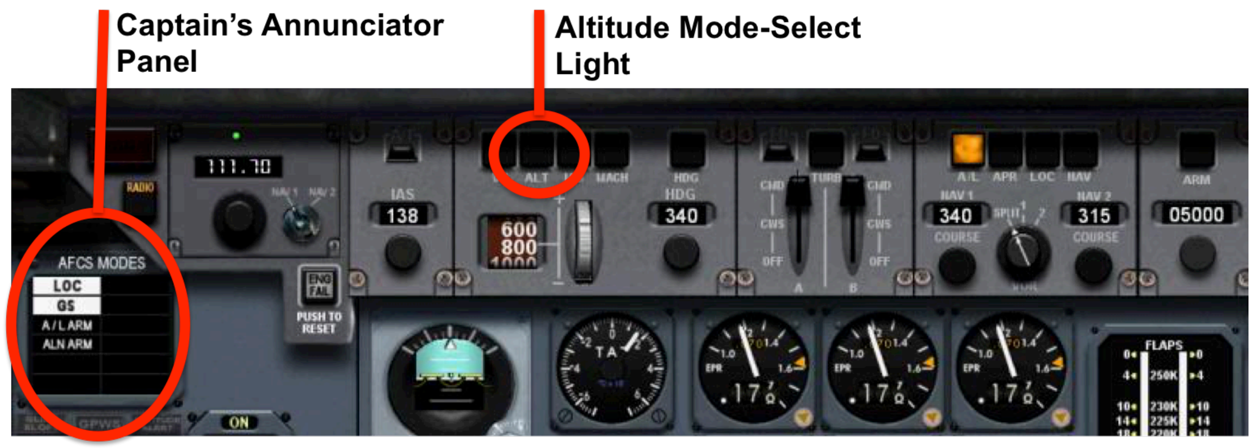

Figure 4-21. Depiction of captain's annunciator panel and altitude mode-select light in the L1011 [adapted from ("L1011 Main Panel Features," 2010)**]**

There was no evidence that the crew observed the auto-pilot altitude hold disconnect or any observables related to it due to the lack of response (to fly manually or re-connect the altitude hold) that would have been expected if the crew had observed the disconnect. While the lack of salience of the disconnect

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part of the pilot, which caused a force to be applied to the control column. Such a force would have been sufficient to disengage the altitude hold mode. It was noted that the pitch transient occurred at the same time the captain commented to the second officer to "Get down there and see if the . . . nose wheel's down. " If the captain had applied a force to the control wheel while turning to talk to the second officer, the altitude hold function might have been accidentally disengaged! Such an occurrence could have been evident to both the captain and first officer by the change on the annunciator panel and the extinguishing of the altitude mode select light." (National Transportation and Safety Board, 1973)

[55] Due to design of the system, the altitude mode select light may have been inhibited below 2,500 ft. (National Transportation and Safety Board, 1973)

possibly played a part, the most prominent factor was likely related to the distraction the crew was facing with troubleshooting the landing gear failure. This apparently captured attentional resources of the entire crew, also highlighting crew resource management issues that could have contributed to these missed observables. Finally since the crew had taken action to set the autopilot to altitude hold at 2000 feet, their expectation had likely updated to reflect that action. It is also possible that expectation of altitude hold could also have resulted in expectation bias influencing the scan of the observables. In addition, the report also noted that the crew likely were not aware of the force required to disengage the altitude hold (National Transportation and Safety Board, 1973). If this was true, it would indicate the presence of a systems understanding issue affecting expectation. The effect of this combination of failures on human information processing is shown in Figure 4-22, The combination and interaction of the failures in the expectation process and observation process likely contaminated the association and state selection processes preventing the individual failures from being contained in those downstream processes. Thus, this apparently resulted in unknown divergence at this point in the divergence timeline.

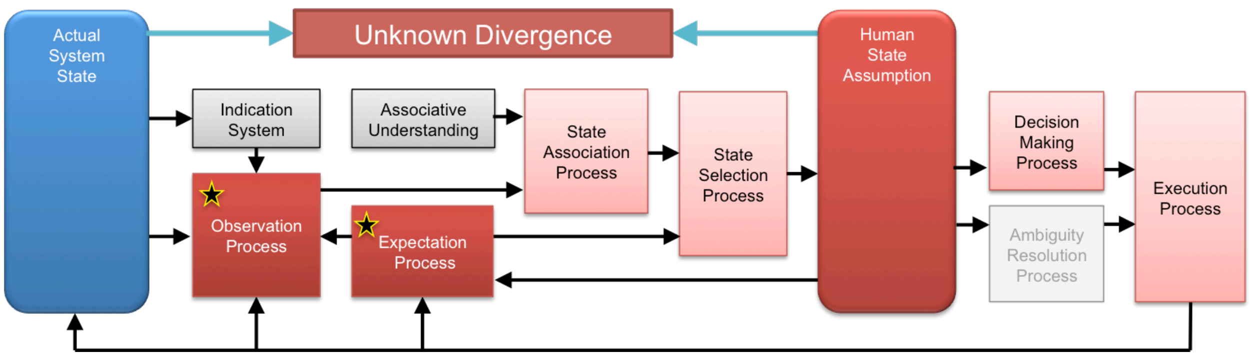

Figure 4-22. Human information processing model of divergence for Eastern 401: Event E1 and Event E2

4.3.3.2 Event E2: Aural Annunciation of 250 feet low

Time	Impact – 01m 34s
Actual State	Auto-pilot vertical mode: OFF
Situation	In holding pattern, slow descent
Event Trigger	Change in observables

While the disconnect did not alert aurally, the crew did apparently receive an aural annunciation that the altitude was low. At 1,850 feet mean sea level (MSL), a half second, c-chord, aural annunciation reportedly triggered indicating that the aircraft was 250 feet below its target altitude. This provided an additional definitive observable into the state of the autopilot. This added information could have triggered known divergence if it had been observed by the crew. However, the distraction from the gear failure was apparently ongoing at this point in the accident timeline, and there was still no evidence apparent in the report that the crew heard the alert. This combination of failures is shown in Figure 4-22. Because the added observable was apparently missed and expectation probably held steady, the crew likely remained in unknown divergence through this time frame.

4.3.3.3 Event E3: First Officer Notices Low Altitude

The first officer eventually verbalized concern about the altitude, which was approximately 400 ft. MSL at this point.[56] This verbalization was likely the result of an observation made by the first officer of the altimeter (based on his comment). At this point prior to verbalization, there was inconsistency between the first officer's and the captain's assumption of state. Because the event was triggered by the first officer alone noticing the altitude deviation, the captain's state was not expected to change during this intermediate event (of the FO noticing the low altitude). Thus, this section is discussed purely concerning the first officer's human information process.

Time	Unknown[57]
Actual State	Auto-pilot vertical mode: OFF
Situation	In holding pattern, slow descent
Event Trigger	Change in observation

At this point in the timeline, the crew had completed troubleshooting the landing gear failure and had decided to return to the airport for landing. This could have alleviated the workload and distraction limitation on the observation process, likely allowing the first officer an opportunity to scan the flight instruments. Failures in the expectation process likely remained despite the apparent observation of the definitive observable of altitude by the first officer. Figure 4-23 shows the recovery of the observation process and its effect on human information processing. The discrepancy between expectation and observation apparently caused the failure to be trapped in the state selection process. This would result in the first officer moving into known divergence. As indicated by the first officer verbalizing his concern

[56] First officer states "We did something to the altitude."

[57] Time of first officer observation of the altimeter was not available in the data, however could have been just prior to verbalization. This verbalization behavior would have been consistent with expected behavior provided he recognized the potential criticality of the situation.

for the altitude, the result of the ambiguity resolution process, showed evidence of the first officer attempting to use communication (at least in part) to resolve the ambiguity. The next event discusses the captain's update in human information process when the first officer told him about the altitude concern.

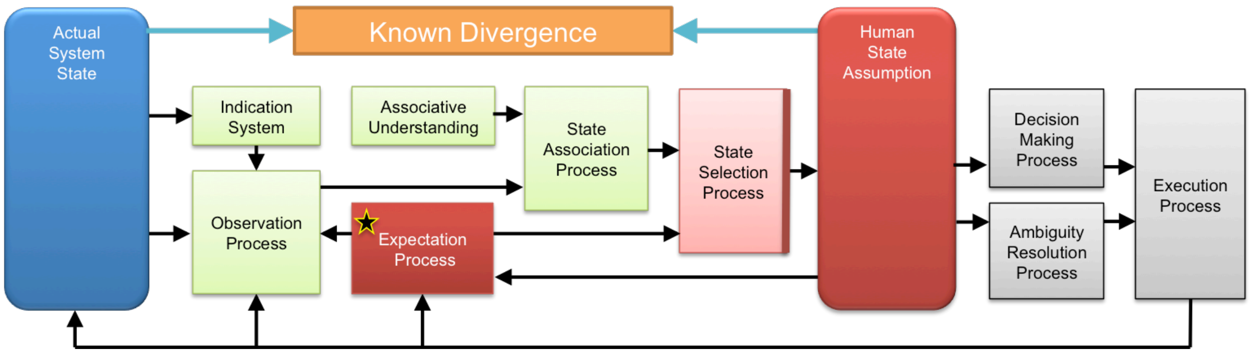

Figure 4-23. Human information processing model of divergence for Eastern 401: Event E3 (first officer)

4.3.3.4 Event E4: First Officer Notifies Captain about Altitude

Time	Impact – 00m 07s
Actual State	Auto-pilot vertical mode: OFF
Situation	In holding pattern, slow descent
Event Trigger	Change in observation

Seven seconds prior to impact the first officer verbalized confusion regarding the altitude. This apparently averted the captain's attention to the altimeter, and the altitude was likely observed as indicated by the confusion verbalized by the captain. If the observation process had recovered, the expectation process failure was likely the only failure that remained.

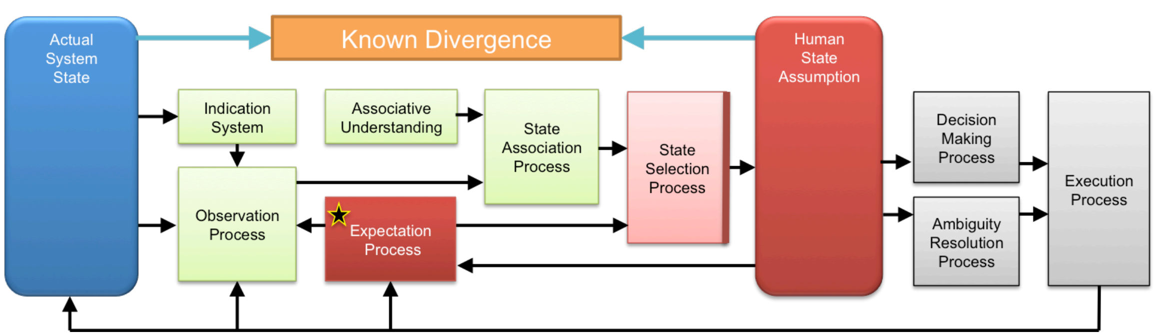

Figure 4-24. Human information processing model of divergence for Eastern 401: Event E4 (captain)

Similarly to the first officer's transition to known divergence, the captain also likely had a failure of the expectation process that was caught in the state selection process, when the expectation was compared to the states consistent with observation. This is shown in Figure 4-24. The captain's verbal response indicated scanning for more information and attempting to resolve the ambiguity.[58] Impact occurred, however, prior to any recovery action by the crew.[59]

4.3.3.5 Summary of Eastern Airlines Flight 401

In this case, the divergence state of interest was the vertical autopilot mode, which directly affected the aircraft altitude. The loss of awareness of the altitude apparently had consequential effects and was initially triggered by the inadvertent disconnection of the autopilot altitude hold. This case is different from the other accidents discussed here considering the availability of definitive observables. In the other accidents, definitive observables were minimally available until a point much later in the divergence timeline. Here, definitive observables were apparently readily available to the crew immediately following the disconnection.

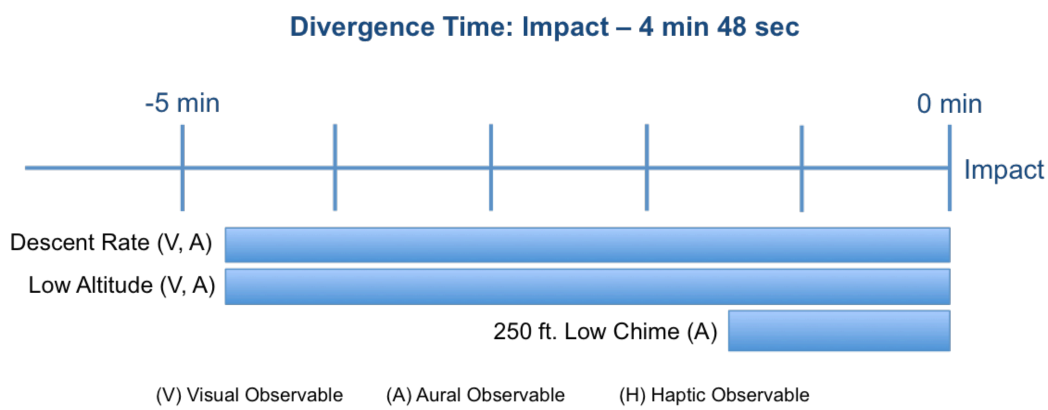

Figure 4-25. Definitive observables in Eastern 401 that were available during the divergence timeline

It appears that the observation process failure was impacted by the distraction of troubleshooting the failure. This is further supported by the observation of altitude being made by the first officer soon after the troubleshooting had ended and the crew had decided to return to the airport for landing. In addition to

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[58] "At 2342:05 , the first officer said, 'We did something to the altitude.' The captain's reply was, 'What?' At 2342:07, the first officer asked, 'We're still at two thousand, right?' and the captain immediately exclaimed, 'Hey, what's happening here?' (National Transportation and Safety Board, 1973)

[59] No assertions were made regarding the point of recoverability in the report of this accident.

distraction there was also likely expectation bias, high workload due to troubleshooting, and design aspects of inhibiting the mode select light below 2,500 ft. that could have affected the observation process failure. There was no evidence of associative understanding problems or ambiguity of observables given the number of definitive observables available to the crew. Finally, the expectation process failure could have been influenced by lack of system understanding of the force required to disengage the altitude hold, an abnormal state transition for the given situation, and was likely perpetuated by divergence. Also, because this divergence occurred during a holding pattern to troubleshoot a failure, there were not apparently a required checklist or procedure for that flight regime that would have caught this divergence.

Table 4-5. Summary of process failures for Eastern 401

Failure / Case	Occurrence of Observation Process Failure					Occurrence of Association Process Failure		Occurrence of Expectation Process Failure		
	Expectation Bias	Distraction	Work-load	Fatigue	Design Influences	Associative Understanding	Ambiguity of Observables	Abnormal Transition	System Understanding	Perpetuation of Divergence
Eastern 401	x	x	x (🡅)	no data	x			x	x	x

These characteristics highlight the influence of situational factors on divergence, information that can be used when aiming mitigations. This was the third and final case study discussed in detail in the body of this thesis, however the next section provides a summary of findings from all of the case studies that were analyzed.

4.4 Divergence in All Case Studies

The remaining accidents and incidents were analyzed in a similar manner to those presented in the previous section and are in Appendix D. The summary of how divergence and re-convergence occurred is presented in this chapter for all of the case studies. In addition, factors that affected process failures are also summarized with which common trends are identified for possible mitigation. Table 4-6 provides the list of accidents and incidents with corresponding details on whether the human, automation, or both transitioned when divergence was initiated, in addition to information on the origin of that transition.[60]

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[60] Also note that China 140 and Indian 605 included cases of multiple episodes of divergence during the event. These episodes were considered separately for this analysis.

Table 4-6. Summary of initiating divergence event in case studies analyzed (underlined states are states which appeared to transition during the divergence event)

		Case [61]	State of Interest	Actual Auto Throttle State		Inferred Human State Assumption		Description of Divergence	Divergence Type Divergence Trigger Divergence Origin
				Before Event	*After Event*	*Before Event*	*After Event*		
Auto-throttle Cases	Low Energy Cases	Asiana 214	Auto-throttle Mode	THR	HOLD	THR	SPD	Unexpected mode transition following improper use of FLCH to descend	D-3 Both Transition Human Origin
Auto-throttle Cases	Low Energy Cases	Turkish 1951	Auto-throttle Mode	SPD	RET	SPD	SPD	Radar altimeter failure caused the transition to RETARD when it would nominally have transitioned to SPD mode	D-1a Automation Transition Automation Origin
Auto-throttle Cases	Low Energy Cases	Thomson-fly (incident)	Auto-throttle Mode	SPD	OFF	SPD	SPD	A/T disengaged (cause unknown)	D-1a Automation Transition Unknown Origin
Auto-throttle Cases	Low Energy Cases	American 903 (incident)	Auto-throttle Mode	SPD	OFF	SPD	SPD	A/T disengaged (cause unknown)	D-1a Automation Transition Unknown Origin
Auto-throttle Cases	Low Energy Cases	Indian 605	Auto-throttle Mode	SPD	IDLE	SPD	SPD	Transition due to MCP Select	D-1b Automation Transition Human Origin
Auto-throttle Cases	Low Energy Cases	Indian 605	Auto-throttle Mode	IDLE	IDLE	IDLE	SPD	Crew behavior indicated that they considered the A/T mode to recover when they turned off FD1	D-2 Human Transition Human Origin
Auto-throttle Cases	High Energy Cases	Tarom 381 (incident)	Auto-throttle Mode	SPD	THR	SPD	SPD	Thrust increased to reach present MCP altitude due to momentary flap overspeed	D-1 Automation Transition Unclear Origin
Auto-throttle Cases	High Energy Cases	China 140	Auto-throttle Mode	SPD	THR	SPD	SPD	Crew inadvertently triggered TOGA	D-1b Automation Transition Human Origin
Auto-throttle Cases	High Energy Cases	China 140	Auto-throttle Mode	OFF	THR	OFF	OFF	Alpha floor initiations	D-1a Automation Transition Automation Origin
Auto-throttle Cases	High Energy Cases	Air France 72	Auto-throttle Mode	SPD	THR	SPD	SPD	Transition to TOGA at end of descent point due to lack of disengagement of the autopilot prior to end of descent point	D-1b Automation Transition Human Origin
CFIT Cases		Air Inter 148	Vert. Flight Path Value	ALT	V/S	ALT	FPA	Crew set FPA for descent however apparently neglected to switch value from V/S to FPA	D-3 Both Transition Human Origin
CFIT Cases		American 965	Lateral A/P Target	FMS-Cali VOR	FMS-ROZO	FMS-Cali VOR	FMS--ROMEO	Crew inadvertently set the first waypoint in the "RO" list likely intending to input ROZO, however enacting ROMEO	D-3 Both Transition Human Origin
CFIT Cases		Eastern 401	Vert. A/P Mode	ALT	OFF	ALT	ALT	Crew likely inadvertently disconnected the altitude hold during a holding procedure	D-1b Automation Transition Human Origin

The details of how divergence occurred varied between cases. While the actual transitions varied, the origin of those transitions were worth investigating. The underlined modes in Table 4-6 indicate the transition trigger for each accident. While the divergence transition was signified by various combination

[61] References for reports reviewed for each event are provided in Section 4.2

of human and automation triggers, the underlying origin of many transitions appeared to be predominantly due to human input.

Even in the eight cases where divergence occurred due to automation mode transition as the trigger, five cases showed evidence of the automation transition being a result of a human action upstream.[62] The Asiana 214, Air France 072, and Indian 605[63] cases apparently involved the crew knowingly commanding a vertical auto-pilot mode, however due to the coupling between the auto-pilot and the auto-throttle, the auto-throttle also reverted to a non-normal mode at some point downstream to the auto-pilot command, initiating divergence. The occurrence of the human origin of many cases of divergence could indicate a deficiency in crew understanding of automation mode effects and interactions. Sometimes procedures can be designed to attempt to reduce this knowledge burden on the human. For many of these cases, procedures actually appeared to be in place which, if followed, could have prevented the abnormal transition; thus, its possible that this may be an opportunity to enforce procedure adherence or reinforce procedure training with specific training on automation logic (Performance Based Aviation Rulemaking Committee & Commercial Aviation Safety Team, 2013). Overall, the results indicated that while divergence could originate with an automation transition, the cause could be often attributed to upstream human input. While it is possible that automation transition could trigger without upstream crew input, for example due to an internal error, the cases analyzed appear to err toward human involvement in initiation of divergence.

While human input could cause the automation state to change, human input could also change the state assumption of the human without actually causing a change in actual state of the system. In many cases, following an action the crew's behavior indicated that their state assumption had updated to a state different than what actually occurred. In Indian 605, the crew appeared to turn off the flight director in efforts to regain a nominal auto-throttle mode, however in reality both flight directors needed to be turned

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[62] For example, in the Asiana 214 case, the crew's abnormal use of vertical autopilot FLCH mode along with the action of retarding the throttles to idle apparently caused the auto-throttle to revert to the less frequently used HOLD mode. This HOLD mode transition was considered as the event where divergence initiated, however it was triggered by human input upstream.

[63] During China 140, the auto-throttle transition to TOGA appeared to be the result of an accidental activation of the TOGA button by the crew. Because this cause appears to be a slip versus a conscious decision by the crew, the discussion focuses on conscious crew input that appeared to result in an unexpected result.

off for the auto-throttle to revert to SPD mode. These cases could indicate a possible deficiency of systems understanding of automation logic. While it may be that, in an unconstrained environment, the crew may appropriately exhibit knowledge of differences between autopilot and auto-throttle disconnection, the high workload of the situations may have reduced the human information bandwidth available to discern the signals or recall the knowledge needed (Orasanu & Martin, 1998).

On the other hand, there were two cases where the origins of divergence could possibly have been attributed to the system. The first was Turkish 1951 where the transition was likely attributed to the faulty radar altimeter (Dutch Safety Board, 2010). The other system origin involved the Tarom 381 incident. In this case, a transient airspeed overspeed appeared to caused the envelope protection to activate and increase pitch and thrust to maintain airspeed within the flight envelope (Bureau d'Enquêtes et d'Analyses, 2000). As can be seen, in one case divergence was apparently caused by a component failure, in the other it was apparently caused by environmental factors associated with a temporary overspeed situation. These two examples highlight the direct design influence on divergence. While again in this case, procedures could in be in place to prevent transition to these abnormal modes, an improvement to the design of automation may be more proactive of a solution.

FINDING A: Divergence triggers and origins spanned both human and automation sources.

- Finding A-1: While divergence was shown in different cases to be triggered by human and/or automation transition, in the events where automation transition triggered divergence, many of these involved human action causing unexpected automation transition later in the timeline.

Re-convergence was apparent in many cases. A summary of re-convergence for each accident and incident analyzed is shown in Table 4-7.

Table 4-7. Summary of re-convergence event details in cases analyzed (underlined states are states which appeared to transition during the re-convergence event)

Case			State of Interest	Actual Auto Throttle State			Inferred Human State Assumption			Known Divergence Trigger	Re-convergence Trigger	Re- Conv. Type
				Before Div. Event	*After Div. Event*	*After Con. Event*	*Before Div. Event*	*After Div. Event*	*After Con. Event*			
Auto-throttle Cases	Low Energy Cases	Asiana 214	Auto-throttle Mode	THR	HO-LD	THR	THR	SPD	THR	Crew recognition of speed decay (Observation)	Crew action to advance throttles (Expectation)	C-3 Both Trans. Human Origin
Auto-throttle Cases	Low Energy Cases	Turkish 1951	Auto-throttle Mode	SPD	RET	OFF	SPD	SPD	OFF	Stick shaker activation (Observation)	Crew disconnection of auto-throttle (Expectation)	C-3 Both Trans. Human Origin
Auto-throttle Cases	Low Energy Cases	Thomson-fly (incident)	Auto-throttle Mode	SPD	OFF	OFF	SPD	SPD	OFF	Crew recognition of speed decay (Observation)	Crew recognition of speed decay (Observation)	C-2 Human Trans. Human Origin
Auto-throttle Cases	Low Energy Cases	American 903 (incident)	Auto-throttle Mode	SPD	OFF	OFF	SPD	SPD	OFF	Crew recognition of speed decay (Observation)	Crew recognition of speed decay (Observation)	C-2 Human Trans. Human Origin
Auto-throttle Cases	Low Energy Cases	Indian 605	Auto-throttle Mode	ALT	IDLE	IDLE	ALT	SPD	IDLE	Crew notices IDLE on display (Observation)	Crew notices IDLE on display (Observation)	C-2 Human Trans. Human Origin
				IDLE	IDLE	THR	IDLE	SPD	THR	Crew recognizes thrust increase when Alpha Floor Activates (Observation)	Crew recognizes thrust increase when Alpha Floor Activates (Observation)	C-3 Both Trans. Human Origin
Auto-throttle Cases	High Energy Cases	Tarom 381 (incident)	Auto-throttle Mode	SPD	THR	OFF	SPD	SPD	OFF	Crew Recognition that thrust was increasing (Observation)	A/T automatic disengagement due to loss of AOA data (Actual State Change)	C-3 Auto Trans. Auto Origin
Auto-throttle Cases	High Energy Cases	China 140	Auto-throttle Mode	SPD	THR	OFF	SPD	SPD	OFF	Crew recognition of thrust increase (Observation)	Disconnection of Auto-throttle (Expectation)	C-3 Both Trans. Human Origin
				OFF	THR	-	OFF	THR	-	Crew recognition of thrust increase (Observation)	No Evidence of Re-convergence	-
Auto-throttle Cases	High Energy Cases	Air France 72	Auto-throttle Mode	SPD	THR	-	SPD	SPD	-	Crew recognition of thrust increase (Observation)	No Evidence of Re-convergence	- -
CFIT Cases		Air Inter 148	Vert. Flight Path Value	ALT	V/S	-	ALT	FPA	-	Possibly when radar altimeter annunciates 200 ft. but no evidence of this (Observation)	No Evidence of Re-convergence	-
CFIT Cases		American 965	Lateral A/P Target	FMS-Cali VOR	FMS-RO-ZO	HDG SEL	Cali VOR	RO-ME-O	HD G SEL	ATC call for position update prompts crew to scan navigation display and recognize the divergence (Observation)	Selection of Heading Select Mode to control lateral target (Expectation)	C-3 Both Trans. Human Origin
CFIT Cases		Eastern 401	Vert. A/P Mode	ALT	OFF	-	ALT	ALT	-	Crew recognizes low altitude (Observation)	No Evidence of Re-convergence	-

- Auto-throttle cases - Re-convergence apparently occurred in all low energy cases analyzed and in 1 of three high energy auto-throttle cases. The distribution of how re-convergence was attained in these accident cases provided insight about how this process can occur; the underlined modes table indicate what transition triggered re-convergence. Re-convergence of Types C-2 and C-3 were common in the case studies and could potentially be stimulated by using operational procedures.
- CFIT cases - Table 4-7 also shows that re-convergence was attained in only one of the accidents that resulted in CFIT. This is likely due to the nature of these accidents where poor of situation awareness of position could contribute to the eventual impact with the terrain (Shappell & Wiegmann, 2003). The American 965 accident also exhibited evidence of divergence in channels other than the lateral mode target, such as vertical flight path awareness, that did not appear to re-converge.

FINDING B: Re-convergence occurred in some cases including accidents.

- Finding B-1: 5 of 5 low energy auto-throttle cases showed evidence of re-convergence occurring prior to impact for accident cases and prior to recovery for incident cases. Three of these were accident cases.
- Finding B-2: 1 of 3 high energy auto-throttle cases showed evidence of re-convergence occurring. This was the only incident case. Neither of the high energy accident cases showed evidence of re-convergence.
- Finding B-3: 0 of 3 CFIT cases showed evidence of re-convergence occurring prior to impact.

Regardless of whether the full re-convergence was achieved, what appears prominent in the re-convergence process in all of these case studies is the use of observation to overcome divergence. In these cases, known divergence was consistently triggered by an observation of information disproving an expectation. While observation was used to transition into known divergence, it wasn't always effective at promoting full re-convergence or mitigating accidents. Some cases of crews reaching known divergence however not re-convergence, likely have to do with the time left to regain re-convergence. For example, in the Eastern Airlines 401 case, the crew identified divergence seven seconds before impact and were in the process of assessing the observation when they impacted the ground. Other cases where crews reach known divergence, but not re-convergence, could be the result of poor understanding of the system. In the case of poor understanding, the mental model couldn't be considered as recovered as this problem outlives the event, incident, or flight most likely. While, this discusses cases of unrecovered mental models resulting in a lack of re-convergence, it may also be possible to have cases where unrecovered mental models could result in re-convergence. For example, in the Turkish Airlines 1951 case, the crew could have had a flawed mental model illustrated by the lack of understanding of the divergence transition in the first place. However, when the crew reached known divergence recognizing that their expectation of auto-throttle state had been flawed, they disconnected the auto-throttle to force re-convergence by moving the automation to a state that was unambiguous to them. Thus, the case studies indicate that a full recovery mental models may not necessary in order for re-convergence to occur.

FINDING C: Known divergence or re-convergence (whichever occurred first) was triggered by an observation in all cases analyzed.

4.4.1 Timing of Divergence and Re-convergence

The accident and incident reports allowed the analysis of the divergence timeline in each of the cases. Time of known divergence and re-convergence were recovered from these reports to create a divergence timeline. Figure 4-26 shows the timeline of divergence events involving the auto-throttle cases, and Figure 4-28 shows the timeline of divergence events for the cases that resulted in CFIT. Initiation of divergence is depicted as a departure between the actual auto-throttle state line (in black) and the crew state assumption line (in blue). Re-convergence, on the other hand, is depicted as the unification of the actual auto-throttle state line and the crew state assumption line. The period shaded in gray indicates the period of known divergence. Time of imminent loss of control is shown with a red star, while time of impact (if applicable) is indicated by a blue cross. In addition, if point of unrecoverability was stated in the accident report, it was shown on the figure as a red hourglass. The time of imminent LOC was defined as the time of stick shaker activation, triggering of alpha floor protection, aerodynamic stall, or impact (whichever was earliest). Finally, period of recovery is shaded as a rounded green bar. This notation can be used to interpret both timeline figures.

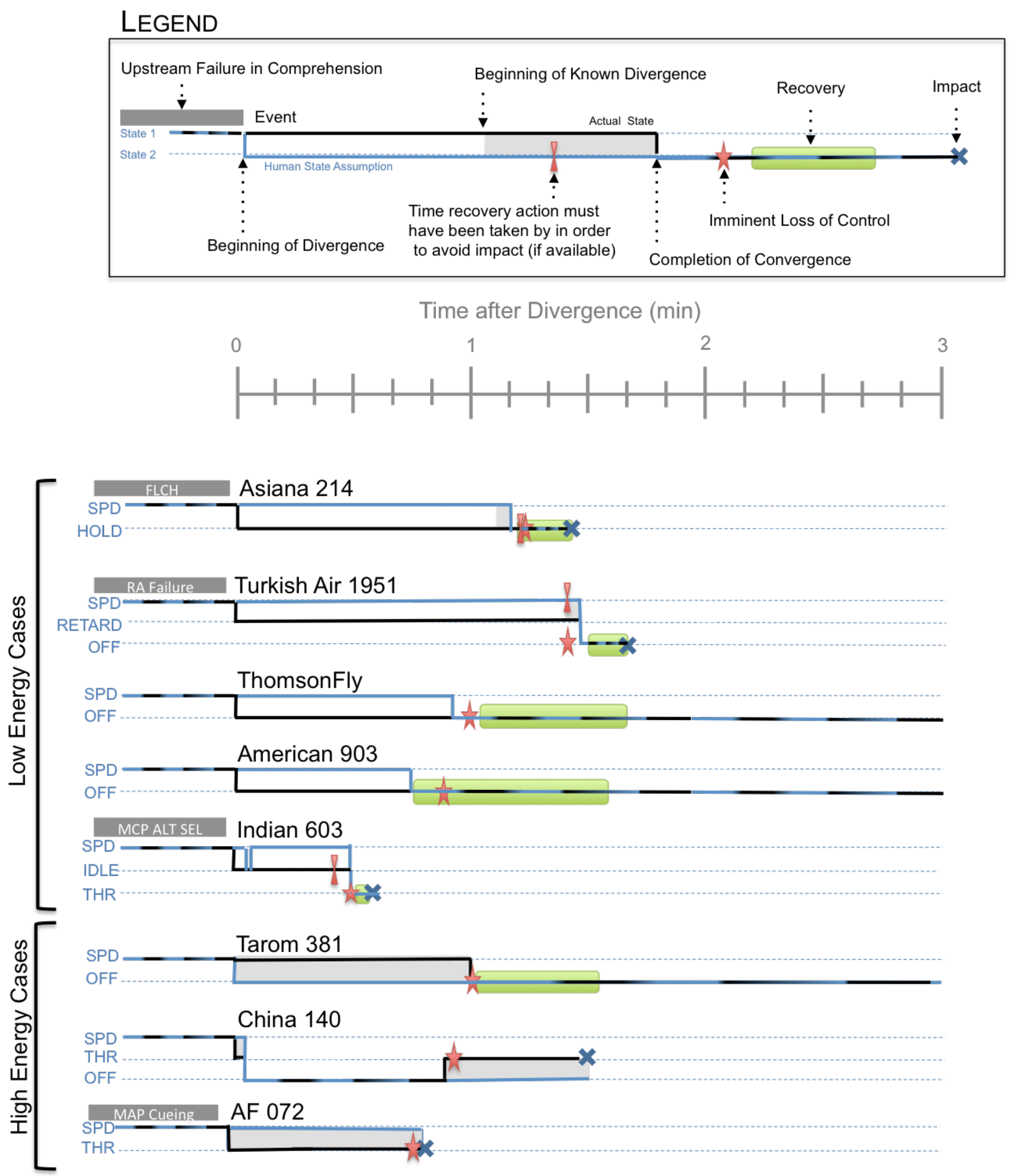

Figure 4-26. Timing of divergence, re-convergence, recovery, and impact for auto-throttle cases

For the auto-throttle cases, Figure 4-26 shows that re-convergence occurred in 6 of 8 cases. The green bars with rounded corners in Figure 4-26 show that the appropriate recovery action was taken in six of eight cases on average 3 seconds (SD = 4 seconds) following re-convergence. However, in the three cases where recovery was successful, the recovery process took an average of 43 seconds (SD = 12 seconds).

The location of the crosses in Figure 4-26 shows that for the cases where recovery was not successful, impact occurred on average 17 seconds (SD = 16 seconds) following re-convergence. The data suggest that the crews ran out of time to successfully recover following re-convergence for the accident cases. This implies that if re-convergence occurred earlier, recovery would have been attempted earlier, and there would be a chance of recovery being initiated before the situation degraded to an unrecoverable state (Silva & Hansman, 2015). The basis of unrecoverability refers typically to the time in which despite execution of the correct recovery action, successful recovery would not be possible given the flight dynamics. However, the point of unrecoverability discussed in this thesis also includes time for human information processing of the anomaly after it is first detected in addition to minimal execution time of the maneuver. The time between re-convergence and initiation of recovery (averaging 3 seconds (SD=4s)) provides some insight into the minimum buffer time necessary for human reaction once a re-convergence occurs. Thus any recovery would ideally have to incorporate the time to avoid LOC plus the 3 second buffer.

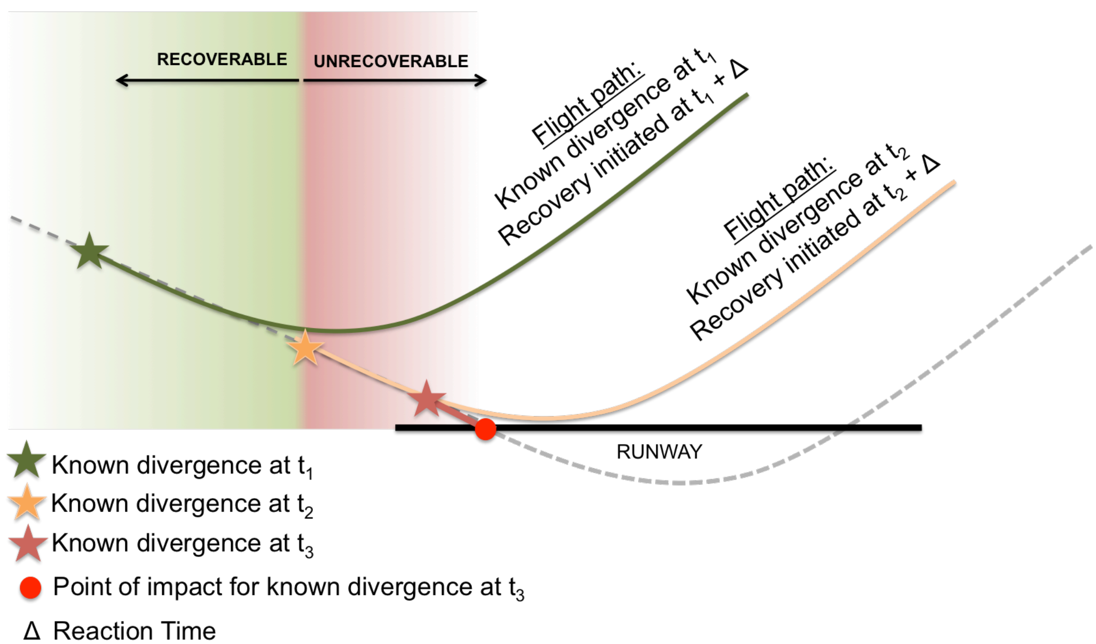

Figure 4-27. Depiction of recoverability profile for low energy approach cases

Timing data was not always available for known divergence since it was typically internal to the human but the time taken was from first indication of known divergence, which sometimes coincided with re-convergence or recovery. Typically for the low energy cases, recovery was initiated shortly after known divergence, however for the high energy cases , known divergence occurred immediately following divergence but the appropriate recovery action was not consistently taken. In these three high energy cases, divergence initiated with an increase in thrust on approach and while this was typically recognized, the crews in these cases elected to continue the approach. This failure in decision making could have been tied to the lack of understanding of the origin of the thrust increase which all three crews showed evidence of and a misjudgment of the consequences of physically resisting the automation which caused an out of trim situation for two of the three cases. These characteristics are different from the low energy cases as correct recovery action was commonly attempted shortly after known divergence. This difference could be indicative of a fundamental difference in training practices between low energy and high energy cases or a inherent belief of difference in criticality between the two cases. It may be possible that when faced with a high energy situation, crews may interpret this as less critical and be more inclined to try and "save" the approach, rather than aborting at the first sign of trouble as they do when they recognize an impending stall situation. This result indicates that divergence may need to be addressed differently for each of these types of auto-throttle cases.

The timing of the CFIT cases was plotted separately due to the different time frame of divergence in these accidents. Figure 4-28 shows the timing of divergence for the CFIT cases. Only one case resulted in re-convergence prior to impact, however this plot only depicts re-convergence of lateral mode target. It appears that divergence in vertical flight path was also apparent and likely contributed to the outcome of this accident as seen in Figure 4-29. Eastern 401 and Air Inter 148 apparently did not achieve full re-convergence. There was evidence that Eastern 401 achieved known divergence 7 seconds prior to impact, however there would not have been enough time to prevent the accident.

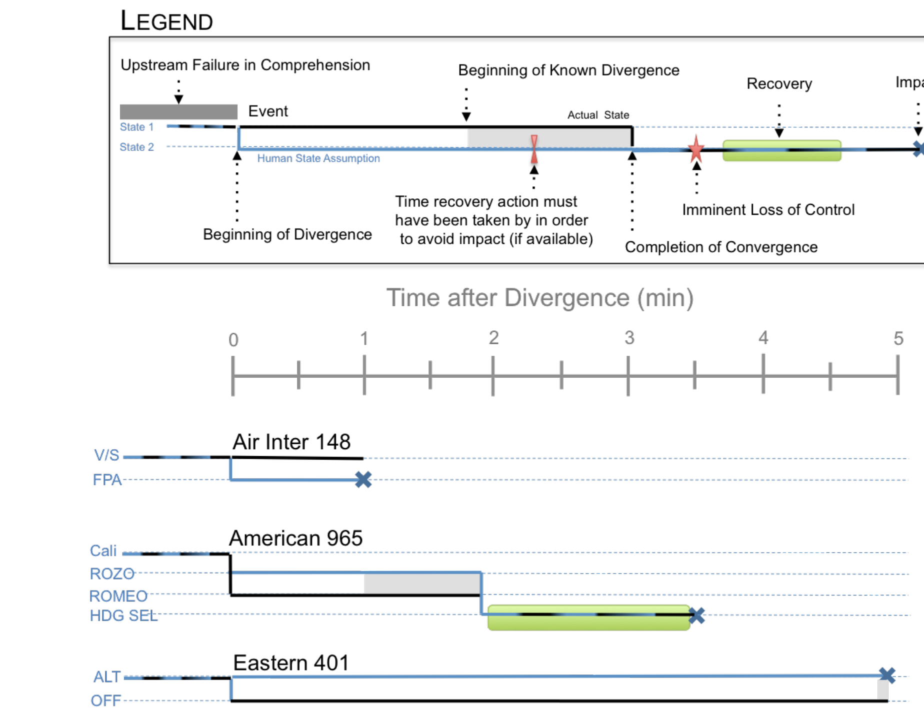

Figure 4-28. Timing of divergence, re-convergence, recovery, and impact for example CFIT cases

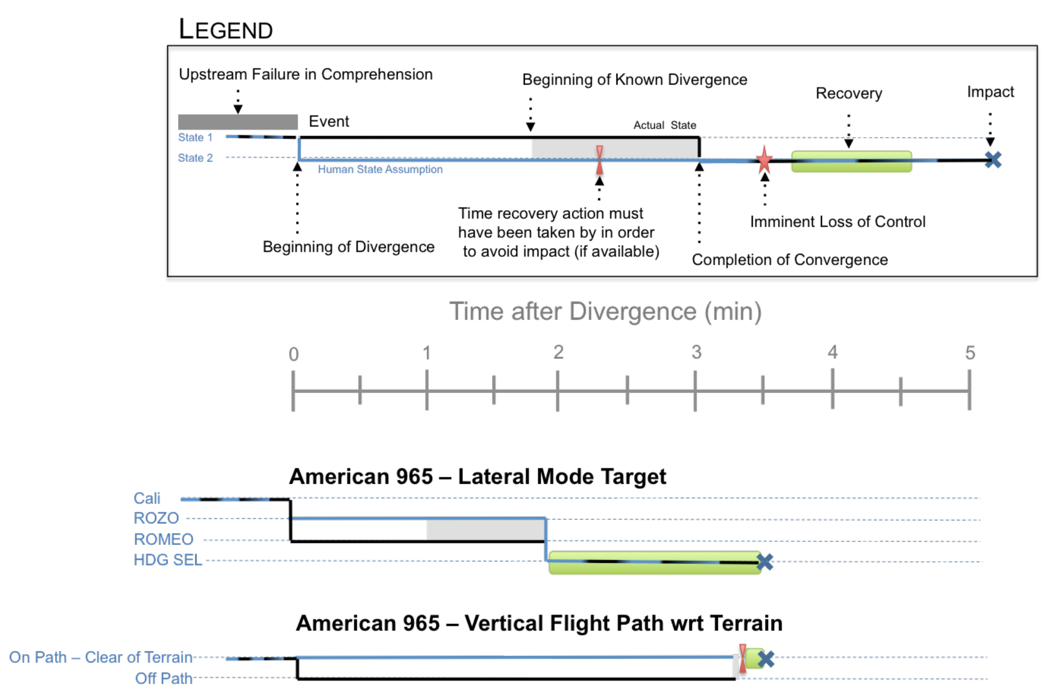

Figure 4-29. Divergence timeline for American 965

The results of the accident timing analysis suggest that accidents can be prevented if recovery begins before the system degrades to an unrecoverable state. The crew must identify the divergence before the appropriate response can be expected from them. Overall, this suggests that it may be prudent to focus mitigation efforts on promoting re-convergence well before the situation exacerbates to an unrecoverable state to avoid consequential effects.

FINDING D: There appeared to be a relationship between timing of the re-convergence process and criticality of situation when assessing consequences of the divergence.

- Finding D-1: For low energy cases, divergence timeline typically involved unknown divergence that prevailed for some time. Known divergence typically occurred as speed decayed, occasionally to the point of stick shaker activation, and typically was followed closely by re-convergence and recovery. If known divergence occurred prior to a certain unrecoverable point for these cases, recovery action was successful, while following the unrecoverable point, despite recovery action being taken, impact occurred.
- Finding D-2: For high energy cases, the initiation of divergence would typically trigger known divergence immediately, however in 2/3 cases known divergence continued until impact. In only one case was re-convergence apparent and this occurred when the automation reached an alpha limit and disconnected the auto-throttle.
- Finding D-3: For CFIT cases, unknown divergence typically prevailed for a majority of the divergence timeline, however in 2/3 cases known divergence appeared to occur but beyond an unrecoverability point. In the final case, no evidence of known divergence or convergence was apparent prior to impact.

4.4.2 Discussion of Factors Influencing Information Processing Failures

In order to effectively promote re-convergence or prevent divergence it was necessary to understand the factors that influence the information processing failures that contribute to divergence. A summary of possible process failures apparent in these cases is provided in Table 4-8.

Table 4-8. Process failures apparent in case studies analyzed

	Failure / Case	Occurrence of Observation Process Failure					Occurrence of Association Process Failure		Occurrence of Expectation Process Failure		
		Expectation Bias	Distraction	Work-load	Fatigue	Design Influences	Associative Understanding	Ambiguity of Observables	Abnormal Trans.	System Understanding	Perpetuation of Divergence
Low Energy Auto-throttle Cases	Asiana 214	x	x	x (high)	x	x		x	x	x	x
	Turkish Air 1951	x	x	x (high)		x		x	x	x	x
	Thomsonfly (Incident)	x	x			x	x	x	x		x
	American 903 (Incident)	x	x	x (high)		x		x	x		x
	Indian Air 605	x	x			x	.	x	x	x	x
High Energy Auto-throttle Cases	Tarom 381 (Incident)	x	x	x (high)	no data				x	x	x
	China Airlines 140		x	x (high)	no data				x		x
	Air France 072		x		x		x		x	x	
CFIT Cases	AirInter 148	x	x	x (high)	no data	x	x	x	x	x	x
	American 965	x	x	x (high)		x	x	x	x	x	x
	Eastern 401	x	x	x (high)	no data	x			x	x	x

As was seen in the in-depth analysis of each of the case studies above, a number of aspects apparently influenced the outcome of the accidents. One important finding is the prominence of expectation process failures, which there was evidence of in all accidents and spanned both the auto-throttle (A/THR) accidents as well as the CFIT accidents. In addition to expectation process failures, a considerable number of observation failures were also apparent in the case studies analyzed. As discussed throughout this thesis, the combination of observation process failures and expectation process failures likely provides no containment possibility for the failures resulting in unknown divergence. This phenomenon was consistently seen in these accidents.

Furthermore, the case studies also showed that when known divergence was attained by the crew, it was the result of an observation. In some cases, this observation triggered re-convergence or triggered the crew to force re-convergence through disconnection of the automation for example. This data suggests that the mechanism for containment was the overcoming of expectation bias by correct observation. This explanation was consistent with the human information processing model of divergence, which identified this form of recovery of the processes shown in Figure 4-30 below reproduced from Chapter 3. Thus, in order to effectively mitigate these types of accidents, it was necessary to understand the contributors to these process failures. These contributors of observation and expectation failures are discussed in the following section.

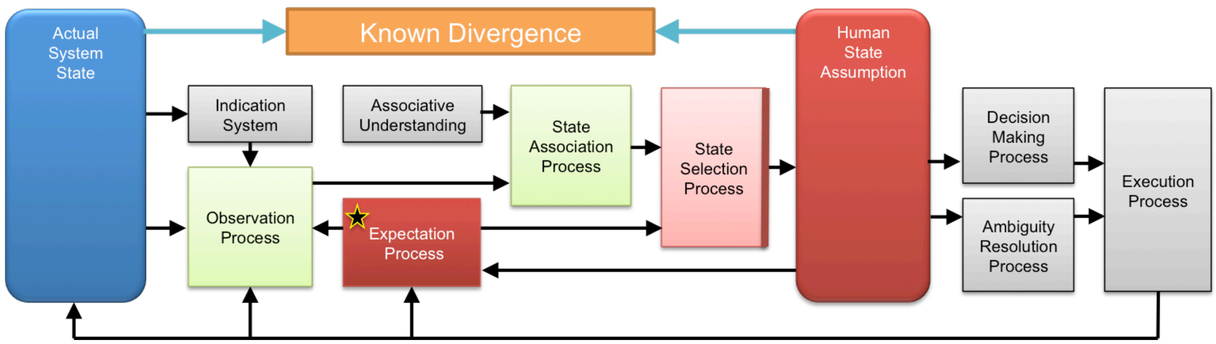

Figure 4-30. Containment of expectation process failure in state selection process

4.4.2.1 Impact of Expectation Process Failures

Expectation, or projection, appears to have a strong effect on human cognition and decision making (D. Jones & Endsley, 1996). This effect was seen in the accident reports discussed in this chapter as well. Breakdowns in human expectation of state were apparent in all eleven accidents analyzed, including the three discussed in this chapter. For Turkish 1951, Asiana 214, Indian 605, Thomsonfly, and American 903, crew behavior was consistent with an expectation of airspeed being maintained within safe limits by the auto-throttle. This reliance possibly played a role in scanning new information and assessing dissenting information (Performance Based Aviation Rulemaking Committee & Commercial Aviation Safety Team, 2013). For Air Inter 148, the crew possibly expected the vertical speed target to be -3.3 degrees FPA and correspondingly did not question or verify their input. For Eastern 401, the crew likely expected the auto-pilot to hold altitude and failed to crosscheck the altitude. All of the case studies analyzed showed evidence of expectation perpetuating divergence, confirming an incorrect expectation. This cycle typically remained until expectation bias was broken by a correct observation. This result is consistent with research regarding plan continuation where "practitioners continue with a plan of action in the face of cues that, in hindsight, warranted changing the plan" (Dekker, 2003; Helmreich, 1997; Khatwa & Helmreich, 1999; Orasanu & Martin, 1998). Orasanu and Martin evaluated aircraft accidents for errors and found that plan continuation errors were a frequent occurrence (Orasanu & Martin, 1998). They suggest that these errors are the result of the higher "cognitive effort needed to revise one's understanding of the situation and consider a new course of action." If these changes are required in times of high workload and other stressors, the crew may not have enough cognitive resources to devote to them. Orasanu also suggests that evidence must be unambiguous and of sufficient weight to prompt a change of plan. This is consistent with the results seen on the progression to known divergence in the case studies analyzed in this chapter. A sufficiently unambiguous observation was made to move into known divergence in these cases.

The other aspect of expectation however is a deficiency in systems understanding. System understanding influences the decisions that are made and the expectation of actions. Knowledge deficiency has been recognized in aviation operations and effects there of have been analyzed extensively in the situation awareness literature (D. Jones & Endsley, 1996; Performance Based Aviation Rulemaking Committee & Commercial Aviation Safety Team, 2013). Knowledge deficiency can also involve a poor or incorrect mental model. This affects the actual projection of the expectation possibly introducing errors downstream (Kieras & Bovair, 1984; Mumaw, Sarter, & Wickens, 2001; Norman, 1983; Rasmussen, 1985; Reason, 1990).

In addition to the human holding the incorrect expectation, it was commonly seen that the mode transitions apparent in these cases were abnormal. While automation can offload human task load in normal situations, it becomes much more difficult for the human to manage in non-normal situations. (Parasuraman & Riley, 1997; Parasuraman, Sheridan, & Wickens, 2000; Wiener, 1988). Thus, the human's expectation likely followed a nominal transition however the system behaved abnormally, a normalization of a non-normal situation. As discussed, the causes of these transitions were apparently due to component failures or even upstream input from the crew. Regardless of cause however, abnormal situations and transitions were apparent in all of these cases. In addition, it appeared that once unknown divergence occurred, it continued for multiple event cycles illustrating the possible perpetuation of divergence due to confident, but incorrect, expectation.

FINDING E: Expectation failures were apparent in all of the cases analyzed.

- <u>Finding E-1:</u> Deficiencies in system knowledge were prevalent in 8 of 11 cases, typically illustrated by the lack of anticipation of the correct result of certain inputs to the automation.
- <u>Finding E-2:</u> All events analyzed showed evidence of states that was not consistent with the crew expectation of nominal states for a given situation. These abnormal modes appeared to occur both through human input coupled with system knowledge deficiency and possibly through automation logic design or failure.
- <u>Finding E-3:</u> Once unknown divergence occurred, there was evidence of a perpetuation of divergence due to a confident, but incorrect, expectation. This illustrates the effect of possible expectation bias.

Within the human information processing model, expectation process failures propagate into both the observation process and the state selection process making them highly impactful and also very difficult to contain. This highlights the importance of addressing discrepancies in human expectation and mitigating them to avoid catastrophic effects. As discussed, one way to break expectation bias is with a correct observation. However, as discussed observation process failures typically accompanied expectation process failures for some portion of the divergence timeline.

4.4.2.2 Impact of Observation Process Failures

Considering the overcoming expectation bias could be dependent on correct observations, it is not surprising that these expectation biases apparently remain intact given the prominence of accompanying observation process failures in the cases analyzed. In all of the cases analyzed at least one definitive observable was available to the crew, however in many of these cases, these observables were missed for a significant amount of the divergence timeline.

For the low energy cases, unknown divergence typically began with limited definitive observables that were discrete in nature such as the flight management annunciation or panel light annunciations. When airspeed decayed below a preset airspeed, more definitive observables became available. These observables tended to be dynamic in nature, such as airspeed or engine settings; variables whose values were available prior, but provided ambiguous information about the state of the system. Ultimately, when known divergence and re-convergence occurred it occurred either through observation of dynamic variables such as airspeed, or discrete annunciations of stall warning.

For the high energy cases, many definitive observables were available to the crew following the initiation of divergence. These observables were both dynamic, such as engine thrust, and discrete, such as a mode annunciation. For these cases known divergence was commonly achieved immediately following the initiation of divergence.

For the CFIT cases, the evolution of the observables were different from many of the auto-throttle cases. In all three accidents, there were arguably a sufficient amount of information provided to the crew following the initiation of divergence of the actual system state. In Air Inter, the descent rate was 3 times the normal rate. In Eastern 401, the altitude was decreasing. In American 965, the aircraft initiated a turn immediately. For the cases analyzed, these observables included discrete observables such as mode annunciations, and dynamic observables such as altitude deviation and excessive vertical speed. These observables typically remained available to the crew throughout the divergence timeline, however in one case the GPWS annunciated providing another definitive observable just prior to impact.

As indicated above, the evolution of definitive observables through the divergence timeline involved information that were dynamic and changed frequently, like airspeed, and involved information that changed less frequently, such as automation state changes. While discrete indications of automation transitions for example, typically accompanied a change in the set of definitive observables, dynamic variables only became definitive observables if they fell into a regime that was inappropriate for the situation, such as airspeed below target airspeed. Thus overall, the frequency of change of the set of observables appeared dependent on the frequency of discrete observable transition and the frequency of dynamic variable transition between appropriate and inappropriate values.

FINDING F: Set of observables can evolve throughout the divergence timeline and can provide different levels of definitive information regarding the state of the system.

- Finding F-1: For the low energy cases, unknown divergence typically began with limited definitive observables that were discrete in nature. In general, when airspeed decayed below a preset airspeed, more definitive observables became available. These observables tended to be dynamic in nature, such as airspeed or engine settings; variables whose values were available prior, but provided ambiguous information about the state of the system. Ultimately, when known divergence and re-convergence occurred it occurred either through observation of dynamic variables such as airspeed, or discrete annunciations of stall warning.
- Finding F-2: For the high-energy cases, many definitive observables were available to the crew following the initiation of divergence. These observables were both dynamic, such as engine thrust, and discrete, such as a mode annunciation. For these cases known divergence was commonly achieved immediately following the initiation of divergence.
- Finding F-3: For the CFIT cases, many definitive observables were available to the crew following the initiation of divergence. For the cases analyzed, these observables included discrete observables such as mode annunciations, and dynamic observables such as altitude deviation and excessive vertical speed.

Despite observables being available, observation failures continued to occur. This is consistent with identified monitoring problems in the flight deck have been the subject of many studies as automation levels in the aircraft increase (Bjorklund, Alfredson, & Dekker, 2006; Civil Aviation Authority, 2004; Federal Aviation Administration, 2003; Mumaw et al., 2001; Parasuraman & Riley, 1997; Sarter et al., 2003; Sarter, Mumaw, & Wickens, 2007; Sumwalt, Thomas, & Dismukes, 2002). When assessing optimal human automation task allocation, it has been seen that human performance decreases on tasks that require high vigilance, such as monitoring of flight data (Grier et al., 2003; Parasuraman, Warm, & See, 1998; Warm, Parasuraman, & Matthews, 2008; Wright & McGown, 2001). For example, a study published by the NTSB found that throughout 37 accidents, 23% of 302 errors were related to inadequate monitoring (National Transportation and Safety Board, 1994). Another study, conducted by the UK civil aviation authority, identified a number of challenges and barriers to effective monitoring (Civil Aviation Authority, 2013). The challenges spanned human limitations to corporate climate. However, the barriers of specific concern for this thesis include the human factors limitations, lack of feedback to pilots when monitoring lapses occur, design of flight deck systems, and inadequate mental models of autoflight systems. These problems are consistent with the factors influencing information processing failures presented in this chapter. The main influences presented in this chapter that impact observation process failures included expectation bias, distraction, workload, fatigue, and design.

Expectation bias was apparent in nine of eleven cases. In these cases, there was evidence suggesting that an incorrect expectation could have affected scan strategies of the human in the observation process, possibly corrupting observations, though the reports did not include information that would identify corruption of observations within the human. As discussed earlier in the thesis, confirmation bias has been observed in complex systems and relates to the selection of expectation-affirming information for comprehension (M. Jones & Sugden, 2001; Klayman, 1995; Lehner et al., 2008; Nickerson, 1998). Some accidents could show evidence of confirmation bias. In Turkish 1951, it could be possible that the human's chose only to perceive information that was consistent with their expectation, which was that the aircraft was in speed mode, such as airspeed decay in the earlier portion of the accident timeline. However, as the accident timeline progressed and affirming cues disappear, it becomes apparent that expectation bias could have also played a part in bypassing all of the feedback available to the crew, possibly for the entire timeline. Expectation, however, was not the only plausible explanation for the missed observables.

In addition to expectation bias, situational influences, such as distraction and workload, also effect observation. Of the eleven accidents analyzed, all showed evidence of distraction and, eight showed evidence of abnormal procedures or troubleshooting that could have contributed to high workload for the crew and possible distraction from the task of maintaining awareness of the mode of interest. While high workload was only apparent in some accidents, distraction was apparent in all of the case studies analyzed. In the Turkish 1951 accident, the crew was intercepting the glide path from above and was apparently behind the aircraft performing checklists later than normal. In Air Inter 148, the crew was apparently distracted by confusion on the lateral profile of an abnormal approach procedure. In Eastern

401, the crew was apparently distracted troubleshooting a landing gear failure. The high workload and distraction potentially affected the observation process and probability of correctly observing definitive observables of relevance likely by affecting attention allocation. The detrimental effects of workload and distraction on human performance have been well documented in the multi-tasking literature (Loukopoulos, Dismukes, & Barshi, 2003). Crew resource management (CRM) has been used as an attempted mitigation to the limitations of human attentional resources. CRM, however, focuses on task splitting, rather than strategies for effectively multiple tasks for each crewmember (Flight Safety Foundation, 2014). In addition, while challenge-response checklists have been implemented as a part of CRM to address monitoring issues, it has been found that non-compliance with checklists continues to be prevalent in actual operations (Performance Based Aviation Rulemaking Committee & Commercial Aviation Safety Team, 2013). The PARC report also stated reasoning for non-compliance being tied to high workload or abnormal situations relating to distraction from the primary flight task. This may explain why many of the crews in these accidents failed to conduct a checklist which could have caught the divergence prior to unrecoverability (Berman & Dismukes, 2010; Charbonneau, 2010; Degani & Wiener, 1993).

In nominal workload levels without abnormal distractions, its possible the crew could have defaulted to their nominal scan patterns of the flight instruments and their nominal compliance with checklists (National Transportation and Safety Board, 2010). This could indicate that mitigations could include measures to manage effects of workload and distraction especially during critical flight regimes. In addition to managing workload and distraction in the cockpit, design of feedback to the crew could also influence the observation.

Eight of eleven cases analyzed showed evidence that design of displays and systems could have been a factor in the crew's observation process failure. In the Turkish 1951, the transition to RETARD was only visually shown on the Flight Management Annunciator. In Air Inter 148, there were an apparent lack of distinguishing indications that were reasonably located within the crew of view and held sufficient readability and distinguishability for the crew to realistically observe. In Eastern 401, the autopilot disconnected without aural annunciation to the crew. In addition many of the analyzed cases included mode indication on the FMA. Despite the training that crews receive to cross check the FMA, the common occurrence of these observation process failures suggests the possible lack of efficacy of the FMA as a salient indication of mode transitions in critical flight regimes (Nikolic et al., 2004; Sarter et al., 2003). Nikolic et al. found that color similarity and movement of background elements, and target eccentricity reduced detection performance of the FMA. In addition to contrast aspects, change blindness could also play a part in the lack of efficacy of the FMA (Flight Safety Foundation, 2014). Change blindness in cognition refers to the phenomenon where "unless a change to a visual scene produces a localizable change or transient at a specific position on the retina, generally, people will not detect it" (Simons & Levin, 1997). This phenomenon relates to the temporal processing of individual visual scenes to form a stable representation across views (Caplovitz, Fendrich, & Hughes, 2008; O'Regan, Rensink, & Clark, 1999). This research suggests that even if the crew was scanning the PFD, it could be possible to miss a change on the FMA (Flight Safety Foundation, 2014). While it does not appear that crews are appropriately prioritizing crosscheck of the FMA, these physiological limitations could also inhibit perception of mode transitions. These two reasons suggest that relying on humans to observe a minimally salient signal during high workload or abnormal situations may not be realistic.

It is also important for designers to consider what observables are actually available to crews. Seven of the eleven accidents involved ambiguity of state observables for at least part of the divergence timeline. For example, observables, such as airspeed and engine noise, were seen to be situationally masked by descents where idle power was expected in the nominal case for at least part of the divergence timeline. Pritchett and Johnson found evidence that pilots may rely on these dynamic variables to maintain awareness of their vertical flight path, reinforcing the potentially negative effect if these dynamic variables were masked (Johnson & Pritchett, 1995). As illustrated by these accidents, with fewer definitive observables, a failure in observation of the definitive observables could become much more susceptible to association process failures and expectation bias. Providing more definitive variables could increase the chance that the crew will observe any definitive variable possibly contributing to maintaining integrity of human information processing. As aircraft become more automated and humans move to functioning "on" the loop, the number of definitive observables could naturally diminish. This is why it may be important that the definitive observables that remain be salient enough to provide an effective indication of flight critical information.

FINDING G: Observation failures were apparent in all of the cases analyzed

- Finding G-1: In most cases, these observation failures were tied to attention allocation on separate tasks, sometimes nominal tasks such as conducting checklists, and other time abnormal tasks such as troubleshooting failures. Distraction was apparent in all the cases analyzed that were sometimes related to increased workload from these non-flying tasks.
- Finding G-2: It is also possible that expectation could have influenced the observation of definitive observables. In all of these cases, if expectation were incorrect, this could have potentially contributed

to the lack of appropriate observation.

4.5 Summary

Divergence is inherently a dynamic process that evolves with time. These dynamics of divergence were evaluated in eleven case studies of accidents involving automation mode confusion. Findings included:

- Finding A: Divergence triggers and origins spanned both human and automation sources
  - Finding A-1: While divergence was shown in different cases to be triggered by human and/or automation transition, in the events where automation transition triggered divergence, many of these involved human action causing unexpected automation transition later in the timeline.
- Finding B: Re-convergence occurred in some cases including accidents.
  - Finding B-1: 5 of 5 low energy auto-throttle cases showed evidence of re-convergence occurring prior to impact for accident cases and prior to recovery for incident cases. Three of these were accident cases.
  - Finding B-2: 1 of 3 high energy auto-throttle cases showed evidence of re-convergence occurring. This was the only incident case. Neither high energy accident cases showed evidence of re-convergence
  - Finding B-3: 0 of 3 CFIT cases showed evidence of re-convergence occurring prior to impact.
- Finding C: Known divergence or re-convergence (whichever occurred first) was triggered by an observation in all cases analyzed.
- Finding D: There appeared to be a relationship between timing of the re-convergence process and criticality of situation when assessing consequences of the divergence.
  - Finding D-1: For low energy cases, divergence timeline typically involved unknown divergence that prevailed for some time. Known divergence typically occurred as speed decayed, occasionally to the point of stick shaker activation, and typically was followed closely by re-convergence and recovery. If known divergence occurred prior to a certain

unrecoverable point for these cases, recovery action was successful, while following the unrecoverable point, despite recovery action being taken, impact occurred.

- Finding D-2: For high energy cases, the initiation of divergence would typically trigger known divergence immediately, however in 2/3 cases known divergence continued until impact. In only one case was re-convergence apparent and this occurred when the automation reached an alpha limit and disconnected the auto-throttle.
- Finding D-3: For CFIT cases, unknown divergence typically prevailed for a majority of the divergence timeline, however in 2/3 cases known divergence appeared to occur but beyond an unrecoverability point. In the final case, no evidence of known divergence or convergence was apparent prior to impact.

- Finding E: Expectation failures were apparent in all of the cases analyzed.
    - Finding E-1: Deficiencies in system knowledge were prevalent in 8 of 11 cases, typically illustrated by the lack of anticipation of the correct result of certain inputs to the automation.
    - Finding E-2: All events analyzed showed evidence of states that was not consistent with the crew expectation of nominal states for a given situation. These abnormal modes appeared to occur both through human input coupled with system knowledge deficiency and possibly through automation logic design or failure.
    - Finding E-3: Once unknown divergence occurred, there was evidence of a perpetuation of divergence due to a confident, but incorrect, expectation. This illustrates the effect of possible expectation bias.
- Finding F: The set of observables can evolve throughout the divergence timeline and can provide different levels of definitive information regarding the state of the system.
    - Finding F-1: For the low energy cases, unknown divergence typically began with limited definitive observables that were discrete in nature. In general, when airspeed decayed below a preset airspeed, more definitive observables became available. These observables tended to be dynamic in nature, such as airspeed or engine settings; variables whose values were available prior, but provided ambiguous information about the state of the system. Ultimately, when known divergence and re-convergence occurred it occurred either through observation of dynamic variables such as airspeed, or discrete annunciations of stall warning.
    - Finding F-2: For the high energy cases, many definitive observables were available to the crew following the initiation of divergence. These observables were both dynamic, such

as engine thrust, and discrete, such as a mode annunciation. For these cases known divergence was commonly achieved immediately following the initiation of divergence.

- Finding F-3: For the CFIT cases, many definitive observables were available to the crew following the initiation of divergence. For the cases analyzed, these observables included discrete observables such as mode annunciations, and dynamic observables such as altitude deviation and excessive vertical speed. These observables typically remained available to the crew throughout the divergence timeline, however in one case the GPWS annunciated providing another definitive observable just prior to impact.

- Finding G: Observation failures were apparent in all of the cases analyzed.
    - Finding G-1: In most cases, these observation failures were tied to attention allocation on separate tasks, sometimes nominal tasks such as conducting checklists, and other time abnormal tasks such as troubleshooting failures. Distraction was apparent in all the cases analyzed that were sometimes related to increased workload from these non-flying tasks.
    - Finding G-2: It is also possible that expectation could have influenced the observation of definitive observables. In all of these cases, if expectation were incorrect, this could have potentially contributed to the lack of appropriate observation.

The analysis showed that the concepts of unknown divergence, known divergence, and re-convergence were understandable in the context of the human information processing model of divergence, illustrating that it can be a useful tool in diagnosing accidents and incidents. This research can be used to infer divergence patterns in varying cases and tie these influences to information flow through the human information processing system, explaining cases of divergence between human state assumption and aircraft system state. The representation of human information processing was useful in determining failure in processes, origins of those failures, and impact of failures on divergence. Unknown divergence, in these cases, was explained by the various combinations of process failures that held no avenue for containment. When failures in processes were apparently alleviated to a point where they had the potential to be contained, they were typically contained in a process downstream, generally resulting in known divergence. Using the knowledge gained from this case study analysis, implications of these findings are discussed in the following chapter.

Chapter 5

Implications of Findings

This chapter explores the implications of the findings of the case studies discussed in Chapter 4. The model of divergence allowed systematic analysis of multiple accidents and incidents. The consistency of analysis provided between cases can be used to understand underlying patterns in a set of accidents/incidents. The findings can be split into two main discussions. One discusses the implications that involve understanding of the process failures that contributed to divergence and delayed/inhibited re-convergence (Findings F, G, C). This understanding can be used to inform what kind of mitigations may effectively alleviate consequences of divergence. The other discussion focuses on implications that involve the occurrence and timing of divergence and re-convergence (Findings A, B, D, E). This understanding can be used to explore how the mitigations can be implemented in order to maximize chances of successful alleviation of divergence.

5.1 Occurrence of Human Information Processing Failures

The information gained by understanding how processing failures may have contributed to divergence or inhibited re-convergence can be used to explore mitigations that can target these failed processes. Expectation failures (Finding E), observation failures (Finding G), and the recovery of expectation bias with observation (Finding C) occurred in all of the accidents analyzed. Due to the interdependence between the expectation and observation processes, these implications are discussed as a together.

- Finding E: Expectation failures were apparent in all of the cases analyzed.
    - <u>Finding E-1:</u> Deficiencies in system knowledge were prevalent in 8 of 11 cases, typically illustrated by the lack of anticipation of the correct result of certain inputs to the automation.
    - <u>Finding E-2:</u> All events analyzed showed evidence of states that was not consistent with the crew expectation of nominal states for a given situation. These abnormal modes

appeared to occur both through human input coupled with system knowledge deficiency and possibly through automation logic design or failure.

  - Finding E-3: Once unknown divergence occurred, there was evidence of a perpetuation of divergence due to a confident, but incorrect, expectation. This illustrates the effect of possible expectation bias.

- Finding G: Observation failures were apparent in all of the cases analyzed.
  - Finding G-1: In most cases, these observation failures were tied to attention allocation on separate tasks, sometimes nominal tasks such as conducting checklists, and other time abnormal tasks such as troubleshooting failures. Distraction was apparent in all the cases analyzed, which was sometimes related to increased workload from these non-flying tasks.
  - Finding G-2: It is also possible that expectation could have influenced the observation of definitive observables. In all of these cases, if expectation were incorrect, this could have potentially contributed to the lack of appropriate observation.
- Finding C: Known divergence or re-convergence (whichever occurred first) was triggered by an observation in all cases analyzed.

The model of divergence allowed us to observe the possible effect of expectation bias within the accident cases. Failures in both the expectation process and the observation process were observed in every case analyzed including both auto-throttle and CFIT cases *(Findings E and G).* The analysis indicated strength of the impacts of these failures on the human state assumption. While poor expectation and monitoring have been found to contribute to accidents in the past, this model highlighted the link between those two failures. Furthermore, since the expectation failures were contained eventually by correct observation, the model possibly showed the recovery of expectation bias *(Finding C).* This suggests that mitigations that can promote observation to force reconsideration of the current expectation of state may be effective in alleviating the consequences of divergence.

Training the crew to be more robust to cases of expectation bias could involve crew training or incorporating procedural crosschecks to strengthen observations that could challenge expectation. This is consistent with recommendations in the field relating to training effective monitoring and training automation logic.

Currently, a number of initiatives exist as monitoring of the flight profile has been established as an area of concern in aviation (Flight Safety Foundation, 2014; Performance Based Aviation Rulemaking Committee & Commercial Aviation Safety Team, 2013). Hutchins et. al. suggests that the training of monitoring can be improved and work can be done to evaluate the interaction between pilot flying and pilot monitoring (Hutchins, Weibel, Emmenegger, Fouse, & Holder, 2013). Crew resource management wasn't explicitly discussed as a factor in this thesis, however it can be used as a powerful tool to enhance monitoring efficacy (Performance Based Aviation Rulemaking Committee & Commercial Aviation Safety Team, 2013). As part of this, the Flight Safety Foundation in their report on pilot monitoring suggests that clearly defining monitoring tasks for each pilot could improve monitoring performance (Flight Safety Foundation, 2014).

The data in this thesis suggests the benefit of training crews to challenge expectations. This could be incorporated into the current flight management monitoring initiatives of training susceptibility to monitoring errors (Flight Safety Foundation, 2014). In addition to training why humans are vulnerable to errors and lapses, ground training could also include why humans are susceptible to expectation bias in addition to informing them on the gravity of the effects if expectation is incorrect. Current monitoring recommendations include training to be aware of monitoring lapses, which goes hand in hand with training crews to be aware of their expectation. Because expectation bias has been shown in the case studies to be naturally contained with a correct observation, this training should reinforce the current efforts in improving flight path monitoring.

The Flight Safety Foundation suggests that some of the current training of predictable scenarios can be replaced with scenario-based training of unanticipated distractions that are more representative of the stressors found in flight (Flight Safety Foundation, 2014). Scenarios that require challenging of expectations can be incorporated into this initiative as the goals go hand in hand. Mode transitions of concern that can be used to inform scenarios, for example, can be identified using analysis such as the one done in Chapter 4. In this thesis, an example of a mode transition of concern is the disconnection of the auto-throttle (or reversion to a flight idle mode) during final approach which commonly appeared in the accidents and incidents analyzed. This scenario could be paired with workload and distraction aspects to create a realistic environment with which divergence could occur, and the crew could learn from it. In addition, there is work being conducted on methods to predict the user's knowledge of system behavior by taking into account the frequency with which the transition scenarios are experienced and the contexts in which they occur (Javaux, 2002). With further development of this research it may be possible to identify transitions that may be more problematic for the crew.

Currently, the Federal Aviation Administration (FAA) is providing airlines with a guidelines to address issues with pilot monitoring (Lowy, 2016). Thus, it can be seen that efforts in mitigating monitoring issues are on their way to being implemented. If the crews in the case studies were effectively trained on challenging expectation by monitoring, it could have been possible to mitigate nine of the eleven cases studied including, Asiana 214, Turkish 1951, Thomsonfly, American 903, Indian 605, Air Inter 148, American 965, and Eastern 401.[64] The success would have been dependent on successful identification of the abnormal situation before the situation became unrecoverable.

5.2 Occurrence and Timing of Divergence and Re-convergence

Since areas to target improvement within the human information processing system were identified, it's necessary to understand how these improvements can be implemented in order to address cases of divergence.

- Finding A: Divergence triggers and origins spanned both human and automation sources
    - Finding A-1: While divergence was shown in different cases to be triggered by human and/or automation transition, in the events where automation transition triggered divergence, many of these involved human action causing unexpected automation transition later in the timeline.

Information of how divergence triggers informs areas to target to prevent divergence. Considering triggers of divergence spanned both the human and automation, mitigations should not necessarily be limited to only addressing design or only improving training. Focusing on one aspect between human and automation could limit the effectiveness of the mitigation. In addition, information about how automation transitions occurred informs how these can specifically be targeted. In these cases specifically, the human appeared to be the origin of many divergence triggers within the analysis. This could point to mitigations that address failures in system understanding in order to improve the accuracy of expectation and enable the anticipation of abnormal modes. These could be in the form of training to fit the human to the system or simplified automation logic to fit the system to the human (Vakil & Hansman, 2002). Issues with preventing divergence in this manner arise however with limitations with long term memory and increasingly complex systems. In addition, monetary and resource limitations arise when discussing

[64] While the remaining cases, China 140, Air France 72, and Tarom 381, showed evidence of expectation failures typically during the divergence transition, the dynamics of the aircraft (increase in thrust) following divergence was typically highly salient indicating divergence, thus many of these crews moved into known divergence immediately and may not have been affected by expectation bias during the time of divergence.

automation re-design. For these reasons, prevention of divergence may not be the most practical way to address divergence. Since re-convergence was possible in these cases, it may be effective to focus efforts on promoting re-convergence if prevention of divergence is impractical.

- Finding B: Re-convergence occurred in some cases including accidents.
  - Finding B-1: 5 of 5 low energy auto-throttle cases showed evidence of re-convergence occurring prior to impact for accident cases and prior to recovery for incident cases. Three of these were accident cases.
  - Finding B-2: 1 of 3 high energy auto-throttle cases showed evidence of re-convergence occurring. This was the only incident case. Neither high energy accident cases showed evidence of re-convergence
  - Finding B-3: 0 of 3 CFIT cases showed evidence of re-convergence occurring prior to impact.

Re-convergence was apparent in all of the low energy auto-throttle cases analyzed. While individual accident reports may allude to the crew recognizing a situation, the result that re-convergence occurs relatively consistently shows that in these cases, the problem may not have been with the actual triggering of re-convergence alone. As mentioned in Chapter 4, timing of the re-convergence process with respect to criticality of the situation also appeared to have an effect. The implication of this relationship is explored later in the discussion related to Finding D.

High energy auto-throttle cases typically resulted in immediate known divergence, however delayed or non-existent re-convergence. In these cases, it is possible that focusing mitigations on fully re-converging could be effective at reducing the catastrophic impact of some of these cases. Because known divergence is typically gained immediately, mitigations promoting observation may not be effective as failures in system understanding were also apparent. In many of these cases, despite observation of definitive observables, such as the FMA, full re-convergence did not occur to due this breakdown in associative understanding. Thus, in these high energy auto-throttle cases, the results suggest that procedures aimed at forcing re-convergence, by disconnecting the automation for example if the crew is confused about what the automation is doing, may be more effective at alleviating the consequential results of divergence in these situations.

CFIT cases, while sometimes showing evidence of known divergence, did not show evidence of re-convergence in any of the accidents analyzed. These cases were unique compared to the auto-throttle cases because the data suggested that known divergence could have been promoted in these cases and efforts could be made to force re-convergence. These mitigations are dependent on the timing and are further discussed in the discussion for Finding D below.

- Finding D: There appeared to be a relationship between timing of the re-convergence process and criticality of situation when assessing consequences of the divergence.
  - Finding D-1: For low energy cases, divergence timeline typically involved unknown divergence that prevailed for some time. Known divergence typically occurred as speed decayed, occasionally to the point of stick shaker activation, and typically was followed closely by re-convergence and recovery. If known divergence occurred prior to a certain unrecoverable point for these cases, recovery action was successful, while following the unrecoverable point, despite recovery action being taken, impact occurred.
  - Finding D-2: For high energy cases, the initiation of divergence would typically trigger known divergence immediately, however in 2/3 cases known divergence continued until impact. In only one case was re-convergence apparent and this occurred when the automation reached an alpha limit and disconnected the auto-throttle.
  - Finding D-3: For CFIT cases, unknown divergence typically prevailed for a majority of the divergence timeline, however in 2/3 cases known divergence appeared to occur but beyond an unrecoverability point. In the final case, no evidence of known divergence or convergence was apparent prior to impact.

While individual accident reports may allude to the crew recognizing a situation, the result that re-convergence occurs relatively consistently shows that in low energy cases, the problem may not have been with the actual triggering of re-convergence alone, but the timing of re-convergence relative to criticality of the situation. This was further supported by the timing analysis for the auto-throttle cases. For auto-throttle mode confusion cases resulting in low energy, the timing between known divergence/re-convergence and recovery was minimal. This could indicate that once known divergence occurs, recovery could be initiated and mitigations could target promoting known divergence for the low energy cases. The analysis of incidents also illustrated the extensive amount of time recovery took in those cases. The time between recovery and impact for the accident cases, and the time to successfully recover in the incident cases alludes to the accident crews effectively “running out of time” to recover the aircraft.

High energy auto-throttle accidents showed evidence of known divergence occurring immediately following initiation of divergence, however re-convergence was rare and these cases sometimes ended in accidents. Thus, as introduced in the discussion regarding B-2, attaining known divergence alone in these cases is not apparently successful at promoting re-convergence and appropriate recovery. This indicates the need to promote re-convergence in these cases as opposed to only known divergence.

There were some differences between the three CFIT cases and the auto-throttle cases. For the CFIT cases, known divergence, if it occurred, occurred much closer to impact. Of the three cases analyzed, American 965 was the only one to show any recovery behavior, likely due to the annunciation of the ground proximity warning system and the immediate action required by that cue. In Air Inter 148, there was not evidence of known divergence prior to impact, and in Eastern 401, the known divergence appeared to occur 7 seconds prior to impact. This pattern may be inherent in this class of accidents provided that the result was "controlled" flight into terrain. Divergence, however provided an explanation that spanned multiple accidents, suggesting that if known divergence can be promoted early enough for recovery to be successful, it may be effective at mitigating these types of accidents. This also provides some insight into the possible efficacy of the GPWS, considering the only accident with the equipment involved was the only one to initiate recovery action prior to impact with terrain. This analysis only reviewed 3 accidents, however with further analysis its possible that further patterns may emerge.

When considering promoting known divergence and re-convergence, the analysis of divergence indicated that a point of unrecoverability can exist in a situation after which, successful recovery would not be possible. These points may be different based on the phase of flight, but the approach phase of flight can be used as an example. [65]

When determining the point on the approach where known divergence should occur by, it should incorporate (1) the potential (time available) for recovery based on aircraft dynamics, and (2) the time required to recognize divergence, initiate recovery, and recover without impacting terrain.

However research can be done to evaluate the optimal point on the approach where known divergence must occur by for successful recovery to be possible. This research would have to include aircraft dynamics information as well as incorporate a buffer time for human recognition and execution of missed approach. Alternatively, the case studies such as the one presented in chapter 4 could also provide insight based on the calculation of the point of un-recoverability.

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[65] The FSF evaluated areas of vulnerability on a typical flight profile (Flight Safety Foundation, 2014). This document highlights that where ever transitions (vertically, laterally, or speed) occur are at a higher vulnerability for monitoring errors, however they consider the possible consequences of those to be less in severity compared to flight within 1,500 feet of the ground.

This information about the point of unrecoverability could be used to inform the best time on approach to implement an automation crosscheck of the FMA. Crosschecking the FMA during critical phases of flight can remain a useful tool in confirming or denying expectation. For example, doing an automation check at the final approach fix at 2000 ft. altitude could provide plenty of time for a crew to recognize and recover from divergence, however divergence actually occurred following this point in some of the accidents studied.[66] Thus, this shows that conducting a crosscheck too early allows time for divergence to develop following the crosscheck increasing susceptibility to consequential divergence. However, as discussed, re-convergence must occur before the situation becomes unrecoverable in order to avoid catastrophic consequences.

A possible addition to the stabilized approach criteria could incorporate a check of the FMA.[67] As can be seen, typically these checks occur at 1000 ft. or 500 ft. and based on the operational evidence a go around initiated at these altitudes could occur successfully (Charbonneau, 2010). If an automation crosscheck was incorporated into the stabilized approach criteria at 500 feet and divergence successfully identified by the crew, this could have been successful at mitigating four of the eleven of the accidents evaluated in Chapter 4, including Asiana 214, Turkish 1951, Air France 72, and Indian 605.[68]

With a defined point of unrecoverability, it also may be possible to design an alert for the crew that annunciates prior to that point if a situation has degraded beyond acceptability or is projected to degrade beyond acceptability. For the auto-throttle cases, this alert could occur for low energy or energy predicted to go below acceptable values following the point of unrecoverability. The purpose of this kind of mitigation would be to stimulate known divergence via observation, by providing a salient definitive

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[66] The following cases involved the initiation of divergence following the FAF: Indian 605, Turkish 1951, Thomsonfly, AF 72, Asiana 214, China 140, Air Inter 148 (7/11 cases)

[67] Some airlines have already incorporated this into their stabilized approach criteria

[68] It is important to discuss a major limitation of procedural cross checks (Degani & Wiener, 1993). As seen in the case studies analyzed, non-compliance with or delayed checklists was common. The reasons behind this non-compliance likely parallel the issues in observation seen with divergence. Typically workload and distraction were apparent. In addition to these factors, there has been research that discusses complacency and fatigue affects on check list compliance (Berman & Dismukes, 2010; Degani & Wiener, 1993; Performance Based Aviation Rulemaking Committee & Commercial Aviation Safety Team, 2013; Smith, Jamieson, & Curtis, 2013). Thus, it is important to consider efforts to improve compliance with procedures in order for an automation crosscheck to be effective at mitigating divergence.

observable, prior to the unrecoverability point. A procedure complimenting this alert could mandate a go-around minimizing time between known divergence, re-convergence, and recovery and improve chances of success of a recovery procedure. This philosophy is consistent with the implementation of the enhanced ground proximity warning system (GPWS) to prevent CFIT accidents (Loomis & Porter, 1982). This system alerts the crew about impending collision with terrain and procedures and training correspondingly provide guidance on the appropriate escape maneuver. This system likely contributed to the 100 fold decrease in the risk of CFIT accidents between 1974 and 2003 (Honeywell, n.d.). Furthermore in the 3 CFIT accidents analyzed in this thesis, the only one that showed any recovery action was the one that received a GPWS warning.

In addition to alerts, it may be affective to provide the crew with a display that includes information on the limits of the flight envelope and integrates the point of unrecoverability into the observables available to the crew. This is consistent with efforts to use displays to enhance crew situation awareness when using envelope protection systems (Ackerman et al., 2012).

- Finding F: The set of observables can evolve throughout the divergence timeline and can provide different levels of definitive information regarding the state of the system.
    - Finding F-1: For the low energy cases, unknown divergence typically began with limited definitive observables that were discrete in nature. In general, when airspeed decayed below a preset airspeed, more definitive observables became available. These observables tended to be dynamic in nature, such as airspeed or engine settings; variables whose values were available prior, but provided ambiguous information about the state of the system. Ultimately, when known divergence and re-convergence occurred it occurred either through observation of dynamic variables such as airspeed, or discrete annunciations of stall warning.
    - Finding F-2: For the high energy cases, many definitive observables were available to the crew following the initiation of divergence. These observables were both dynamic, such as engine thrust, and discrete, such as a mode annunciation. For these cases known divergence was commonly achieved immediately following the initiation of divergence.
    - Finding F-3: For the CFIT cases, many definitive observables were available to the crew following the initiation of divergence. For the cases analyzed, these observables included discrete observables such as mode annunciations, and dynamic observables such as altitude deviation and excessive vertical speed. These observables typically remained available to the crew throughout the divergence timeline, however in one case the GPWS annunciated providing another definitive observable just prior to impact.

Another pattern revealed when using the model of divergence for the auto-throttle cases is the dynamic behavior of observables as the divergence timeline progressed. While individual accident reports suggest the indications available to the crew, divergence allowed us to see that in many cases, limited definitive cues were available to the crew, specifically for the low energy auto-throttle cases. This insight highlights this period in an accident timeline where cues could be strengthened or added prior to the situation becoming critical for the auto-throttle cases. The analysis also indicated that while visual mode information was provided to the crew at the beginning of the divergence timeline, more dynamic observables such as airspeed and engine noise became definitive as the situation degraded. Ultimately, analysis indicated that in most cases, crews reached known divergence through observation of these dynamic variables, possibly highlighting that prediction of these dynamic variables may provide an added buffer time of recognizing that these parameters, which may be nominal for a current situation, but abnormal for a future situation.

Since many observables were available for the high energy auto-throttle cases and were effective at promoting known divergence, these observables were not effective in promoting re-convergence. These could be related to breakdowns in system understanding; thus, consistent with the in the discussion of Finding B-2, forcing re-convergence using procedures may be effective at preventing these types of accidents.

For the CFIT cases, the evolution of the set of observables was different from many of the auto-throttle cases. In all three accidents, there was arguably a sufficient amount of information provided to the crew following the initiation of divergence of the actual system state. In Air Inter, the descent rate was 3 times the normal rate. In Eastern 401, the altitude was decreasing. In American 965, the aircraft initiated a turn immediately. Thus, it may not be effective to provide more indications to the crews in these accident cases, however it may be beneficial to target the factors influencing the observation failures tied to the divergence such as distraction. Air Inter and American 965 were pre-occupied with their lateral profile and Eastern 401 was preoccupied with troubleshooting a failure. Thus, enforcing operational requirements such as not accepting a visual approach may keep workload to a minimum. Efforts could also focus on prioritization of tasks during training.

5.3 Summary

The findings above indicated that timing between the re-convergence process and the criticality of the situation is important to address. Using this information, mitigations can target promoting re-convergence prior to the situation becoming unrecoverable. In order to do this, the findings suggest that targeting mitigation of expectation and observation process failures may be most effective. The dependent nature of these two process failures should also be addressed in order to effectively mitigate these cases.[69]

The information on how divergence, known divergence, and re-convergence manifest in the different types of cases informed what mitigations may be more effective for those cases given the observation and expectation failures seen. Low energy cases showed a clear trend of unknown divergence with a period of limited observables followed by an increase in observables. These cases eventually resulted in known divergence, followed quickly by re-convergence and recovery. The implications of these results indicate that if known divergence can be promoted in the low-energy cases, with procedures, improved feedback, or training, chances for successful recovery may increase. For high energy cases, observables were available early in the divergence timeline. Known divergence typically occurred immediately, but did not guarantee re-convergence. This finding suggests that procedures to force re-convergence in these cases may be more effective than other mitigations such as those that provide more or more salient observables. Finally, the results for CFIT cases indicated that mitigations targeting both promotion of known divergence and forcing of re-convergence may be most effective due to the apparent lack of known divergence prior to unrecoverability and time criticality of these flight profiles.

This chapter discussed the implications of the findings of the case study analysis. Overall, information gained by using the model of divergence to analyze this set of accidents not only identifies the patterns, but also provides a framework with which to understand how potential mitigations could affect the human state assumption and, ultimately, divergence.

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[69] It should be noted that this thesis makes no claim that these initiatives have not already been proposed in the field. On the contrary actually, this thesis provides more data to support the possible effectiveness of these mitigations. It is also important to remember that this is by no means an exhaustive list of how to address divergence.

Chapter 6

Summary and Conclusions

6.1 Summary

This thesis defines and develops the concept of divergence between the human state assumption and aircraft system state. The concept of divergence can be used to evaluate human-system interaction in many different types of systems, however the system of interest presented in this thesis related to automation systems of modern commercial aircraft. Divergence was explored as a concept by (1) reviewing the pertinent literature regarding human error, human information processing, situation awareness and mode awareness, (2) developing a framework that can be used to understand possible causes of divergence, (3) illustrating use of the framework with accident case studies, and (4) discussing the implications of the findings of the case studies. The results of this evaluation of divergence are presented below.

Since the ultimate result of divergence is performance error, it was important to understand current frameworks of human error and where divergence fit within them. Since error can originate from human processing of information, as suggested by divergence, it was necessary to understand the current work on human information processing and how that relates to the human state assumption. The basic elements of models developed by Wickens and Endsley were incorporated into the model of divergence (Endsley, 1995; Wickens & Hollands, 2000). These include aspects of perception, cognition, decision making, and execution. Certain processes were adapted to discuss determination of state specifically, but the result maintained consistency with the established literature. Reason's Fallible Machine was also used to develop details of the association and expectation processes (Reason, 1990). The model of divergence incorporated different aspects of the current literature to understand the human processes which a human state assumption is formed on.

With this information processing framework, failures affecting individual processes could be evaluated for their impact on divergence. The framework highlighted the interaction of indications in the system, and the processes of observation, association, state selection, expectation, and ambiguity resolution in the human. The model was used to identify causes of divergence as process failures and evaluate the effects of those failures on downstream processes and the human state assumption. Ultimately, the impacts of process failures were assessed for consequential effects using accident case studies.

Eleven accident case studies involving automation mode confusion were conducted to evaluate divergence using the process model of divergence. Eight of these cases related to auto-throttle failures. The other three cases evaluated cases of mode confusion outside of the auto-throttle realm that resulted in CFIT illustrating possible generalizability of the concept on another type of accidents important to current safety initiatives. The case studies were used to identify trends in divergence and successfully illustrated the use of divergence to analyze the mode confusion. Findings of the case studies showed prevalence of observation and expectation process failures in time frames involving divergence. The implications of these findings on the industry were then discussed.

6.2 Conclusions

The contribution of this thesis lies in the framework developed with which causes of divergence can be analyzed and patterns in divergence can be identified and understood. When the framework was used to assess accident case studies, failures in observation and expectation processes were prominent. Many causes were consistent with the findings in the accident reports also reinforcing the results of previous literature; what the divergence framework added was a clear impact of expectation on different processes in human cognition. This knowledge of the prevalence and influence of expectation process failures informed mitigations for divergence that could be effective based on these results. Analysis of the different types of accidents showed that different mitigations may be effective for different types of accidents.

This thesis, as mentioned, provided a framework with which divergence could be analyzed. This framework was built on inherent assumptions. Further work can be conducted to expand the use of the model. For example, the association, state selection, and expectation processes were modeled using basic comparison or decision tree logic. It is well known that these processes can be very complex and effort can be directed into developing a more robust model of these processes possibly incorporating Bayesian methods. For expectation in particular, the relationship between confidence and expectation is likely more complicated that modeled in this thesis. Current research in the expectation field only relates to marketing aspects of expectation and there is a gap in the literature that looks more deeply into the process of how expectations are formed, refuted, or reinforced in dynamic systems. In addition, the ambiguity process was used for its outputs, however this work did not address how those outputs were formed, so this could be a rich area to explore and contribute to the existing decision making literature. Finally, the mitigations discussed in the previous chapter can be explored in more detail and evaluated for feasibility. As can be seen, while this work explored the concept of divergence and developed a functional framework, there are many opportunities for further exploration of the divergence concept, framework, and example mitigations.

While this framework of divergence has been shown to provide insight into flight deck issues, it is not restricted to use within the aviation industry. The process model of divergence can be applied to any human-machine system such as human-robot interaction in the medical field, nuclear power plant operation, or other transportation operations such as rail transport or air traffic control. Divergence can be used as a systematic framework to assess patterns in human performance, the findings of which can inform safety improvements within these systems.

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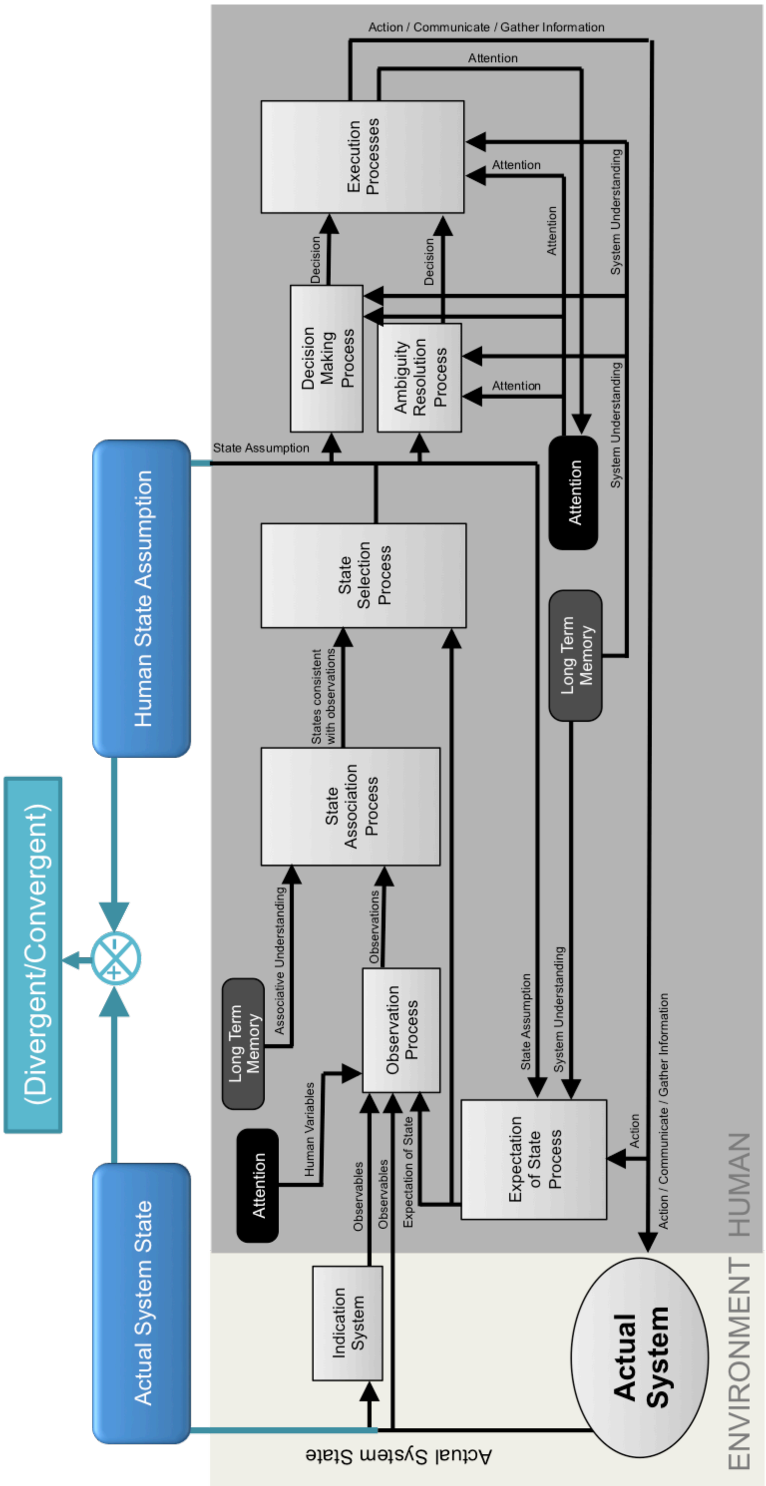
Appendix A: Definitions

- *Abnormal Transition* – State transition that is not included in the nominal set of transitions for a situation
- *Actual System State* – Actual value or trend of actual system state
- *Ambiguity of State Assumption* – Level of ambiguity associated with the human state assumption
- *Ambiguity Resolution Process* – Process by which ambiguity is resolved when an ambiguous state signal is present.
- *Association Process* – Process by which each of the set of observations are assessed for consistency with the human's expected observables for a given state
- Associative Understanding – Understanding of the observables associated with each state of the system
- *Decision Making Process* – Process by which human state assumption is used to make decisions.
- *Definitive Observable* – Observable which must be observed in order to discriminate between multiple possible states
- *Event* – The occurrence of any of the following in the system:
  - Change in actual state or human state assumption
  - Change in observables, observations or expectation of state
  - Change in situation
- *Execution Process* – Process by which decisions are executed
- *Expectation of State* – Human expectation of state of system
- *Expectation Process* – Process by which an expectation of state is formed, reinforced, or refuted
- *Human State Assumption* – Human's assumption of state of system
- *Human Variables* – Variables providing information such as attention, fatigue, workload, salience, distraction, and information gathering.
- *Indication System* – Process by which observables are provided to the human
- *Observable* – Variables whose information could be useful for the user in determining the state of the system
- *Observation Process* – Process by which each of the observables are observed by the human
- *Observations* – The value/trend of observables that were actually observed
- *Situation* – Description of contextual variables relevant to the situation including phase of flight, position, aircraft configuration, air traffic control clearance, etc. The situation is included in the actual state of the system and includes its own observables to provide insight into the situation.

- *States Consistent with Set of Observations* – List of states where the set of observations is consistent with the human's understanding of the system.
- *State Selection Process* – Process by which the human state assumption is selected or ambiguity is detected.
- *System State(s) of Interest* – System state(s) being analyzed for divergence
- *System Understanding* – Understanding of the system based on prior experience including flight and ground training.

Appendix B: Detailed Human Information Processing Model of Divergence



Appendix C: Assumptions of Human Information Processing Model of Divergence

Assumptions were made throughout the development of human information processing of divergence representation. In general, the reader should remember that in operation, uncertainty can exist throughout the entire process, affecting both inputs and outputs. Many processes were discussed deterministically, however this limitation should be considered when using the model to assess cases in a non-ideal world where uncertainty is prominent and results could occur stochastically. Specific assumptions affecting individual processes are summarized below.

Association Process Assumptions

- The association process is modeled as a director comparator
- The states used for comparison in the association process may be limited
- The observables used for comparison in the association process include only the observables observed, correctly or incorrectly, in the observation process.

State Selection Process Assumptions

- The state selection process is modeled with decision tree logic

Expectation Process Assumptions

- The expectation process is modeled with decision tree logic and simple comparison
- An expectation can only be formed for states which the human has a mental model. (Known states versus unknown states)

Decision Making Processes Assumptions

- Ambiguity resolution and nominal decision making processes are parallel processes

The assumptions made in this model above illustrate the boundaries of the model. Decision tree logic and simple comparators for the association, determination, and execution processes may be overly simplified and not exactly mapped with true dynamics of those systems. Further research can be conducted to investigate other hypotheses for modeling of these processes.

Appendix D: Accident/Incident Case Studies (Auto-throttle)

D1: Accident: Asiana Airlines Flight 214

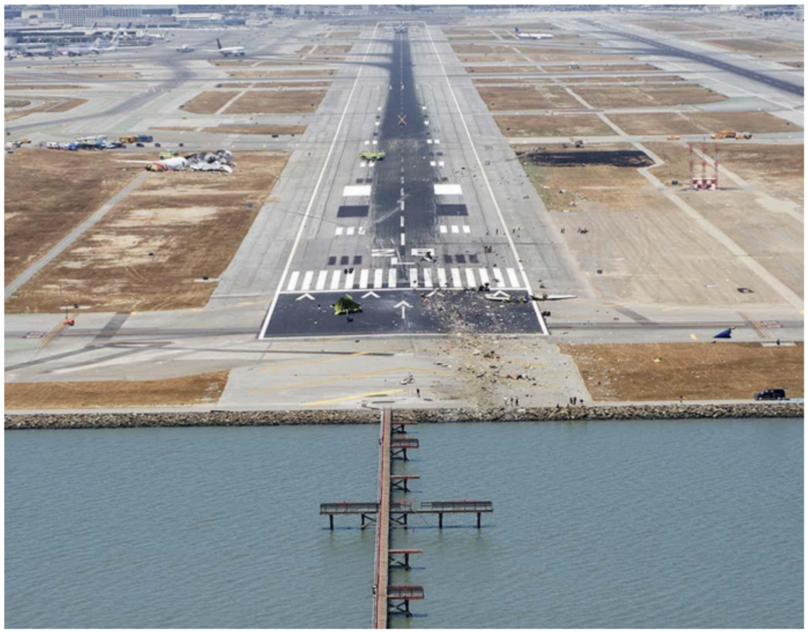


Figure D- 1. Wreckage of Asiana Flight 214 (National Transportation and Safety Board, 2013)

The accident of Asiana Airlines Flight 214 occurred on July 6, 2013 in San Francisco, California. During final approach the crew attempted to descend using FLCH mode, however this caused a mode transition to THR, in response the crew retarded throttles manually causing the auto-throttle to revert to a dormant HOLD mode.[70] In the crew interviews indicated that their assumption during the approach was that the auto-throttle system would capture approach speed, however in actuality the auto-throttle had defaulted to a dormant mode that maintained throttle position, which had been set to idle power (National Transportation and Safety Board, 2013). In this case, there was an apparent divergence between the state of the auto-throttle in actuality (HOLD mode) and the human state assumption. In this accident, while in HOLD mode and throttles at idle, the speed of the aircraft decayed below the pre-set approach airspeed.

[70] According to FDR data, the AFCS-initiated forward movement of the thrust levers that began when the A/T mode changed to THR was manually overridden, and the thrust levers were moved aft.

The analysis of divergence may explain the delayed crew response to this low speed situation. The crew eventually noticed the low airspeed, however was not able to recover in time to avoid impacting the sea wall short of the runway threshold.

Event E1: Initiation of Divergence

Time	Impact – 01m 17s
Actual State	HOLD
Situation	Recovery from abnormal use of FLCH that caused THR mode on final descent
Event Trigger	Change in actual state
Divergence Type	D-1b: Actual state transitions due to upstream input by the crew

Unknown divergence apparently initiated when the auto-throttle reverted to HOLD mode. This was apparently a result of the PF attempting to descend using FLCH. This input caused the auto-throttle to transition to THR mode. The PF reduced the throttles in response to this, however this action caused the auto-throttle to revert to HOLD mode, unbeknownst to the crew (National Transportation and Safety Board, 2013).

In this case, because the aircraft was high on the approach already, the HOLD on the FMA was likely their only definitive variable at this point. Airspeed information, pitch information, and engine thrust feedback were all indefinitive since the aircraft was high and descending to intercept a normal glide path. The observables would have been indicative of SPD mode as well as HOLD mode.

The evidence suggested that the crew did not observe the HOLD on the FMA since no action was taken to recover engine control until 7 seconds prior to impact. There were apparently a number of factors influencing the observation failure. The crew could have been distracted with their late checklists and unstabilized approach possibly causing them to fixate on the vertical profile. In addition, during the initiating mode transition for divergence the crew was still conducting their checklists.[71] In addition, workload could have been higher than normal due to the lack of a glide slope signal for the approach. The

[71] 1126:33, the thrust levers reached the idle position, and the A/T mode changed to HOLD. Immediately before the A/T mode change occurred, at 1126:32.5, the PM stated, “flight director,” and immediately after the change, at 1126:34.0, the PF replied, “check.”

PF was also being evaluated which could have put additional pressure on him to recover the vertical profile. In addition, the crew's behavior had indications consistent with behavior under fatigue.[72] As discussed in other accidents, the HOLD on the FMA has not been shown to be a very salient cue, thus this design influence could also have affected the likely missed indication of the single definitive observable.[73] Finally, expectation bias also may have influenced the observation process if the crew held an incorrect expectation.

If the HOLD on the FMA was not observed, the only observations that fed into the association process were likely indefinitive indicating the effect of high ambiguity of observables. This failure could have been trapped in the state association process if expectation were correct, however an expectation process failure was also likely. The behavior of the crew and crew interviews stated that they had expected the auto-throttle to capture the mode control panel (MCP) airspeed. This shows a problem with system understanding since they did not understand that their actions could have resulted in the aircraft auto-throttles reverting to HOLD mode. Once this occurred, it's apparent that the divergence propagated the expectation failure.

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[72] "The PF made several errors that might be attributable, at least in part, to fatigue. These errors included his selection of FLCH SPD at 1,550 ft. without remembering that he had already selected the go-around altitude in the MCP altitude window less than 1 minute earlier, being slow to understand and respond to the observer's sink rate callouts, not noticing the decrease in airspeed between 500 and 200 ft., and not promptly initiating a go-around after he detected the low airspeed condition.

The PM also made several errors that might be attributable, at least in part, to fatigue. These errors included not noticing the PF's activation of FLCH SPD at 1,550 ft. or subsequent indications on the FMA, not ensuring that a "stabilized" callout was made at 500 ft., not noticing the decay in airspeed between 500 and 200 ft., and not immediately ensuring a timely correction to thrust was made when he detected the low airspeed. "

[73] During a post accident interview, the PF stated that he considered pressing the FLCH push-button to obtain a higher descent rate but could not recall whether he did so or not. When interviewed, none of the three flight crewmembers recalled seeing the changes to the A/T mode displayed on each primary flight display's (PFD) flight mode annunciator (FMA) that resulted from the selection of FLCH.

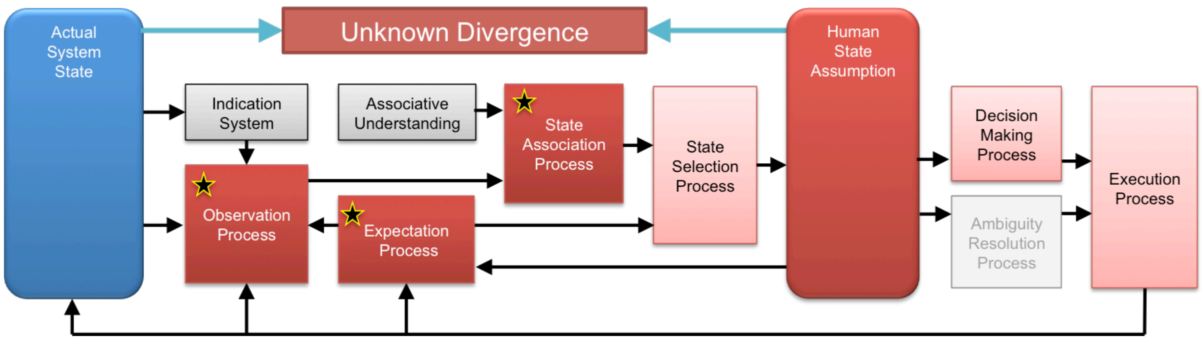

Figure D- 2. Human information processing model for Asiana: Event E1

Event E2: Speed Decay Below MCP Set Airspeed

Time	Impact – 00m 35s
Actual State	HOLD
Situation	Final approach descent
Event Trigger	Change in observables

At 35 seconds prior to impact, the speed decayed below the MCP set airspeed of 137 knots. The HOLD on the FMA remained a definitive observable at this event, however more observables also became definitive. Airspeed value and airspeed trend, throttle location, pitch attitude, engine parameters all became definitive once the airspeed dropped below 137 knots. In addition, pitch forces would have increased as the aircraft speed decayed toward stall.[74]

Since no change in behavior was apparent, the crew likely continued to miss the FMA indication as well as the other definitive observables. The workload, distraction, and fatigue factors remained. Again here, the crew was conducting checklists at the time the speed decayed below the MCP speed.[75] The design

[74] If airspeed decreases below the minimum maneuvering speed, further nose-up pitch trim is inhibited. As speed decreases within the amber band's range, the force required to pull back on the control column increases. The pilot may still override the force with increased effort. These features are designed to provide a tactile cue that the airspeed is dropping below the minimum maneuvering speed.

[75] 1127:15.1 Airspeed drops below MCP-speed; 1127:16.6 PF: "landing checklist"; 1127:17.5 PM: "landing checklist complete cleared to land"; 1127:19.8 PM: "on glide path sir" / PAPI WWRR; 1127:21.2 PF: "check" (National Transportation and Safety Board, 2013)

issue of salience on the FMA also remained however at this point, the crew had multiple other cues so the effect of the design issue could have alleviated if any other observable were actually observed.

Due to the added definitive observables, it the ambiguity of observables likely alleviated in the association process, however this process likely continued to be affected by the observation failure. The expectation failure also likely remained due to the divergence feedback into expectation.

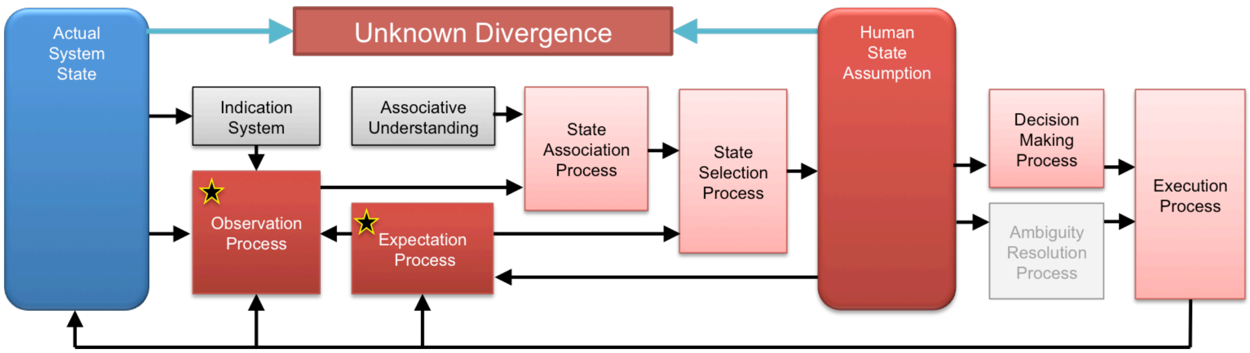

Figure D- 3. Human information processing model for Asiana: Event E2

<u>Event E3: Recognition of Speed Decay (Pilot Monitoring)</u>

Time	Impact – 00m 17s
Actual State	HOLD
Situation	Final approach descent
Event Trigger	Change in observation

During post-accident interviews, the PM stated that "at about 200 ft. RA, the airspeed was about 120 knots; he saw four red lights on the PAPI and thought perhaps the A/T was not working" (National Transportation and Safety Board, 2013). This indicates a that the PM may have moved into known divergence at this point due to a recovery of his observation process failure.

This recovery of the observation process failure, also likely recovered its downstream effect on the association process. In this case, the expectation failure that remained would have been trapped in the state selection process for the pilot monitoring.

It is possible that the PM attempted to verbalize the low airspeed to the PF. Immediately after the 200 ft. RA call, the PM stated "it's low," and the PF responded, "yeah." It is unclear however, whether the PM was verbalizing about the low altitude or the low airspeed. Regardless, this verbalization did not appear to trigger known divergence for the PF.

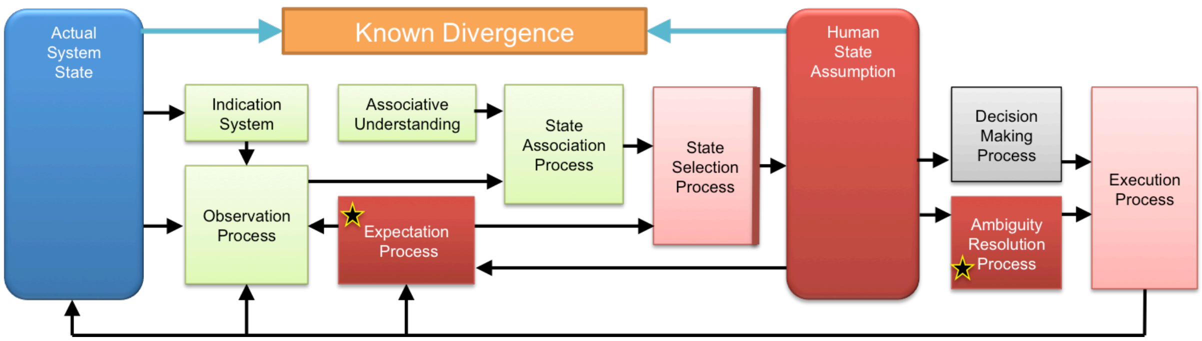

Figure D- 4. Human information processing model for Asiana: Event E3

It may be debatable however, whether this verbalization reaction was an appropriate decision given the gravity of the situation. Immediate recovery action was likely warranted given the low speed of the aircraft. Since the PM decided not to take action to recover the aircraft immediately given his observation, this could be considered as a failure in the ambiguity resolution process.

<u>E4: Low Airspeed Alert Annunciates</u>

Time	Impact – 00m 11s
Actual State	HOLD
Situation	Final approach descent
Event Trigger	Change in Observables

Six seconds after the PM reportedly identified that the airspeed was low, an added indication became available. The B777 was designed to provide an "AIRSPEED LOW" EICAS message annunciation, accompanied by a caution-level aural alert when the airspeed drops below maneuvering speed.[76] The quadruple chime was recorded on the CVR, 11 seconds prior to impact.

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[76] "The 777 low airspeed alerting systems include a low airspeed alert and a stick shaker. The low airspeed alert is a caution-level alert and occurs when airspeed decreases about 30% below the top of the amber band. The visual cues that accompany a low airspeed alert include changing the color of the airspeed box on the PFD to amber, displaying an "AIRSPEED LOW" caution message on the EICAS,

Since the PM had likely already reached known divergence, it's possible that this added cue did not change the status of his processes. However, it may have helped him to decide to take control of the aircraft three seconds later, possibly addressing the ambiguity resolution failure.

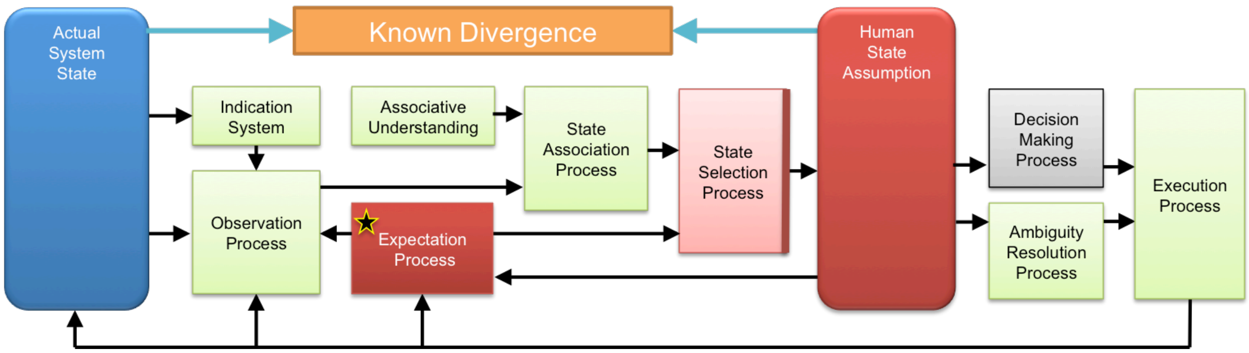

Figure D- 5. Human information processing model for Asiana: Event E4

There was no evidence of the PF updating his state assumption, likely until the PM took control of the aircraft and went around.

<u>Event E5: Pilot Monitoring Verbalization of "Speed" and Advances Thrust Levers</u>

Time	Impact – 00m 08s
Actual State	THR
Situation	Transition to go around
Event Trigger	Change in Actual State
Re-convergence Type	C-3

At 8 seconds prior to impact, the PM stated "speed," and advanced thrust levers. Since he takes action, it's likely that his expectation updated to reflect the THR expected with the go around. This action would have updated the actual state and his state assumption likely resulting in re-convergence.

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and illuminating the master caution lights. The caution-level aural alert (quadruple chime) will also sound." (National Transportation and Safety Board, 2013)

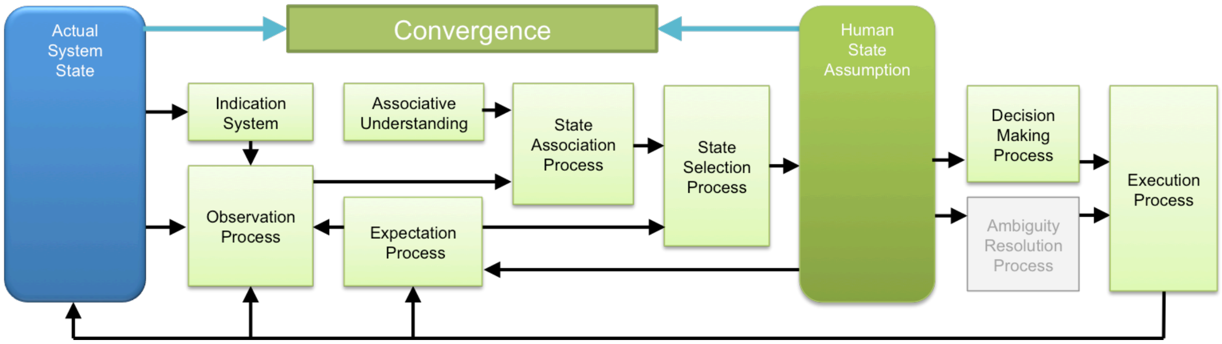

Figure D- 6. Human information processing model for Asiana: Event E5

Despite recovery actions, the aircraft impacted the seawall short of the runway. Analysis in the report suggested that if recovery had been initiated 3 seconds earlier, the accident could have been prevented (National Transportation and Safety Board, 2013).

On the topic of whether this accident could have been prevented if checklists were complied with, the PM verbalized a 1000 ft. call out, however no stabilized criteria was discussed in response to that call. Thus, it is possible that if the crew had complied with stabilized approach criteria that they would have scanned the airspeed and recognized that the auto-throttles were not maintaining it.

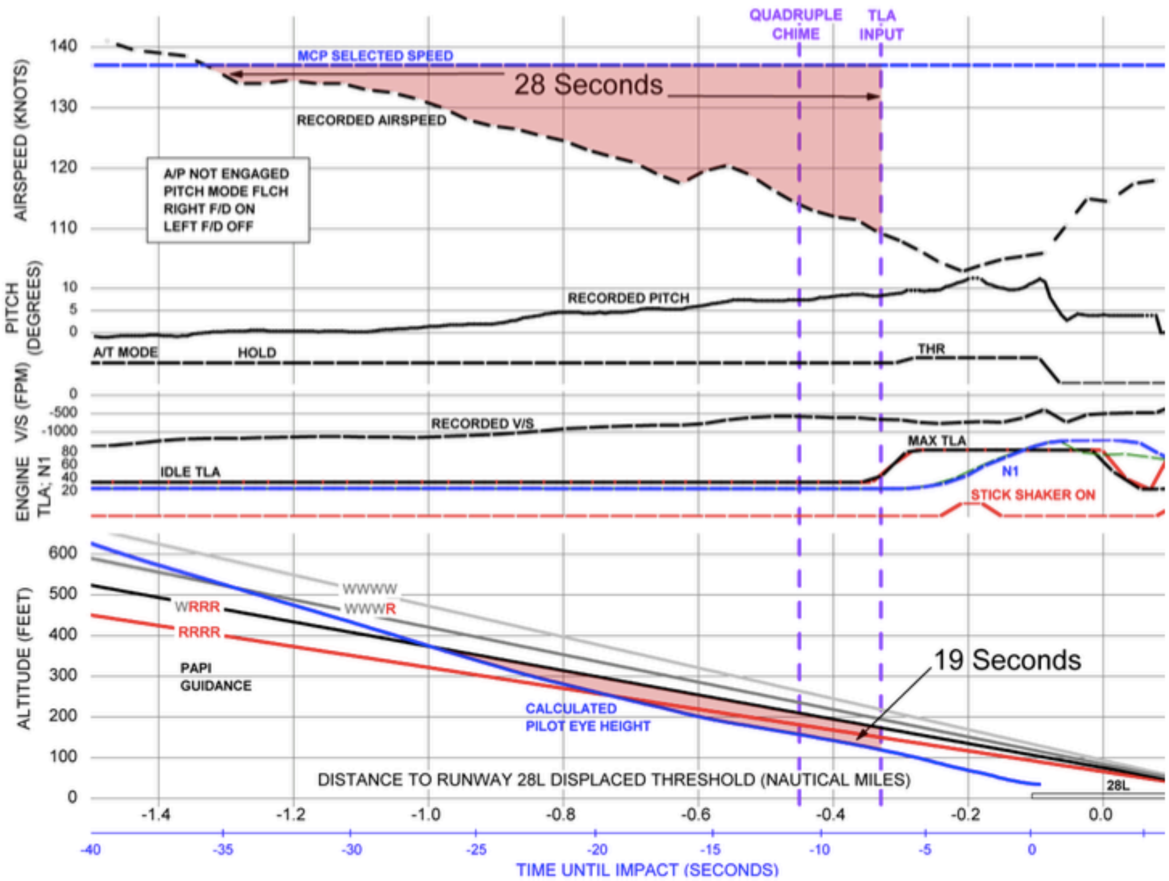

Figure D- 7. Profile view of the final 40 seconds of Asiana Flight 2014 (National Transportation and Safety Board, 2013)

The accident of Asiana 214 exhibited failures in the observation, association, and expectation processes. Within observation, the likely crew's expectation of SPD could have influenced their scanning strategies of new information. In addition, the crew could have been experiencing high workload and distraction due to their unstabilized approach, late checklists, and a lack of a glide slope. During at least two events that could have provided the crew with information regarding the change of state of the aircraft, the crew was actively conducting checklists illustrating the effect of this distraction. The report also suggested that the crew's behavior could have been consistent with fatigue effects. In addition, design of the FMA and the lack of salience there of, could have also played a part in the observation failure. In addition to the observation failure, there was ambiguity in many observables at the beginning of the divergence timeline due to a descent. Finally, systems understanding failures were apparent from the crew's action to use FLCH to descend on approach, and illustrated by the confusion verbalized in the cockpit after this action and the lack of response to the HOLD mode transition, a likely abnormal transition to the crew. This systems understanding problem combined with the perpetuation of divergence once divergence had occurred, likely contributed to the expectation failure not being caught until later in the divergence timeline.

Table D - 1. Summary of information processing failures in Asiana 214

Failure / Case	Occurrence of Observation Process Failure					Occurrence of Association Process Failure		Occurrence of Expectation Process Failure		
	Expect-ation Bias	Dist-raction	Work -load	Fatigue	Design Influences	Associative Under-standing	Ambiguity of Observables	Abnormal Transition	System Under-standing	Perpetuation of Divergence
Asiana 214	x	x	x (high)	no data	x		x	x	x	x

D2: Incident: Thomsonfly Airlines – Aerodynamic Stall on Landing Approach

This incident occurred on September 23, 2007 on approach to Bournemouth Airport, Hampshire, UK (Department for Transport/Air Accidents Investigation Branch, 2009). During the final approach segment with the auto-throttles engaged in SPD mode and auto-pilot on, the auto-throttle disconnected. This disconnection apparently went unnoticed by the crew, despite an aural tone accompanying the disconnect which required a manual button press to silence. The crew apparently noticed the low speed and initiated a go around. The crew recovered the aircraft, however did suffer an aerodynamic stall when performing the missed approach. The data for this analysis was taken from the aircraft's Quick Access Recorder (QAR) and crew interviews. The incident was not reported immediately, thus the FDR and the CVR had been overwritten.

Event E1: Initiation of Divergence

Time	Initiation of Recovery – 01m 04s
Actual State	OFF
Situation	Final approach descent
Event Trigger	Change in actual state
Divergence Type	D-1

The initiation of divergence apparently occurred when the auto-throttle disconnected and the crew did not notice this disconnect. The source of the disconnect was not determined. The aircraft was at an altitude of approximately 2200 feet on the glide slope but fast on the approach. When the disconnect occurred, the crew was configuring the aircraft for landing and the thrust lever was full aft according to the QAR data.

In the B737, there were a number of indications to the crew regarding this disconnect (Department for Transport/Air Accidents Investigation Branch, 2009). The FMA would have transitioned to blank in the Auto-throttle mode box. Apparently a continuous aural auto-throttle warning annunciated. A green annunciator light beside the auto-throttle switch would have extinguished, and a flashing red A/T P/RST autoflight status annunciator on the instrument panel would have illuminated. This panel is shown below.

Figure D- 8. Flashing red A/T P/RST (Department for Transport/Air Accidents Investigation Branch, 2009)

Figure D- 9. Flashing amber A/T P/RST (Department for Transport/Air Accidents Investigation Branch, 2009)

Despite a number of definitive observables, of both visual and auditory modality, it appears that these indications could have all been missed, since one would have expected the crew to take manual control of the throttles if they had recognized the failure. During crew interviews, the captain stated that he didn't notice the auto-throttle failure until he put his checklist down and saw the airspeed. This observation failure could have been influenced by a number of different factors. There was not evidence of abnormally high workload the crew was facing. Distraction could have played a part since they were conducting checklists during the final approach. There were no fatigue issues reported by the pilots. In addition, the indications to the crew regarding the disconnect included multiple definitive observables thus not indicating a design influence affecting observation. Finally, expectation bias could have been a factor. The crew reported not hearing the auto-throttle disconnect tone, which could have been a result of the expectation bias since the crew's comments suggested they expected the auto-throttle to be in SPD mode.

In addition to the apparent observation failure, there could have also been association failures that led to this case of divergence. There was apparently ambiguity of observables given that when the auto-throttle disconnected, the thrust was at IDLE in order to decay airspeed. This would have been indicative of SPD mode as well as OFF in this case. The report states that "The aircraft's Indicated Airspeed (IAS) decayed in line with crew expectations for an idle thrust approach and this constant deceleration approach masked the disengagement of the autothrottle"[77](Department for Transport/Air Accidents Investigation Branch, 2009).

In addition to this failure in association, another failure in association could have explained the crew's lack of response to a flashing AT/WARN light. In addition to flashing red in the case of an auto-throttle failure, this annunciator will also illuminate with a flashing amber if the auto-throttle is not holding the target speed.[78] The report also stated that on "approach, with the aircraft decelerating, the caption will routinely flash for extended periods" (Department for Transport/Air Accidents Investigation Branch, 2009). Considering the flashing amber was common, it may have been possible that the crew discounted this flashing signal as an observable of value if they considered these nuisance alerts. In this case, it could indicate a failure in associative understanding if they did not realize that red flashing was a different indication that amber flashing. The alternative to this hypothesis is that expectation bias could have manipulated the color of the light when it fed into association or purely the flashing was perceived and not the color. Either way – the association process would have likely treated this cue as an ambiguous observable. Both failures in ambiguity and associative understanding could have been possible here.

The combination of failures in the observation, association, and expectation processes likely resulted in unknown divergence.

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[77] The autopilot remained engaged and continued to track both the localizer and the glideslope. The aircraft's speed decayed at about one knot per second, in line with the PF's expectations for the approach. As the speed decreased below 150 kts, flap 25 was selected. The autopilot tracked the glideslope accurately, gradually increasing the pitch of the aircraft to minimize glideslope deviation and adjusting the stabilizer angle to keep the aircraft in trim. Temporary reductions in pitch were evident during flap position transitions.

[78] "There are three conditions when this light will flash; the airspeed is 10 kts above the target speed and not decreasing, the airspeed is 5 kts below the target speed and not increasing, or the airspeed has dropped to alpha floor (a factor of 1.3 above the stall speed) during a dual channel autopilot approach."

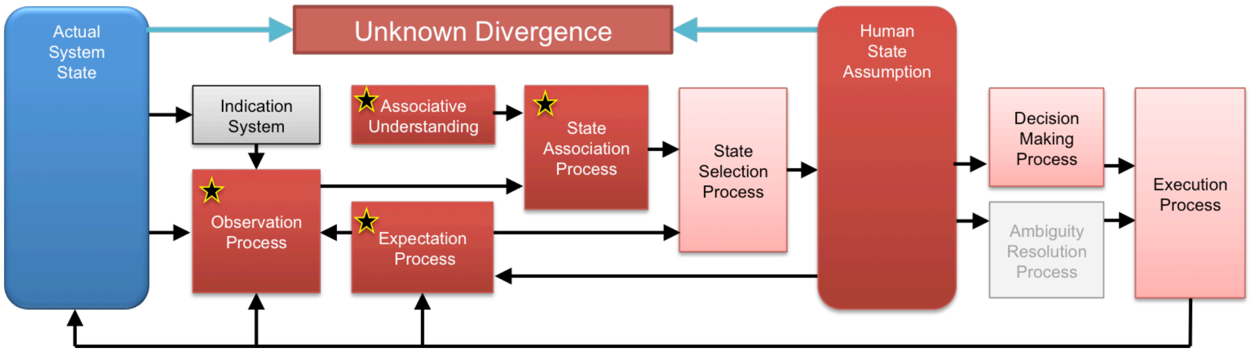

Figure D- 10. Human information processing model for Thomsonfly: Event E1

<u>Event E2: Speed drops below MCP set airspeed</u>

Time	Initiation of Recovery – 00m 11s
Actual State	OFF
Situation	Final approach descent – Speed below MCP airspeed
Event Trigger	Change in observables

At 11 seconds prior to the initiation of recovery the speed drops below the MCP set airspeed introducing a number of definitive observables (Department for Transport/Air Accidents Investigation Branch, 2009). Airspeed, airspeed trend, engine parameters, and throttle location could have provided additional information to the crew regarding the state of the system. There was no change in behavior, nor any verbalization at this point in the approach, so it is not likely that the crew updated their state assumption.

While the ambiguity of observables may have alleviated at this point, the possible failure in associative understanding could have remained indicating a continued association process failure. In addition, there was no evidence to suggest that the crew's expectation had changed during this event. Thus, the continuing failures in the observation, association, and expectation processes likely contributed to continuing unknown divergence.

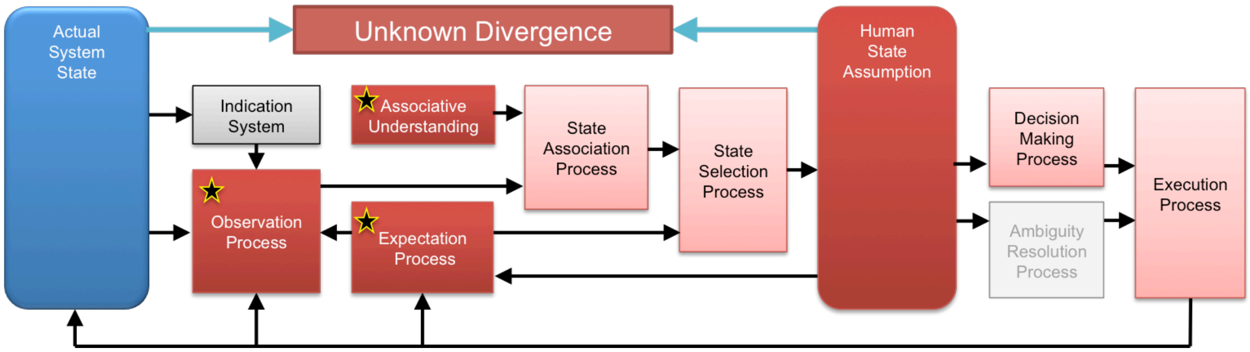

Figure D- 11. Human information processing model for Thomsonfly: Event E2

<u>Event E3: Pilot Monitoring Notices Speed Decay</u>

Time	Initiation of Recovery – 00m 00s
Actual State	OFF
Situation	Final approach descent
Event Trigger	Change in observation

The captain, who held PM duties at this point in the timeline, reported in his interview that once he completed the landing checklist, he scanned the flight instruments and noticed that the speed had decayed to 125 knots.[79] Because airspeed was a definitive variable at this time, the possible failure discussed previously in associative understanding was likely overcome by definitive information. Thus, this left the

[79] The commander stowed the checklist on top of the instrument panel and when he looked down he saw an IAS of 125 kt. He called "SPEED", the PF made a small forward movement with the thrust levers and the commander called "I HAVE CONTROL". The commander moved the thrust levers fully forward and called "GO-AROUND FLAP 15 CHECK THRUST"(Department for Transport/Air Accidents Investigation Branch, 2009).

Recorded data shows that, at a CAS of 110 kts and an altitude of 1,540 ft., the autothrottle manual disconnect was pressed and the thrust levers moved forward slightly. Within 1.5 seconds the stick-shaker (stall warning) activated and in the following two seconds the thrust levers were advanced to the full forward position.

expectation as the remaining failure. Human information processing model shows that since the airspeed information was different from the expectation, this would have resulted in known divergence.

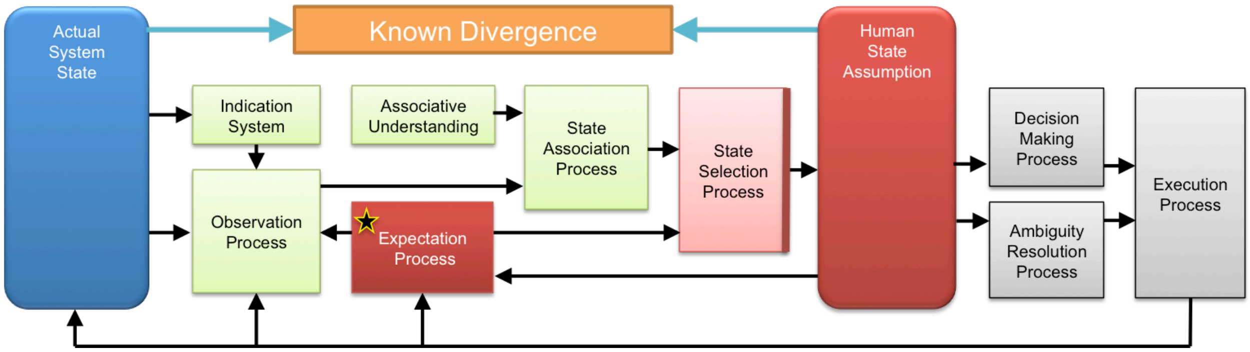

Figure D- 12. Human information processing model for Thomsonfly: Event E3 – Known Divergence

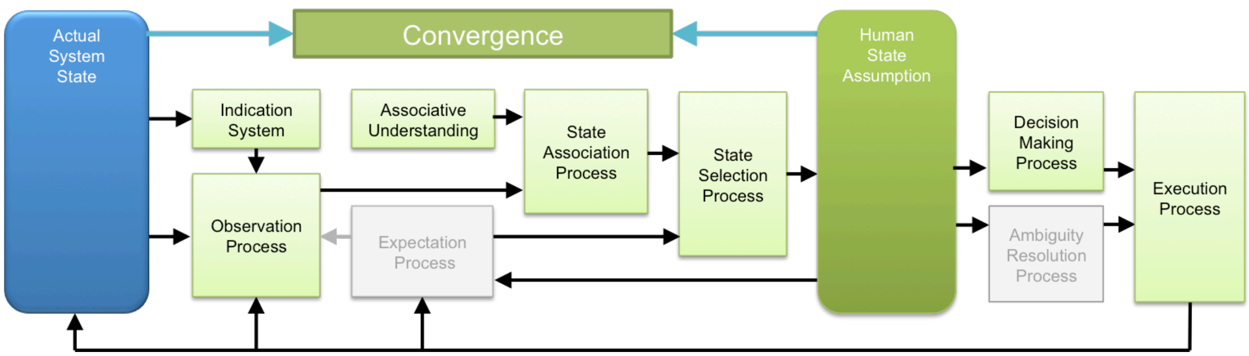

Figure D- 13. Human information processing model for Thomsonfly: Event E3 - Re-convergence

Event E4: Re-convergence: Initiation of Recovery

Time	Initiation of Recovery – 00m 00s
Actual State	OFF
Situation	Initiation of go around
Event Trigger	Change in actual state

Apparently as the flight descended on the glide path, the autopilot had trimmed the airplane nose up to counteract the lack of thrust and stay on the glide path. Thus when the thrust was advanced for recovery, the high nose up trim apparently made recovery difficult ultimately leading to an aerodynamic stall. The crew was able to recover the aircraft however, it took 49 seconds to complete the recovery.[80]

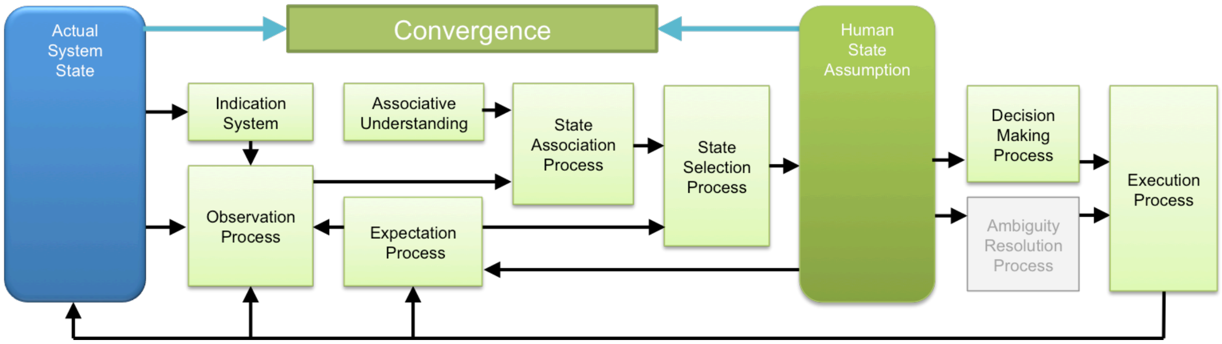

Figure D- 14. Human information processing model for Thomsonfly: Event E4

Summary

In the incident of Thomsonfly, there were failures apparent in the observation, association, and expectation processes. Since the crew had begun the approach with the auto-throttle in SPD mode, it is possible they held this expectation throughout the divergence timeline until known divergence. This expectation could have influenced the crew's scan pattern of new information or not perceive the aural auto-throttle disconnect tone. In addition, the crew conducting checklists during divergence timeline, which could have distracted them from maintaining speed awareness. In addition, there were design influences involving nuisance alerting that could have contributed to the crew possibly disregarding the flashing light observable. This adaptation to disregarding the flashing light, could have occurred in associative understanding where the observable could have no longer been useful in determining state of the system. In addition to this association failure, the speed was high on approach, so idle power was expected by the crew for some period of the divergence timeline suggesting an ambiguity of observables. Finally, as mentioned prior the expectation was likely propagated by the occurrence of divergence, however no evidence of problems with crew system understanding was identified in this incident.

[80] Because the crew initiated recovery above 1000 ft. altitude, the stabilized approach checklist would not be expected to have been conducted at this point in the approach.

Table D - 2 Summary of information processing failures in Thomsonfly incident

Failure / Case	Occurrence of Observation Process Failure					Occurrence of Association Process Failure		Occurrence of Expectation Process Failure		
	Expect-ation Bias	Dist-raction	Work -load	Fatigue	Design Influences	Associative Under-standing	Ambiguity of Observables	Abnormal Transition	System Under-standing	Perpetuation of Divergence
Thomsonfly (Incident)	x	x			x	x	x	x		x

D3: Incident: Tarom Airlines Flight 381

The incident of Tarom Airlines Flight 381 occurred on September 24, 1994 on an approach to Orly, France (Bureau d'Enquêtes et d'Analyses, 2000). During this accident, a mode transition of the auto-throttle occurred to a transient flap overspeed condition, apparently causing divergence. The reaction of the crew to push forward on the yoke in response to this transition caused an out of trim condition that eventually led to a stall and recovery. Divergence could have occurred on multiple channels here however the auto-throttle state is chosen as the state of interest.

Event E1: Initiation of Divergence: A/T mode transition due to flap overspeed

Time	Initiation of Recovery – 01m 09s
Actual State	THR
Situation	Initiation of Go Around
Event Trigger	Change in actual state

The transition of the auto-throttle from SPD to THR mode during the approach was apparently the source of divergence. The crew had set the go around altitude into the MCP earlier than normal and when the overspeed occurred, the automation transitioned to thrust to climb to that altitude of 4000ft. In this case, definitive observables were prevalent such as the FMA, increase in thrust, and increase in engine parameters. It was apparent that the crew recognized the abnormal behavior of the aircraft, considering they likely had an expectation that the auto-throttle was in SPD mode from when they set it[81] (Bureau d'Enquêtes et d'Analyses, 2000)

Workload was likely increased due to the shortened approach path and ILS intercept suggested by ATC. Because of this abnormal approach, the autopilot would not automatically capture the glide path. In response, the crew disconnected the autopilot and flew with only the auto-throttle engaged. It was stated

[81] Captain "Hey! What's it doing?" The co-pilot said "take over manually". At 10 h 4 m 01 s, the Captain declared "Hey, its doing a go around" (Bureau d'Enquêtes et d'Analyses, 2000),

in the report that crew resource management was an issue in addition to checklists being performed out of sequence.[82]

However despite, the high workload encountered by the crew, the observation of the mode transition was made. If the crew likely believed the aircraft would remain in SPD mode, this expectation would have conflicted with the behavior observed by the pilots and likely trapped the divergence in the state selection process, apparently triggering known divergence.

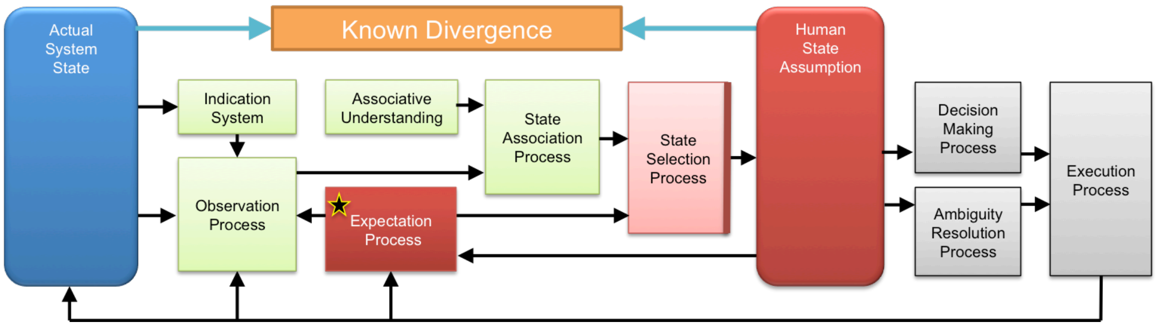

Figure D- 15. Human information processing model for Tarom 381: Event E1

The crew at this point showed confusion regarding the behavior of the automation. Relevant to auto-throttle awareness, the crew manually manipulated the throttles to retard and later increased[83]

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[82] "Premature selection of the go around altitude and precipitous setting of the configuration with slats and flaps at 20-20, which led to activation of the speed protection" Crew showed "Difficulty in understanding the action of the auto-throttle increasing thrust in its overspeed protection function" (Bureau d'Enquêtes et d'Analyses, 2000)

[83] "To try and explain the first positioning of the throttle levers to maximum thrust, we can propose two hypotheses : (a) the Captain, noticing the strong reduction in the VC trend, may have thought that the speed was going to decrease significantly. He may have advanced the throttle to avoid stalling, (b) the Captain, noticing the problem in the pitch attitude, which would prevent him from continuing his landing, seems to have decided to climb so as to obtain more favorable conditions to deal with the problem" (Bureau d'Enquêtes et d'Analyses, 2000)

Event E2: Re-convergence: A/THR automatically disconnects – due to loss of AOA data – strong inflight drift

Time	Initiation of Recovery – 00m 04s
Actual State	OFF
Situation	Auto-throttle automatically disconnects at high angle of attack
Event Trigger	Change in actual state
Re-convergence Type	C-1

Approximately 4 seconds prior to the initiation of recovery, the auto-throttle automatically disconnected due to loss of angle of attack data, likely due to strong inflight drift corrupting flow over the sensors. If the crew believed that the auto-throttle was off, this would have brought the crew into re-convergence. However, it is difficult to surmise the crew state assumption due to the confusion verbalized, however their recovery procedure following the disconnect was appropriate according to Tarom standards (Bureau d'Enquêtes et d'Analyses, 2000).

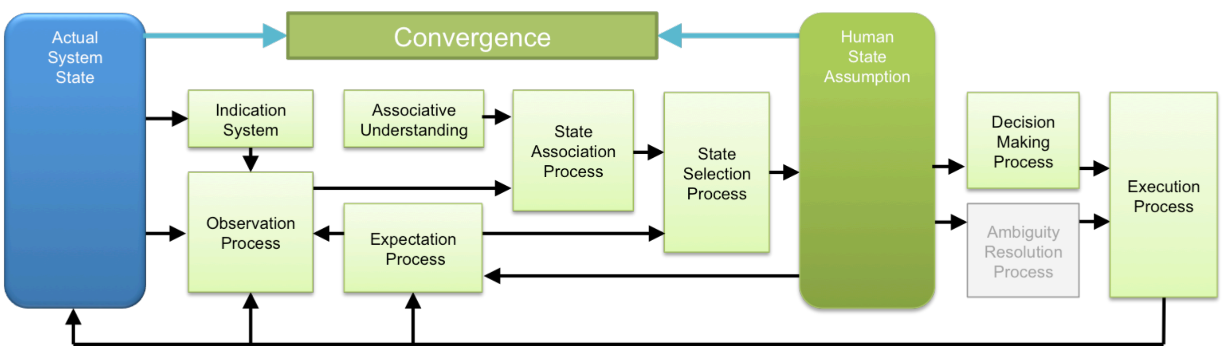

Figure D- 16. Human information processing model for Tarom 381: Event E2

Initiation of Recovery occurred 4 seconds later and the recovery process took approximately 30 seconds to complete. The crew performed a successful go around and returned for an uneventful landing.

Summary

The incident of Tarom 381 showed evidence of observation process failures and expectation process failures. The expectation bias of the aircraft remaining in SPD mode could have influenced their scan patterns. The crew was apparently distracted by a shortened approach procedure, which likely increased their workload as well. In terms of expectation failures, the report suggested that a lack of crew understanding of the envelope protection function could have contributed to their lack of anticipation of the mode change. These failures combined resulted in known divergence for some period of this incident.

Table D - 3. Summary of information processing failures in Tarom 381 incident

Failure / Case	Occurrence of Observation Process Failure					Occurrence of Association Process Failure		Occurrence of Expectation Process Failure		
	Expect-ation Bias	Dist-raction	Work -load	Fatigue	Design Influences	Associative Under-standing	Ambiguity of Observables	Abnormal Transition	System Under-standing	Perpetuation of Divergence
Tarom 381 (Incident)	x	x	x (high)	no data				x	x	x

In this accident, the dynamics were complex and it is possible that analysis of divergence of the auto-throttle mode isn't sufficient for understanding of all impacts of information processing failures. For this accident, additional analysis could have been conducted on vertical flight path awareness, vertical auto-pilot mode, or airspeed. However, the results found for the auto-throttle state did provide some insight and can be compared with other cases involving auto-throttle mode awareness.

D4: Incident: American Airlines Flight 903

The incident of American Airlines Flight 903 occurred near West Palm Beach, Florida on May 12, 1997 (National Transportation and Safety Board, 1998). During this case, the crew was flying a holding pattern due to adverse weather in the area. During a descent to 16,000 feet, the auto-throttle disconnected, however this apparently went unbeknownst to the crew. Upon level-off, the speed decayed to a point where aerodynamic stall was imminent. The flying pilot apparently recognized the speed decay prior to the point, however the aircraft departed controlled flight. The crew recovered from the stall at approximately 13,000 ft. altitude. In this case, the disconnection of the auto-pilot, which went unnoticed by the crew, was apparently the initiation of divergence.

Event E1: Disconnection of Auto-throttle

Time	Initiation of Recovery - 03m 13s to 00m 46s[84]
Actual State	OFF
Situation	Descent to 16,000 feet in a holding pattern
Event Trigger	Change in Actual State

The initiation of divergence apparently occurred when the auto-throttle disconnected on the descent. The exact time of disconnection was not recorded, however was inferred to be between the last recorded input to the auto-throttle 03m13s prior to initiation of recovery and the beginning of level off which was 46s prior to recovery. Because no action was taken by the auto-throttle to increase speed during level off contrary to what was expected if the auto-throttle was engaged in SPD mode, it was apparent that the auto-throttle had disconnected prior to that point at some point during the descent. Since the auto-throttle likely disconnected during the descent, the lack of information on the FMA would have been a definitive observable of the state of the system. Because the crew stated that they did not notice anything abnormal until after level off, it can be considered that the crew missed the FMA observable. In addition, the crew was facing high workload due to weather in the area and planning of a possible diversion. This could have also led to distraction from performing a normal scan. In addition, during crew interviews the flying pilot stated that he had opted to enter the hold manually because he didn't think there was adequate time to

[84] Exact time of autothrottle disconnection was not recorded. The range of times provided are the time of last input to auto-throttle to the time of level off where throttle input would have been expected. Theoretically, the disconnection could have occurred anywhere in that time frame.

“build it into the FMS” (National Transportation and Safety Board, 1998). This manual entry to a holding pattern, while trained early in a pilot’s career, could have increased his workload as well as he may have had to remember the details of the entry if he hadn’t completed a manual hold entry recently. No definitive fatigue conclusion was provided in the report. Finally, the crew likely held an expectation that the auto-throttle was in speed mode as they had initiated the descent with that mode engaged (as they reported in their post-incident interview). It is possible that this expectation influenced their scan strategies for gathering new information.

As mentioned, the only definitive variable to the crew was the FMA, however many indefinitive observables existed and rendered ambiguous due to the descent. Idle thrust, throttle location, airspeed, all could have been indicative of either SPD mode or the failed auto-throttle OFF mode.

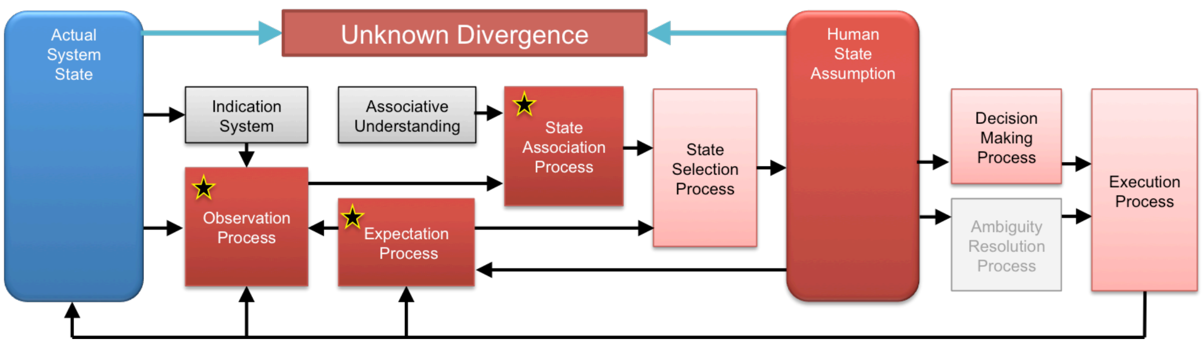

Figure D- 17. Human information processing model for American Flight 903: Event E1

<u>Event E2: Level off of Descent</u>

Time	Initiation of Recovery – 00m 46s
Actual State	OFF
Situation	Level off at 16,000 feet in a holding pattern
Event Trigger	Change in Observables

At 46 seconds prior to the initiation of recovery, the aircraft leveled off at 16,000 feet and more observables became definitive indications of an auto-throttle failure. These included the lack of engine thrust, the lack of throttle moving forward, speed decay and progress below the MCP set speed of 210 knots. It appears however that these indications were missed as well. This is inferred from the lack of crew response but also the crew’s report during the post-incident interview. The PF stated he noticed the speed decay sometime following level off. At this point, the ambiguity of observables had alleviated since more definitive observables were available, however expectation likely continued to hold strong.

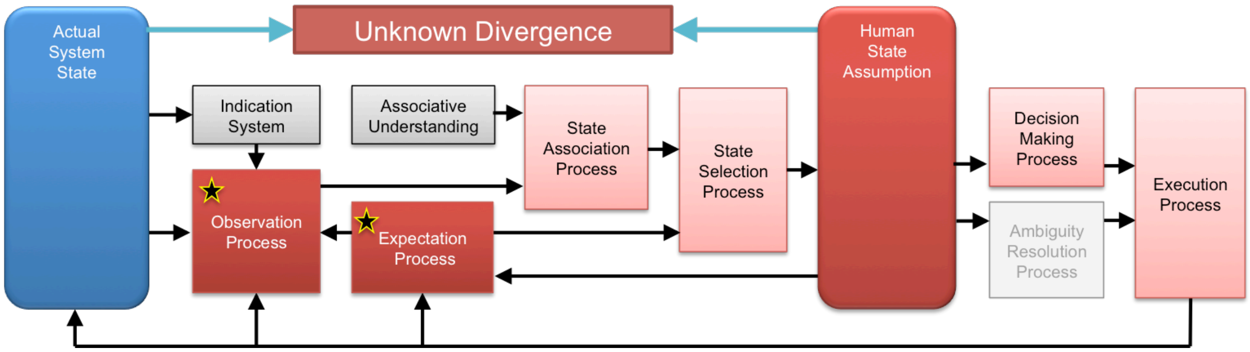

Figure D- 18. Human information processing model for American Flight 903: Event E2

<u>Event E3: PF notices speed</u>

Time	Initiation of Recovery – 00m 06s
Actual State	OFF
Situation	Level at 16,000 feet in a holding pattern
Event Trigger	Change in Observations

At approximately 6 seconds prior to the initiation of recovery, the pilot flying reports noticing that the speed had decayed below 210 knots.[85] In his interview, he stated that he thought that the auto-throttle was not holding airspeed.[86] Because of this insight, it is possible that this point in the timeline could have signified both known divergence and re-convergence. The observation process failure had recovered and recovered the association process as well. With these processes uncorrupted, the expectation process failure was likely trapped in the state selection process when the expectation was inconsistent with the states consistent with the observation.

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[85] Because the situation was in a holding pattern, there were not necessarily procedures the crew missed that would have cued them to the auto-throttle failure.

[86] The PF mentioned "Sorry about the speed" to the PM once he recognized the divergence. (National Transportation and Safety Board, 1998)

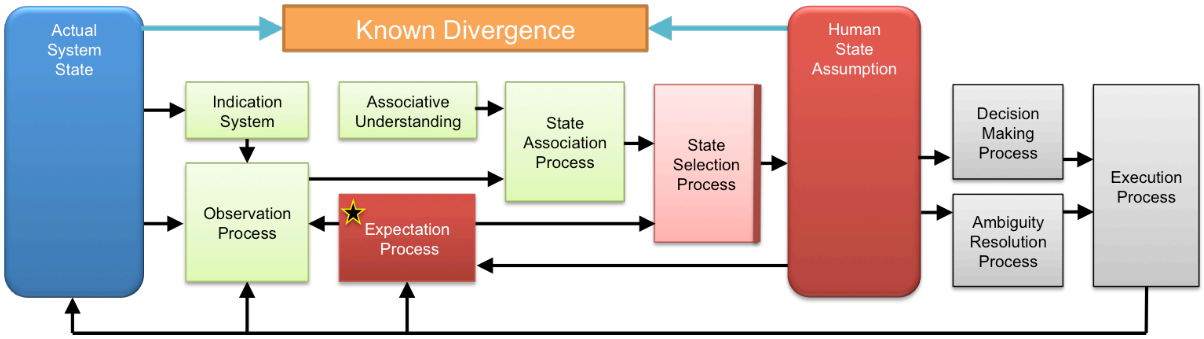

Figure D- 19. Human information processing model for American Flight 903: Event E3 – Known Divergence

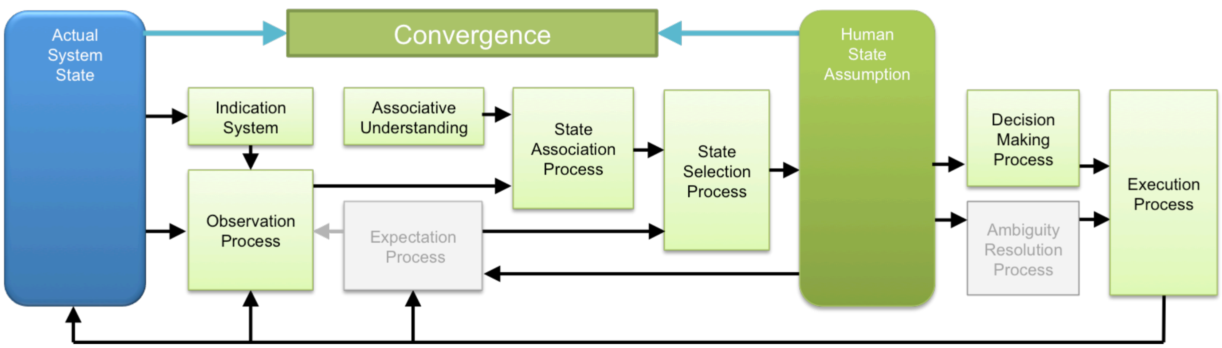

Figure D- 20. Human information processing model for American Flight 903: Event E3 – Re-convergence

<u>Event E4: PF pushes throttles forward to recover</u>

Time	Initiation of Recovery - 00m 00s
Actual State	OFF
Situation	Level at 16,000 feet in a holding pattern
Event Trigger	Actual State Transition

Upon recognizing that the auto-throttle wasn't functioning as expected, the flying pilot pushed the throttles forward manually to recover from the low energy situation.[87] This recovery however, was too late and the aircraft stalled and departed controlled flight 9 seconds later. It took 41 seconds for the recovery to complete successfully.

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[87] "FO said he pushed up the throttles because auto-throttles were not responding to maintain 210 knots and the trend arrow did not go up as it should" (National Transportation and Safety Board, 1998)

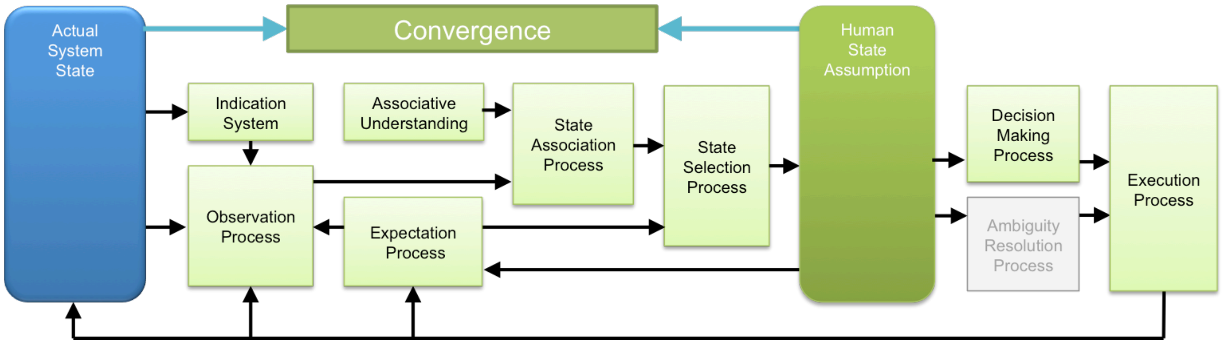

Figure D- 21. Human information processing model for American Flight 903: Event E4

Summary

In the incident of American 903, failures in the observation, association, and expectation processes were apparent. Since the crew likely held an expectation of the auto-throttle being in SPD mode since they had set it prior, it's possible that this expectation caused them to rely on this expectation and not scan the flight instruments effectively. In addition the crew were likely distracted with high workload due to the weather in the area and planning for a possible diversion. Finally, the FMA indication could have had salience issues in notifying the crew of an auto-throttle disconnection. Situationally, many observables were indefinitive due to the descent, and only became definitive during level off. The was not evidence of problems with crew understanding of systems, however the expectation failure was likely propagated by the divergence.

Table D - 4. Summary of information processing failures in American 903 incident

Failure / Case	Occurrence of Observation Process Failure					Occurrence of Association Process Failure		Occurrence of Expectation Process Failure		
	Expect-ation Bias	Dist-raction	Work -load	Fatigue	Design Influences	Associative Under-standing	Ambiguity of Observables	Abnormal Transition	System Under-standing	Perpetuation of Divergence
American 903 (Incident)	x	x	x (high)		x		x	x		x

D5: Accident: China Airlines Flight 140

The accident of China Airlines Flight 140 occurred on April, 26, 1994 in Nagoya, Japan (Aircraft Accident Investigation Commission - Ministry of Transport, 1996). During this case, the flying pilot apparently inadvertently activated TOGA mode during final approach descent, likely initiating divergence. Despite recognizing the error almost immediately, the crew continued to show behavior of confusion and inappropriate decision actions. One of these inappropriate actions initiated with the engagement of the autopilot. The autopilot attempting to Go Around combined with the pilot's forward yoke pressure caused an out of trim position and eventually when Go Around did occur, the aircraft pitched up uncontrollably and the aircraft stalled. It impacted the ground in a stalled condition.

Event E1: Initiation of Divergence: Activation of TOGA

Time	Impact - 01m 40s
Actual State	THR
Situation	Final Approach Descent
Event Trigger	Actual State Transition

The initiation of divergence apparently occurred when the flying pilot (F/O) inadvertently activated the Go Around (GO) Lever on approach to the runway.[88] This action caused the auto-throttles to transition

[88] "It is considered that the F/O may have mistaken the GO lever for the AT disconnect push button in an attempt to change the ATS into manual thrust, or that he tried to move the thrust levers to control the thrust and thereby inadvertently triggered the GO lever. The reasons why are not clear, but, at any rate, he inadvertently triggered the GO lever" The GO lever of the A300-600R type aircraft is positioned below the thrust lever knob. The direction that the GO lever is operated in is the same as the direction in which the thrust lever is retarded, or as the same direction that the fingers move when gripping the thrust lever knob. With this arrangement, the possibility exists for an inadvertent activation of the GO lever during normal operation of the thrust levers It is recognized that the F/O (P/F) triggered the GO lever at 1114:05 , judging from the following: the increase in engine thrust starting at 1114:05, as recorded on DFDR; the CAP's (PNF) utterance at 1114:06, the sound of LANDING CAPABILITY CHANGE at 1114:09, the CAP's caution at 1114:10, and the F/O's response at 1114:11, all of which were recorded on CVR." (Aircraft Accident Investigation Commission - Ministry of Transport, 1996)

from SPD mode into THR mode. This transition would have been indicated by a change in the FMA, engine noise and parameters increasing, and corresponding effect on the flight path. The FMA and engine parameters would have likely been definitive observables at this point.

According to verbalization from the PNF (Captain) the observables were apparently recognized.[89] No apparent failures in association were identified. However, there was likely an expectation failure since the pilot did not intend to trigger TOGA, he likely would have expected that the aircraft would have remained in SPD mode. This discrepancy between expectation and the observables would have likely have been trapped in the state selection process and triggered known divergence.

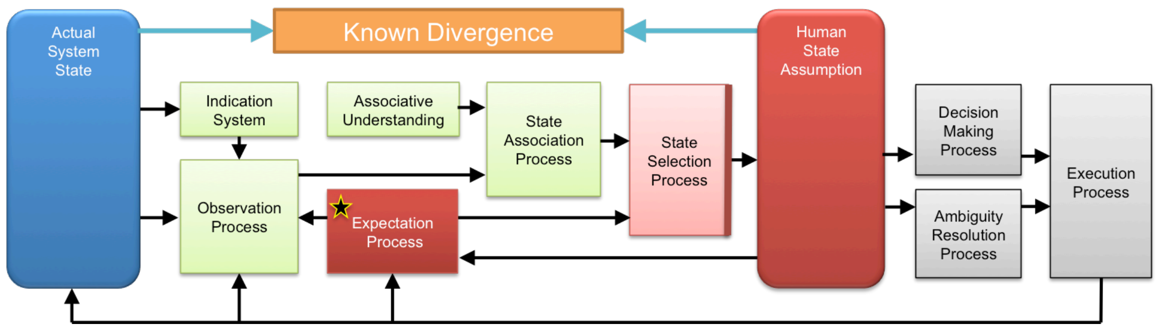

Figure D- 22. Human information processing model for China 140: Event E1

<u>Event E2. Disconnection of the Auto-Throttle by the First Officer</u>

Time	Impact - 01m 37s
Actual State	OFF
Situation	Final Approach Descent
Event Trigger	Change Actual State

Following the recognition that thrust was increasing, the pilot flying responded by disconnecting the auto-throttle and retarding throttles. This caused a change in the state of the auto-throttles to an off mode. Given that the first officer performed this action, it is reasonable to assume that his expectation also updated to reflect this action, which could have forced re-convergence in terms of auto-throttle state. This

[89] The report "considered that at 1114:06 the CAP said "EH. EH. AH," on seeing the display change on the FMA" (Aircraft Accident Investigation Commission - Ministry of Transport, 1996)

was likely true for the pilot flying (First officer), however there is no evidence on the captain's state assumption at this point.

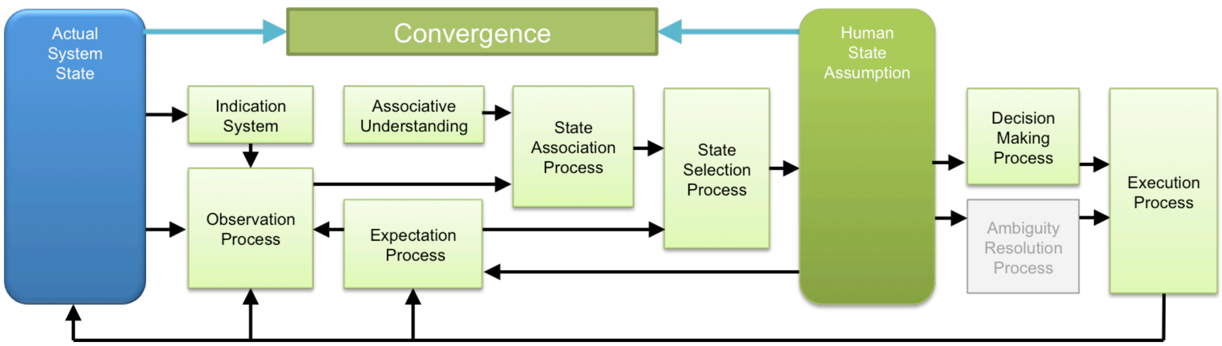

Figure D- 23. Human information processing model for China 140: Event E2

Following this action, much confusion ensued in the cockpit. The crew's behavior showed much confusion and inappropriate resource management throughout the divergence timeline, however the main actions the crew took are discussed in this thesis.[90] The first of these actions include the engagement of the autopilot in response to the TOGA activation. It was not determined why the crew engaged the autopilot, however it appeared that they could have expected to use it to use LAND mode to override the Go Around mode.[91] The FDR indicated that the crew attempted to activate LAND mode 47 seconds prior to impact (Aircraft Accident Investigation Commission - Ministry of Transport, 1996).

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[90] At 1059:04 and 1113:14, the CAP (PNF) read out the approach checklist and the landing checklist at the request of the F/O (PF), but these were not performed in the proper manner because the CAP (PNF) read the items only to himself, including those to which the CAP and F/O (PF) should responded together. The FCOM 2.03.18 (page 3) stipulates under the title of "STANDARD OPERATING PROCEDURES - STANDARD/APPROACH" that if the speed exceeds VAPP +10 Kts. or becomes less than V APP -5 Kts., or if the aircraft deviates a dot or more from the glide slope during an approach, the PNF should call out the fact. At 1114:17, the aircraft deviated more than a dot upward from the glide slope, and speed decreased to less than -5 Kts. from the VAPP of 140 KCAS as the aircraft continued approach. Despite this, the CAP did not call out these facts as PNF (Aircraft Accident Investigation Commission - Ministry of Transport, 1996).

[91] "The reason why either the CAP or the FIO engaged the APs may have been that the crew intended to regain the normal glide path by selecting LAND mode and engaging the AP" "In order to disengage GO

Event E3. Initiation of alpha floor

Time	Impact - 00m 48s
Actual State	THR
Situation	Alpha Floor Initiates
Event Trigger	Change in Observables

The activation of the auto-pilot in Go around mode and the manual thrust reduced, eventually caused a speed decay to the point that alpha floor initiated 48 seconds prior to impact. This resulted in the auto-throttle transitioning to THR mode. An observation was apparently made by the PF (F/O) who reported that "Sir, throttle latched again" after presumably observing the THR-L on the FMA(Aircraft Accident Investigation Commission - Ministry of Transport, 1996). As observed, this action appeared unexpected by the crew[92] and likely resulted in known divergence due to the conflict between observations and expectation in the state selection process.

AROUND mode, both lateral mode and longitudinal mode (except LAND mode) must be selected. Direct access to the LAND mode button cannot disengage GO AROUND mode (by selection of either lateral or longitudinal mode a display of GO AROUND on FMA will turn off). However, judging that GO AROUND mode still remained engaged, it is estimated that what the crew's operation on FCU was not correct procedure to disengage it : he must only have pulled LAND mode button. And also, taking into account that the CAP said "I, that LAND mode?" at 111458, the CAP seemed to have intended to disengage the GO AROUND mode and select LAND mode. The procedure for performing an approach by disengaging GO AROUND mode once engaged and then engaging LAND mode is unusual in the final phase of approach. However, the fact that the crew did not change modes as intended seems to have been due to their lack of understanding of the Automatic Flight System (AFS)." (Aircraft Accident Investigation Commission - Ministry of Transport, 1996).

[92] "The CAP (PF) said, "What's the matter with this? Damn it, how comes like this?" It is considered that the CAP's words expressed his puzzlement that the nose-up tendency was continuing, even though he had pushed the control wheel fully forward and decreased thrust." (Aircraft Accident Investigation Commission - Ministry of Transport, 1996).

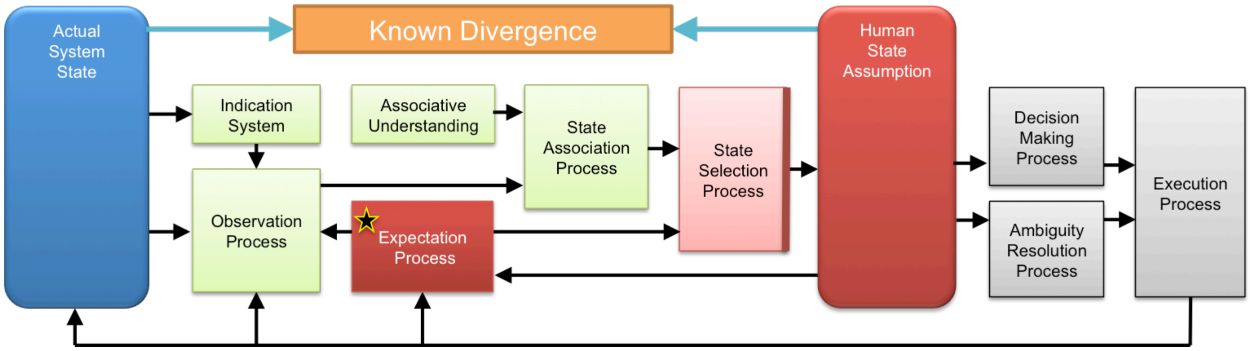

Figure D- 24. Human information processing model for China 140: Event E3

<u>Summary</u>

During the Accident of China Airlines Flight 140, failures in observation and expectation of auto-throttle state were found. There was evidence of distraction, once divergence occurred due to the crew attempting to maintain the glide path and control of the aircraft. Workload was also likely high for these same reasons of the unstabilized approach.

Table D - 5. Summary of information processing failures in China Airlines Flight 140

Failure / Case	Occurrence of Observation Process Failure					Occurrence of Association Process Failure		Occurrence of Expectation Process Failure		
	Expect-ation Bias	Dist-raction	Work -load	Fatigue	Design Influences	Associative Under-standing	Ambiguity of Observables	Abnormal Transition	System Under-standing	Perpetuation of Divergence
China Airlines 140		x	x (high)	no data				x		x

Ultimately, this analysis of the accident provided insight regarding the complexity of these types of accidents. Divergence in auto-throttle state was not necessarily the only channel of divergence, and it is possible that other channels could provide more information regarding the breakdowns seen in this accident such as autopilot mode or airspeed. It does not appear that the analysis of only auto-throttle state was sufficient here. An analysis of autopilot mode for example would have uncovered a number of systems understanding problems underlying expectation such as the lack of understanding of when how the Go Around mode could be disconnected.

D6: Accident: Air France Airlines Flight 72

The accident of Air France Flight 72 occurred on September 13, 1993 in Tahiti (Bureau d'Enquêtes et d'Analyses, 1999). In this accident, during the final approach into the airport, the automation transitioned to go around at the end of descent point along the approach. This transition was apparently unexpected by the crew. The crew responded by attempting to disconnect the auto-pilot and when that did not have an effect, the PF elected to manually hold the throttles aft. Upon landing, it appears that his hand slipped off of one of the throttles and it proceeded to advance upon touchdown. This caused spoilers to deploy unevenly and created a lateral force on the aircraft. Ultimately, this resulted in the aircraft departing the runway.

Event E1: Transition of A/T to THR at the End of Descent Point

Time	Impact[93] – 00m 57s
Actual State	THR
Situation	Final approach descent
Event Trigger	Change in Actual State

At the end of descent point on the approach, at approximately 500 feet MSL, the automation transitioned into a go around mode (Bureau d'Enquêtes et d'Analyses, 1999). This transition was apparently triggered because the automation was not disconnected prior to the end of descent point, as the automation assumes that if disconnection hasn't occurred, then a missed approach must be conducted.[94] The feedback to the crew regarding this transition appeared to be salient. Engine thrust advanced, speed increased, and altitude increased essentially de-stabilizing the flight path. Considering there is a delay for engine spooling, the crew for a few seconds would only have the FMA and flight director cues as an indication.

[93] In this accident, impact was considered the time of departure from the runway on landing roll.

[94] It is part of the design of the automatic flight system that if the End of Descent point is reached with the system still active, the automatic flight system concludes that the visual approach has not occurred and, therefore, the missed approach procedure must be applied. (Bureau d'Enquêtes et d'Analyses, 1999).

An observation failure could have occurred if the crew missed the two definitive observables in those few seconds. There was likely an expectation failure considering the crew's confusion later indicated they apparently did not expect the auto-throttle to transition to THR at this point. This combination of observation and expectation failure could have resulted in a brief period of unknown divergence.

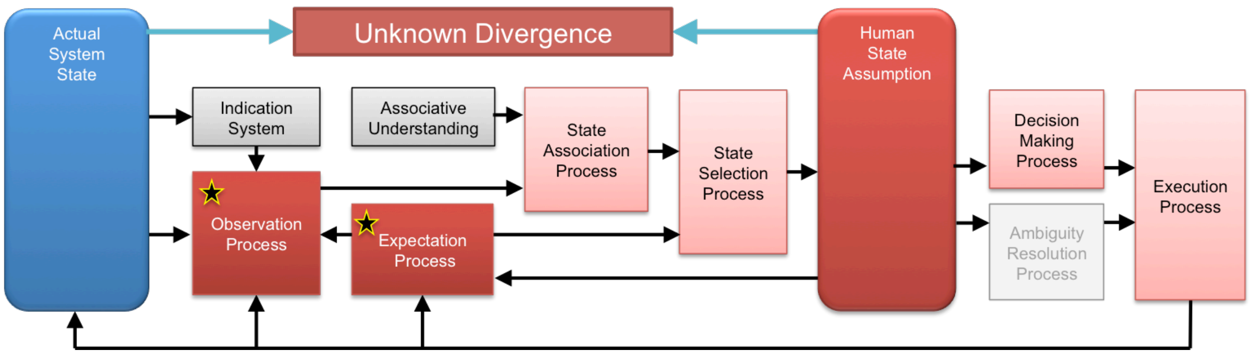

Figure D- 25. Human information processing model for Air France Flight 72: Event E1

<u>Event E2: The PNF calls "Thrust Reference VNAV Speed"</u>

Time	Impact – 00m 54s
Actual State	THR
Situation	Final approach descent
Event Trigger	Change in Observation

At 3 seconds following the automation transition, the PNF calls "Thrust Reference VNAV Speed." This specific verbiage indicates observation of the FMA. Considering this recovery of the observation process and the call out of the state of the actual system. It is possible that the crew transitioned through known divergence to re-convergence during this time, however the PNF stated in interviews following the accident that he "made the call-out (notably, Thrust Reference)… as prescribed by the instructions, but in a mechanical fashion, without analyzing the content of the message" (Bureau d'Enquêtes et d'Analyses, 1999). With this information, the evidence could suggest the lack of full re-convergence at this point in the timeline.

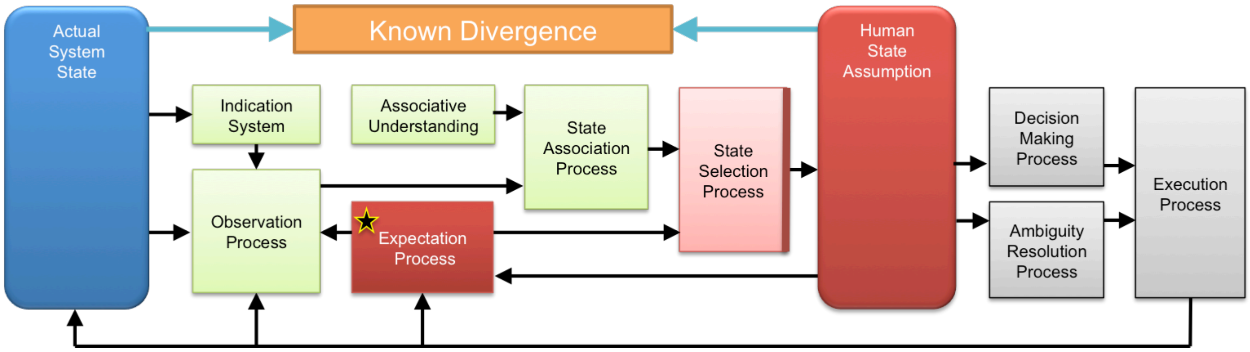

Figure D- 26. Human information processing model for Air France Flight 72: Event E2

<u>Event E3: PF states "OK, Disconnect" –</u>

Time	Impact – 00m 33s
Actual State	THR
Situation	Final approach descent
Event Trigger	Change in Human State Assumption

Just prior to 33 seconds prior to impact, the states his confusion and says "I haven't got (incomprehensible word)". Then the PF added "What's happening? Oh yeah, it's because." At 33 seconds prior to impact, he states "OK, disconnect" without further elaboration (Bureau d'Enquêtes et d'Analyses, 1999).. This conversation could have indicated that the PF attempted to disconnect the auto-pilot (which had been disconnected prior to initiation of the approach) or a command to disconnect the auto-throttle. It was not determined what the PF meant by this statement. The communication between the crew was noted in the report to be an issue. It mentioned the lack of several required call-outs throughout the approach that could have prevented the accident.[95]

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[95] The following are examples stated in the report regarding crew procedure compliance and communication (a) "At 21 h 04 min 17 s, when the PNF called out « Thrust reference VNAV Speed », the PF should have acknowledged and commented on this call-out. He did not. Here, they missed an opportunity to understand what was happening. (b) The PF did not indicate that the throttle controls were tending to move forward, although this is information that is of fundamental importance. All he said was "I dunno what's happening . . . oh yeah, because," which, in reality, amounts to a meaningless message. What is more, this message failed to elicit a response from the captain, if indeed he heard it. (c)

Following this statement the PF apparently retards the throttles manually and maintains them in IDLE position for the remainder of the approach.

During this event, it was clear that while some observables may continue to have been missed, the crew was aware that the engines were advancing thrust. It appears that there could have been an associative understanding failure due to the inability of the crew to associate this behavior with a certain state. It could be that associative understanding was outputting no states that were consistent with the observations if the crew did not include this possibility in their repository for this situation. Since expectation could have been disregarded at this point due to the confusion, it wouldn't have factored into the observation or the state selection process. If these indeed occurred, the failure in associative understanding likely continued the known divergence. In addition the incorrect choice of action could indicate a failure in the ambiguity resolution process as well.

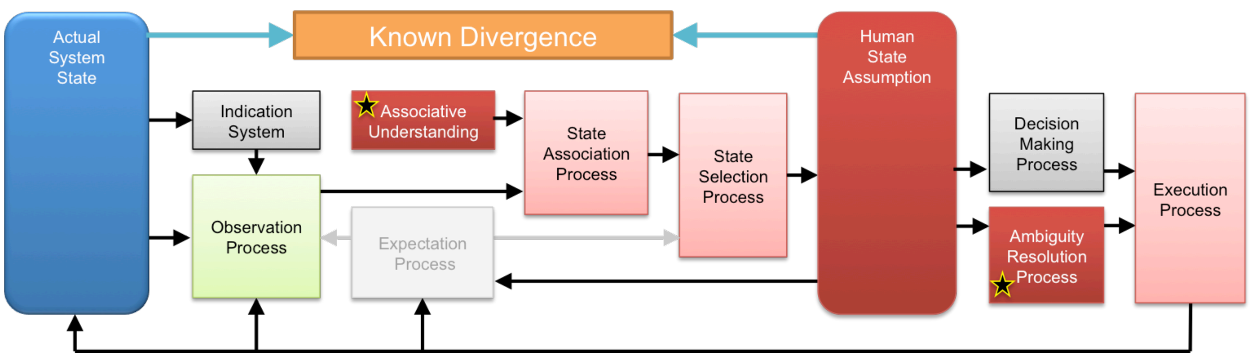

Figure D- 27. Human information processing model for Air France Flight 72: Event E3

Since the throttles were held in IDLE manually, apparently the PF's hand slipped of the Engine number 1 thrust lever when he was repositioning his hands to activate the thrust reversers immediately and the auto-throttle proceeded to advance Engine 1 (Bureau d'Enquêtes et d'Analyses, 1999). This occurred approximately 2 seconds prior to touchdown.

Similarly, the message « OK . . . disconnect . . . » is not explicit. He should have said specifically that it was the autothrottle control that needed to be disconnected (there are numerous such utterances on the CVR in which the copilot does not finish his sentences). Here again, the captain did not respond to the request. (d) Following touchdown, the PNF did not make the required call-outs, and the PF did not comment on this matter." (Bureau d'Enquêtes et d'Analyses, 1999).

Event E4: Following touchdown, auto-throttles automatically disconnect

Time	Impact – 00m 19s
Actual State	OFF
Situation	Final approach descent
Event Trigger	Change in Actual State

The aircraft touched down on the runway 21 seconds before impact, and the auto-throttles disconnected, as designed, 2 seconds following touchdown. This event triggered a change in actual state, however the crew behavior in this case continued to show confusion. The report indicated that the crew did not recognize the high thrust level of Engine No 1 (Bureau d'Enquêtes et d'Analyses, 1999).. The report suggested that both pilots were focused outside and this distraction contributed to the observation failure of the Engine No.1 thrust.

Their verbalization also indicated confusion about why the aircraft was behaving the way it was. It is possible that this scenario was not accounted for in their associative understanding. If that were the case, there would be no states that were consistent with the observations they did perceive of the aircraft which appeared to be the asymmetric moment which they apparently attributed to a lack of thrust reverser deployment.[96] While this was true, the reason the thrust reverser on Engine No. 1 didn't deploy was because it was producing full thrust.

Thus, the failure in observation and association may not have yielded enough information for the crew to determine a state of the auto-throttle if the result of the association process did not produce any possible states.

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[96] At 21 h 04 min 59 s, and 21 h 05 min 11 s, there were several utterances regarding the thrust reversers, ending with "great, one of the reversers isn't kicking in" from the PF. (Bureau d'Enquêtes et d'Analyses, 1999).

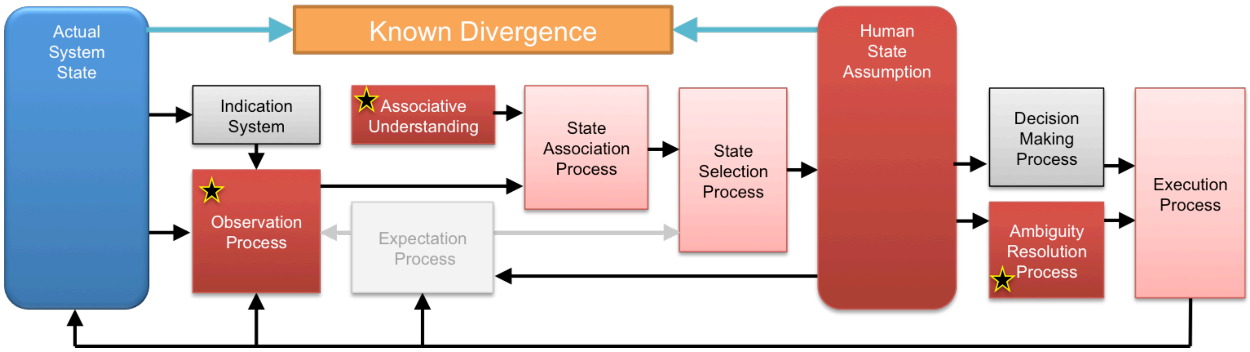

Figure D- 28. Human information processing model for Air France Flight 72: Event E4

The aircraft eventually taxied off the side of the runway and ended in a bank of shallow water. Full re-convergence was not apparent in this case.[97]

Summary

In the Air France 72 accident, there was evidence of observation, association, and expectation process failures. The observation failures included some aspects of distraction of controlling the asymmetric thrust of the aircraft on the ground in addition to possible fatigue. There could have been failures in associative understanding as it appeared that the crew had trouble identifying the state of the system with the cues they observed. Finally, expectation process failures were also apparent. Problems with system understanding was shown by the lack of anticipation of the transition to TOGA at the end of the descent point. In this case, because the crew reached known divergence almost immediately, the perpetuation of divergence through confirmation of expectation was not apparent here. It did not appear that the crew held a clear expectation after the initiating mode transition occurred.

Table D - 6. Summary of information processing failures in Air France 72

Failure / Case	Occurrence of Observation Process Failure					Occurrence of Association Process Failure		Occurrence of Expectation Process Failure		
	Expect-ation Bias	Dist-raction	Work -load	Fatigue	Design Influences	Associative Under-standing	Ambiguity of Observables	Abnormal Transition	System Under-standing	Perpetuation of Divergence
Air France 072		x		x		x		x	x	

[97] No data was available in the report regarding point of unrecoverability for this accident

D7: Accident: Indian Airlines Flight 605

The accident of Indian Airlines Flight 605 occurred on February 14, 1990 in Bangalore, India (Ministry of Civil Aviation, 1990). During the localizer approach into Bangalore, the crew was using the auto-throttle and auto-flight system to maintain control of the speed and flight path. Due to an input of a 700 ft. altitude into the MCP altitude, the autoflight system initiated an descent in the IDLE – Open Descent mode, which did not incorporate speed protection. The crew apparently recognized the IDLE approach and attempted to address it by turning off a flight director. However, both flight directors needed to be turned off in order for the auto-throttle system to take over in SPD mode. The airspeed decayed until Alpha Floor initiated just short of the runway. However, this was not enough time to recover and the aircraft impacted the ground.

Event E1: Initiation of Divergence

Time	Impact – 00m 35s
Actual State	IDLE
Situation	Final Approach Descent
Event Trigger	Change in Actual State
Divergence Type	D-3: Both human state assumption and actual state transition

The apparent initiation of divergence occurred when the PNF tuned in 700 feet into the MCP altitude box. The altitude of 700 feet was well below field elevation. The reason for this action was debated within the investigative community (Ministry of Civil Aviation, 1990).. The report suggested that "the most probable cause for the engagement of idle/open descent mode was that instead of selecting a vertical speed of 700 feet per minute, the PNF had inadvertently selected an altitude of 700 feet (the vertical speed and altitude selection knobs of the Flight Control Unit (FCU) are close to each other). The altitude of 700 feet that got selected in this manner was lower than the aircraft altitude at that time and therefore the aircraft had gone into idle/open descent mode" (Ministry of Civil Aviation, 1990)[98] If this was the cause

[98] The other hypotheses for this action included:(a) "The PNF dialed the wrong (Altitude) knob (thinking that he dialed the Vertical Speed knob) resulting in the selection of a lower altitude. It was probable that he wanted to select go around altitude but the words just told to him by the PF regarding vertical speed, influenced his action and thus he selected the altitude of 700 feet without realizing that he selected the wrong altitude." And (2) The PNF first selected a higher altitude towards missed approach alt. of 6000

of the engagement of the IDLE mode, it would have been the result of a slip, where the PNF apparently activated the wrong knob when intending to set the vertical speed mode. This slip however would have updated the expectation to update to the result of the intended action – which was that the auto-throttle remained in SPD mode however the actual state updated to reflect the actual action and transitioned to IDLE mode.

Considering a descent was expected at this point, the IDLE on the FMA was the only definitive observable available to the crew at this point. Crew behavior indicated that they did not notice this indication immediately. It's possible that an expectation of SPD prevailed and influenced the crew's scan of new information. There was also the possibility that the crew was distracted with configuring the aircraft for a visual approach. While the report suggested that the crew was not affected by fatigue, crew verbalization indicated the possibility that the crew could have been overwhelmed in the situation and was having trouble interacting with the FCU. In this accident, the FMA, while missed during this event, was eventually observed.

Ambiguity in the dynamic variables was also apparent until the speed dropped below Vapp suggesting evidence for an association failure. And as mentioned prior, an expectation of SPD mode could have prevailed when they initiated the descent.

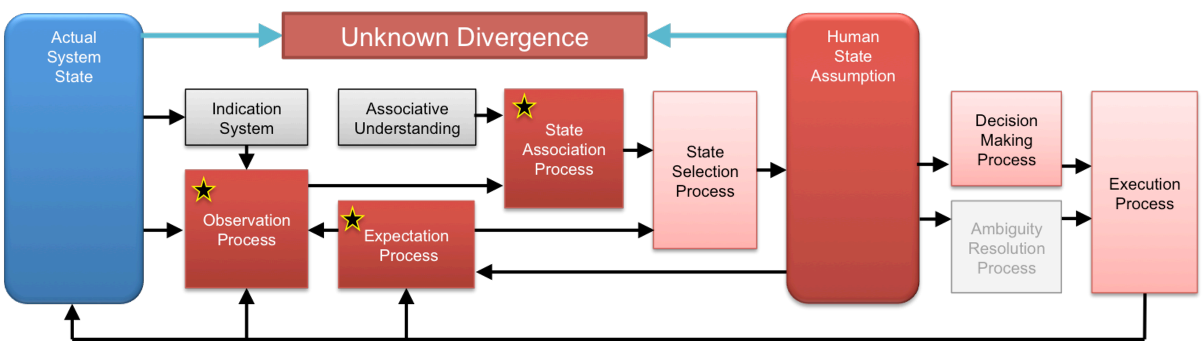

Figure D- 29. Human information processing model for Indian Airlines Flight 605: Event E1

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feet and then realizing that this would activate Open Climb, immediately reversed the alt knob to a lower altitude by a wrist flick which caused the aircraft to go to Idle Open descent" (Ministry of Civil Aviation, 1990).

Event E2. Airspeed drops below Vapp of 132 knots.

Time	Impact – 00m 28s
Actual State	IDLE
Situation	Final Approach Descent
Event Trigger	Change in Observables

Once the airspeed drops below Vapp, more definitive observables become available to the crew. These include the low airspeed, decreasing airspeed trend, and low engine thrust. In this Airbus A320, the thrust levers were non-moving thus the cue of the thrust lever movement was not available to this crew. The behavior of the crew however did not indicate that they observed this new information. Thus it appeared that the observation failure continued. The association failure of ambiguity of observables was likely alleviated by appearance of more definitive observables. However, the crew likely continued to hold a false expectation of SPD mode. Thus, with the observation and expectation failures, unknown divergence appeared to continue.

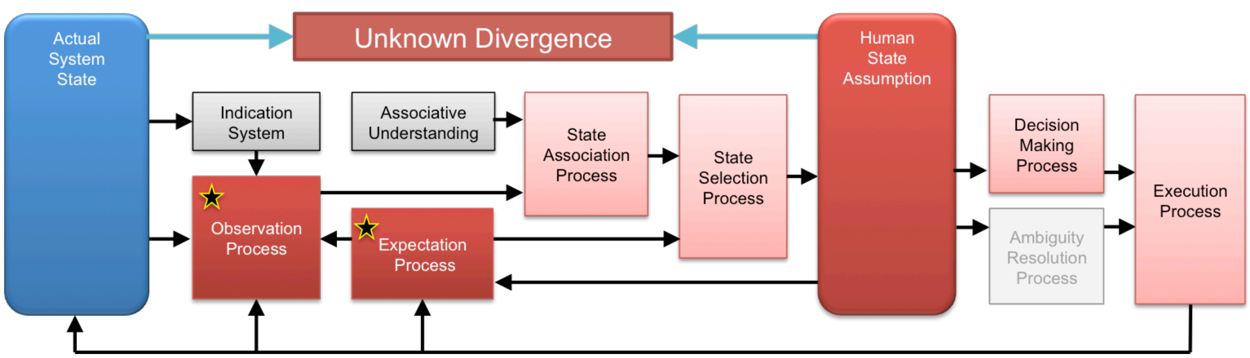

Figure D- 30. Human information processing model for Indian Airlines Flight 605: Event E2

Event E3: PNF notices IDLE

Time	Impact – 00m 24s
Actual State	IDLE
Situation	Final Approach Descent
Event Trigger	Change in Observation

At 24 seconds prior to impact, the PNF commented, “You are descending on idle open descent, ha, all this time” (Ministry of Civil Aviation, 1990). This comment suggests that the crew noticed the IDLE on the FMA and updated their state assumption to reflect that. This re-convergence could have occurred through one event or multiple cycles through the process transitioning first to known divergence and then re-convergence. If the crew entered known divergence first, it suggests that the observation provided cues conflicting with the expectation and the failure was trapped in the state selection process. Likely, in the next cycle through, without an expectation- the crew likely deducted that the auto-throttle was in IDLE mode, reaching re-convergence.

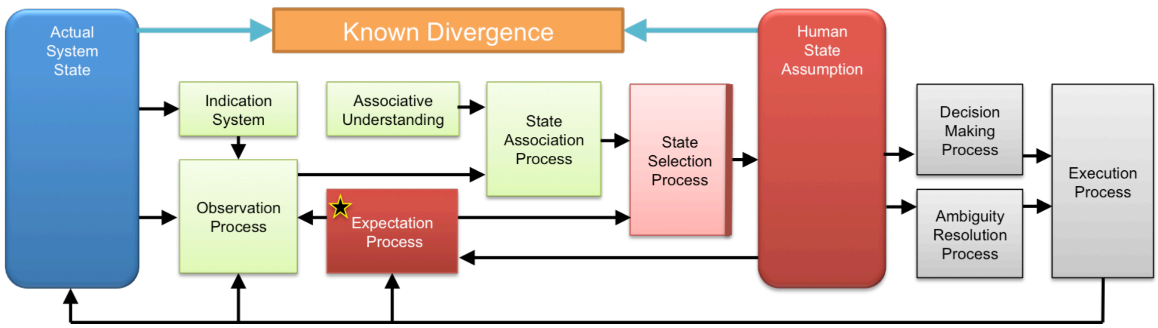

Figure D- 31. Human information processing model for Indian Airlines Flight 605: Event E3 – Known Divergence

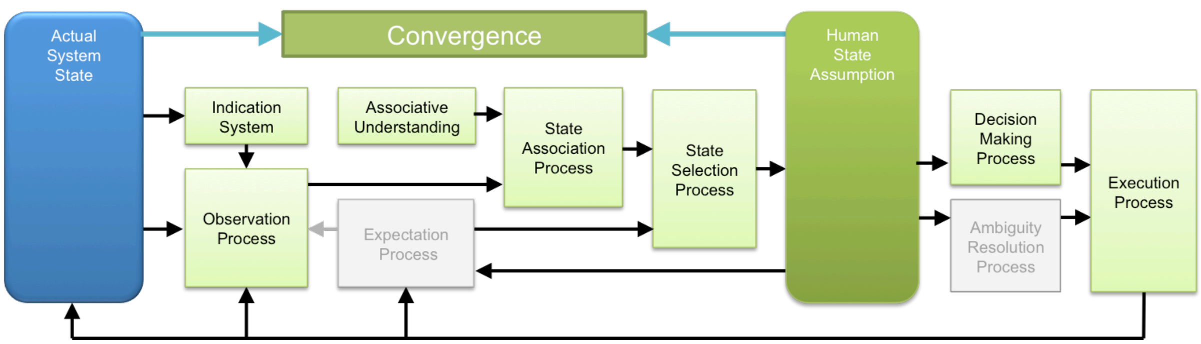

Figure D- 32. Human information processing model for Indian Airlines Flight 605: Event E3 – Re-convergence

Event E4: PF Disconnects his Flight Director

Time	Impact – 00m 23s
Actual State	IDLE
Situation	Final Approach Descent
Event Trigger	Change in Human State Assumption

In response to the throttles being in IDLE, the PF turns off his flight director 23 seconds prior to impact. This action showed some understanding of the system, however also highlights gaps in the pilots' system understanding. In reality, when the auto-pilot is off and BOTH flight directors are off, the autothrottle will transition to speed mode, however by only turning off one flight director the auto-throttle remained in IDLE mode.[99] The PNF appeared to question the PF regarding this 2 seconds later. He states "You want the flight directors off now?" The PF responds, "Yes. OK, I already put it off." PNF comments "But you did not put off mine" (Ministry of Civil Aviation, 1990). No action to was taken by the PNF to turn off his flight director after this conversation.[100]

In addition to the system understanding and expectation failure, it appears that the observables indicating IDLE Open Descent (same as Event E2) were missed due to the lack of response to the low energy state. The combination of the expectation failure and the observation failure apparently result in re-development of the unknown divergence.

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[99] "Turning off BOTH flight directors (with Auto-pilot disengaged) will cause the FMGS vertical and lateral modes to be removed from the Primary Flight Display guidance, the FMA vertical and lateral annunciations to blank out, and the auto-thrust mode will go to Speed Mode using the FMGS target speed (Vapp). Turning off only one of the Flight Directors will cause the flight director steering commands to be removed from that side display, however, since auto-flight guidance is still active (since one pilot still had an active Flight Director), the auto-thrust mode will remain in the current active mode (Idle Descent for Flight 605)." (Ministry of Civil Aviation, 1990).

[100] The Board of Inquiry provided an analysis of what might have occurred (a) "The (right seat pilot) was the PNF, it was his task to have switched off both FDs. Further, in FCOM chapter 3.02.01 page 3 it has been stated that "procedures will be initiated on (PF) command. PNF – Pilot-non-flying is responsible for execution of required action or request for execution by PF, if applicable." …... In this case (the PNF), instead of putting off both FDs merely asked (the PF)." (b) "It appears that even after saying that, (the PNF) still did not put off his own (right side) FD as revealed by the DFDR parameters."(c)"Since the auto-thrust did not change to speed mode, by inference, it is to be concluded that at least one FD remained ON. Since it is known from CVR that PF switched off the FD1, therefore it has to be concluded that FD2 remained on." (Ministry of Civil Aviation, 1990).

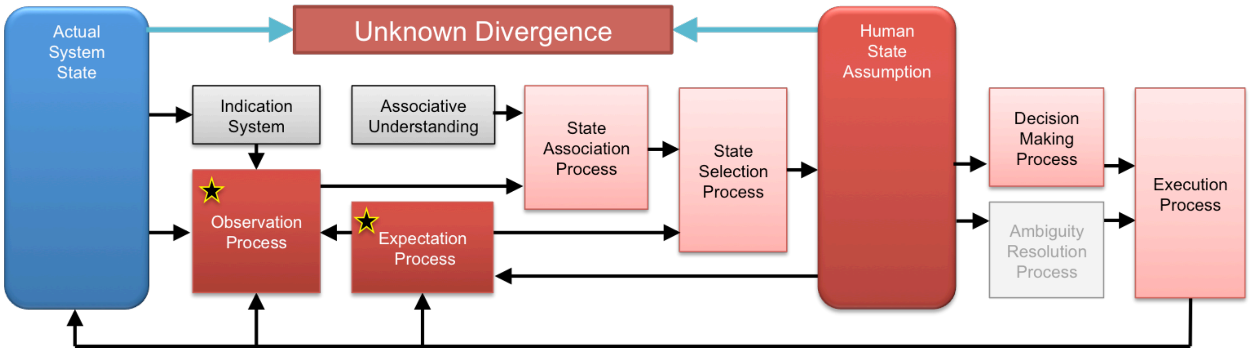

Figure D- 33. Human information processing model for Indian Airlines Flight 605: Event E4

<u>Event E5: Initiation of Alpha Floor</u>

Time	Impact – 00m 08s
Actual State	THR
Situation	Initiation of Alpha Floor
Event Trigger	Change in Actual State

At 8 seconds prior to impact, the speed decayed to the point that Alpha Floor protection was activated. This caused the automation to advance thrust. It is likely that the observables tied to this transition were salient to the crew. These would include increase in engine noise and thrust values in addition to a change in the FMA. If the crew did observe these cues, this would have indicated a recovery of the observation process leaving only the expectation process failure. The discrepancy between these two would have likely caused known divergence. This is supported by the PF comment one second after Alpha Floor initiation, "Hey, we are going down" (Ministry of Civil Aviation, 1990). At this point, the PF advanced throttles forward. This action had no effect due to the activation of Alpha Floor, indicating that while he recognized there was something wrong, he may not have been converged. It is possible that on his next cycle through human information processing, he may have recognized the auto-throttle state, however there is no evidence on this.

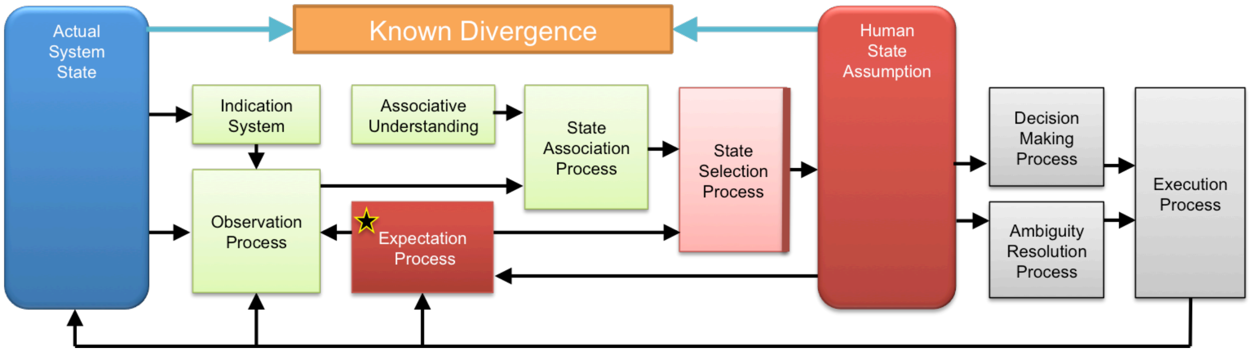

Figure D- 34. Human information processing model for Indian Airlines Flight 605: Event E5 – Known Divergence

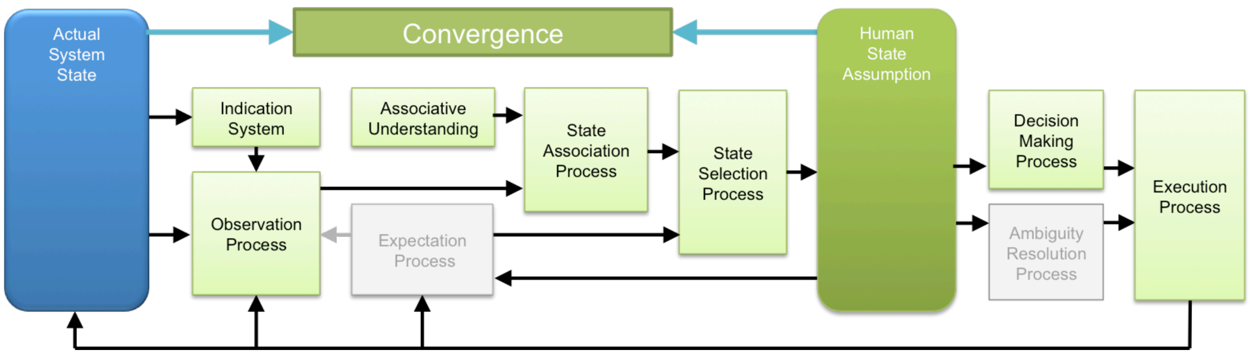

Figure D- 35. Human information processing model for Indian Airlines Flight 605: Event E5 – Re-convergence

Despite these recovery actions, the aircraft impacted the ground short of the runway.[101,102]

<u>Summary</u>

Indian Airlines 605 showed evidence of observation, association, and expectation process failures. It is possible that an incorrect expectation of SPD affected the crew's scan patterns exhibiting expectation bias. It was also possible that the crew was distracted by setting up the automation for their visual

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[101] The report stated that "At that time of 316 or for that matter even up to 320 seconds, if the thrust levers had been moved up to TOGA this aircraft would have survived" (Ministry of Civil Aviation, 1990). Impact occurred at 328 seconds.

[102] It may have been possible that had the crew complied with stabilized approach criteria that they would have aborted the approach prior to it becoming unrecoverable.

approach. For a small period of time, there were likely ambiguous observables due to excess airspeed. Finally, there was evidence of problems with crew understanding of the system, such as the effect of the operation of a single FD on the auto-throttle system. These combined failures likely contributed the case of unknown divergence seen in this accident.

Table D - 7. Summary of information processing failures in Indian Airlines 605

Failure / Case	Occurrence of Observation Process Failure					Occurrence of Association Process Failure		Occurrence of Expectation Process Failure		
	Expect-ation Bias	Dist-raction	Work -load	Fatigue	Design Influences	Associative Under-standing	Ambiguity of Observables	Abnormal Transition	System Under-standing	Perpetuation of Divergence
Indian Air 605	x	x					x	x	x	x

D8: Accident: American Airlines Flight 965

The accident of American Airlines Flight 965 occurred on December 20, 1995 near Cali, Colombia (Aeronautica Civil of the Republic of Columbia, 1995). In this case, on approach into Cali, the crew accepted a runway change that significantly shortened their approach. While reconfiguring the FMS, the crew apparently inadvertently selected the incorrect waypoint into the FMS, which was considered the initiation of divergence. This resulted in the aircraft executing a left turn during the approach descent. About a minute later, the crew showed confusion regarding their location and made a turn back to the right. However, the aircraft had crossed a mountain range during the initial lateral deviation and the turn back to the right, combined with the descent had resulted in the aircraft impacting the mountain range. Using the waypoint set in FMS as the state of interest, divergence apparently occurred when the incorrect waypoint was set in the FMS. Known divergence was indicated by the confusion verbalized by the crew, but there was no evidence of re-convergence in this case.

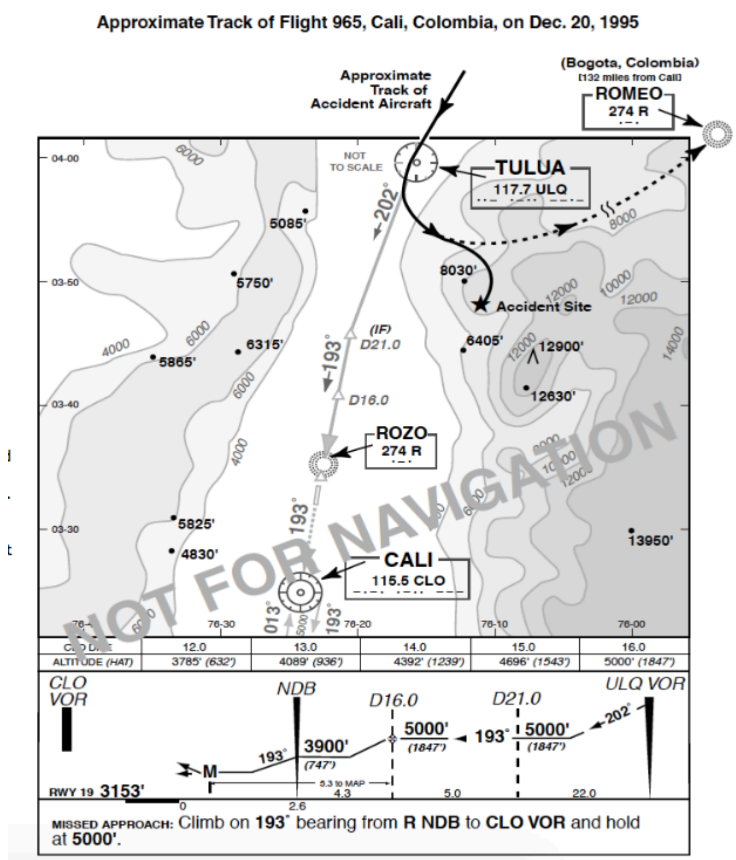

Figure D- 36. Depiction of lateral profile for AA 865 (http://code7700.com/mishap_american_airlines_965.html)

Event E1: Initiation of Divergence – Setting of ROMEO into FMS

Time	Impact – 03m 27s
Actual State	FMS – Waypoint ROMEO
Situation	On approach into Cali, Colombia
Event Trigger	Change in Actual State

In this case, divergence likely occurred when the crew apparently inadvertently set ROMEO into their FMS when intending to set ROZO. In order to recognize the mistake, they would have needed to refer to the EHSI display or conduct considerable calculation. Romeo was located 132 miles east of their position, so the aircraft initiated a left turn following activation of this waypoint (Aeronautica Civil of the Republic of Columbia, 1995). This turn away from the airport and the EHSI display were reportedly the definitive observables at this point in the accident timeline that were available to the crew.[103]

At this point in the accident timeline there was apparently an observation failure since the crew did not take action to return the aircraft to the approach path, nor verbalize the flight off course. This could have been due to expectation bias. Based on their action to enact the waypoint, they likely updated their expectation to ROZO since they intended to set that waypoint, but the actual change in the environment was ROMEO. This expectation failure however, could have influenced the crew to change their scan pattern for new information. When the crew accepted the runway change, the crew workload appeared to increase drastically as indicated by the confusion and discussion in the cockpit as the crew attempted to reconfigure the cockpit for the runway change. This likely contributed to the lack of scan of the waypoint after it was input into the FMS. Also, this change also apparently introduced distraction of both flight

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[103] According to the report, "The evidence indicates that either the captain or the first officer selected and executed a direct course to the identifier "R," in the mistaken belief that R was Rozo as it was identified on the approach chart." In addition, "the first automation-related error by the flight crew, the selection of Romeo instead of Rozo, was a simple one, based on the method used to generate a selection of navaids from the FMS data base, using the single letter identifier. All navaids having that identifier are displayed, in descending order of proximity to the airplane. The one closest to the airplane is presented first, the second is farther from their position and so on. Selecting R resulted in a display of 12 NDBs, each of which used the "R" as an identifier. Choosing the first beacon presented in this list resulted from a logical assumption by the pilot.

crew members as they attempted to use the FMS to determine their position immediately following activation of the waypoint.[104] The report did not make a conclusion of whether fatigue was a factor in the accident, however it did cite problems with procedure compliance and CRM (Aeronautica Civil of the Republic of Columbia, 1995).[105]

When assessing association failures, there was evidence some ambiguity of the observables given that both beacons "had the same radio frequency, 274 kilohertz, and had the same identifier "R" provided in Morse code on that frequency". Thus, if the observation was made, it is possible that this ambiguity would have affected the association process. Also, the crew did not appear to recognize that the left turn toward Bogota was abnormal, if they had observed it. This could have resulted in a problem with associative understanding, which could have been built from their situation awareness of the environment. It appeared that they did not have a clear model of where the waypoints were in relation to their position, thus it's possible that they could have considered the left turn appropriate for a direct to ROZO.

As mentioned in the discussion of observation process failures, the crew likely held an expectation of ROZO based on their action to set it. There was apparently problems with their system understanding illustrated by their use of the FMS and lack of anticipation of the behavior there of. It was argued in the investigative report that, design logic for the FMS could have contributed to this poor understanding.[106]

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[104] According to the report, after they initiated the transition to ROMEO, " both pilots also attempted to determine the airplane's position in relation to ULQ, the initial approach fix Neither flight crew member was able to determine why the navaid was not where they believed it should be, and neither noted nor commented on the continued descent."

[105] The report also stated, "Although the differences between the presentation of the same information could be confusing and the selection of Romeo instead of Rozo can be understood according to the logic of the FMS, the fact remains that one of the pilots of AA965 executed a direct heading to Romeo in violation of AA's policy of requiring flight crew members of FMS-equipped aircraft to verify coordinates and to obtain approval of the other pilot before executing a change of course though the FMS."

[106] "The investigation determined that because of rules governing the structure of the FMS data base, Rozo, despite its prominent display as "R" on the approach chart, was not available for selection as "R" from the FMS, but only by its full name. The evidence indicates that this information was not known by the flight crew of AA965."

In this case, the possible failures in the observation, association, and expectation processes likely resulted in unknown divergence at the initiation of the waypoint transition.

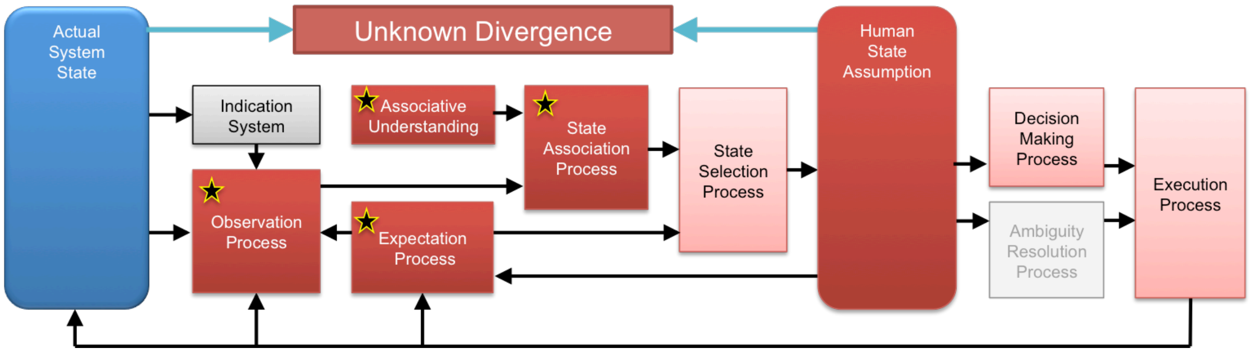

Figure D- 37. Human information processing model for American 965: Event E1

<u>Event E2: Verbalization of Confusion</u>

Time	Impact – 02m 39s
Actual State	FMS – Waypoint ROMEO
Situation	Deviation from approach into Cali, Colombia
Event Trigger	Change in Observation

At 2 minutes 39 seconds prior to impact, the crew apparently recognized the deviation from the approach course which was highlighted by verbalized confusion in the cockpit (Aeronautica Civil of the Republic of Columbia, 1995).[107] This conversation indicated possible scanning of the instruments perhaps addressing the observation failures seen in the previous event. However, the factors of workload, distraction, and expectation bias could still have been a factor at this point. The associative understanding

[107] "The CVR indicates that the flight crew became confused and attempted to determine their position through the FMS. For example, at 2138:49 the first officer asked, "Uh, where are we?" and again 9 seconds later asked, "Where [are] we headed?" The captain responded, "I don't know ... what happened here?" The discussion continued as each attempted to determine the position and path of the airplane relative to the VOR DME 19 approach to Cali. At 2140:40, the captain indicated that he was having difficulty again apparently in locating Tulua VOR through the FMS." (Aeronautica Civil of the Republic of Columbia, 1995).

failure could have alleviated as the crew gained more awareness of their position, while not complete, was sufficient to recognize their deviation.

Thus, if the observation and associative understanding failures alleviated feeding definitive information into the association process, ambiguity could have recovered also. This indicates that only an expectation failure remained at this point. With the observation and association processes feeding contrary information to the state selection process compared to expectation, it's likely this was trapped in state selection.

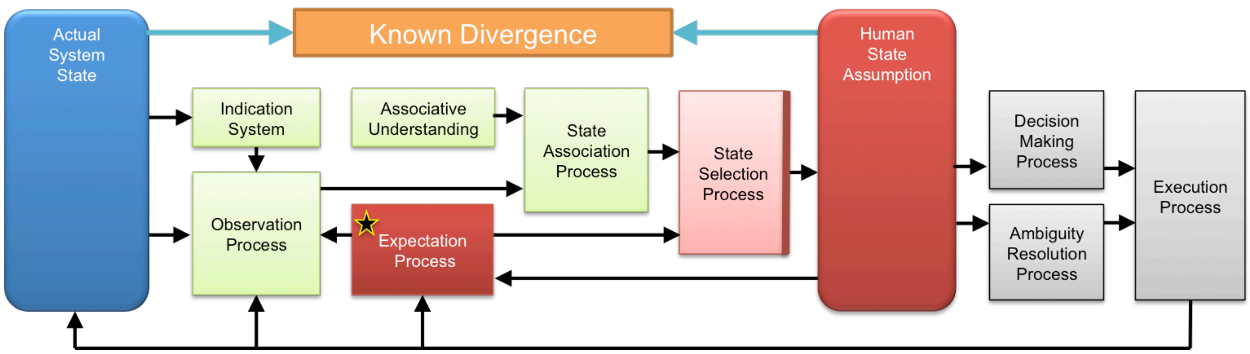

Figure D- 38. Human information processing model for American 965: Event E2

<u>Event E3: Re-convergence: Change of lateral mode to heading select</u>

Time	Impact – 01m 32s
Actual State	Heading Select
Situation	Deviation from approach into Cali, Colombia
Event Trigger	Change in Actual State

In response to the lateral deviation, the crew decided to turn right back towards Cali. In this case the crew apparently transitioned the automation to enact Heading Select mode.[108] In this mode, the lateral target for the autopilot is no longer taken from FMS, but from the heading selected on the MCP. It is possible that the crew, not understanding the behavior of the automation decided to switch the lateral control, effectively contributing to re-convergence in the lateral mode of the auto-pilot.

[108] The crew verbalization included the PM stating, "come to the right, right now, come to the right, right now." The PF responded "yeah, we're, we're in a heading select to the right."

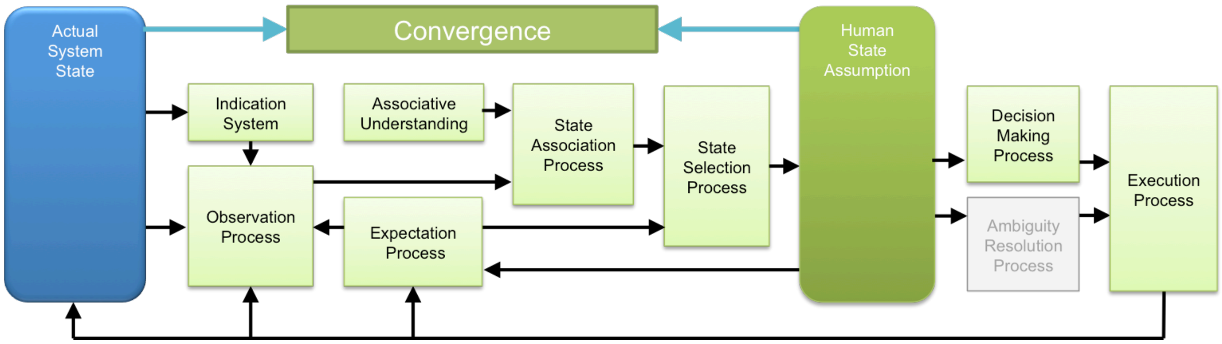

Figure D- 39. Human information processing model for American 965: Event E3

In this case however, re-convergence of the lateral mode of the auto-throttle, was not sufficient to prevent the accident as impact occurred approximately one minute later. This accident was complex and divergence appeared to occur in multiple channels such as vertical and lateral flight path, terrain awareness, in addition to the lateral flight mode of the automation. Thus, it's likely that the continued divergence in vertical flight path or terrain awareness could have remained and further contributed to the accident.[109] Seventeen seconds prior to the accident, the GPWS annunciated and prompted the crew to initiate a recovery to avoid terrain, however this recovery was not successful and ended with the aircraft impacting the mountain (Aeronautica Civil of the Republic of Columbia, 1995)..

Summary

The accident of American Flight 965 showed evidence of observation, association, and expectation process failures. Observation failures could have been attributed to many factors. Expectation of the waypoint selection could have influenced the crew's lack of verification of the waypoint selection. Distraction and workload also appeared to play a large part in terms of the lack of observation. In addition, the report specified that there could have been improved feedback to the crew regarding this error so design also appeared to influence the crew's performance in observation. In addition, there was also the possibility that as the crew's situation awareness of the situation changed, their associative understanding of the situation also updated. A failure in associative understanding could have occurred if the crew had recognized the left turn, but didn't consider it abnormal. In this case, it is possible that their insufficient understanding of where the waypoints were disabled them from associating the observations

[109] No data was available in the report regarding point of unrecoverability for this accident. However it was stated that if the speed brakes had been stowed during recovery that the recovery would have been successful.

properly. In addition, the report also mentioned that the feedback differentiating ROZO from ROMEO was minimal and this ambiguity of observables also could have influenced the association process. Finally, in terms of expectation, there was indication of system understanding failures suggested by the crew confusion and lack of anticipation of automation behavior.

Table D - 8. Summary of information processing failures in American 965

Failure / Case	Occurrence of Observation Process Failure					Occurrence of Association Process Failure		Occurrence of Expectation Process Failure		
	Expect-ation Bias	Dist-raction	Work -load	Fatigue	Design Influences	Associative Under-standing	Ambiguity of Observables	Abnormal Transition	System Under-standing	Perpetuation of Divergence
American 965	x	x	x (high)	No data	x	x	x	x	x	x

In the case of American 965, it was clear that while analyzing the lateral mode target of the auto-pilot for divergence, it was not the only channel of divergence. More comprehensive results could have been achieved if multiple channels were analyzed, such as the vertical flight path awareness for example. This illustrates a limitation in assessing a single state of interest and care should be taken in interpreting these results.

D9: Severity of Cases Analyzed

Since it has been established that some cases of divergence are inconsequential while others can have major consequences, it may be more impactful if mitigations were implemented for transitions that are particularly prone to divergence, specifically cases of divergence that have potentially severe consequences. Mode transitions of concern for the purpose of this thesis are defined as transitions that have high potential for divergence and high potential for serious consequences of divergence.

The cases discussed in the previous chapter provided examples of divergence with various levels of consequences. Figure D- 40 depicts the varying degree of severity of the cases analyzed. On the less severe side are incidents. These could be further differentiated by the minimum altitude achieved during the case. According to this differentiation, American 903 would have been the least severe of all cases analyzed due to the lack of injury and the fact that the minimum altitude reached during the case was at 13,000 feet (Federal Aviation Administration, 2016). The other two incidents occurred on the final approach segment and correspondingly had much less altitude buffer, which could indicate higher severity than if the same divergence had occurred at a higher altitude. Accidents without fatality were considered as more severe than incidents but less severe than fatal accidents. The only case that fell into this category in our analysis was Air France 72 which where the divergence resulted in a runway excursion. Finally, fatal accidents were considered the most severe of the cases analyzed. Depending on the number of fatalities of these accidents, it may be possible to further rate these accidents, however for the purpose of this thesis, all fatal accidents are weighted equally.

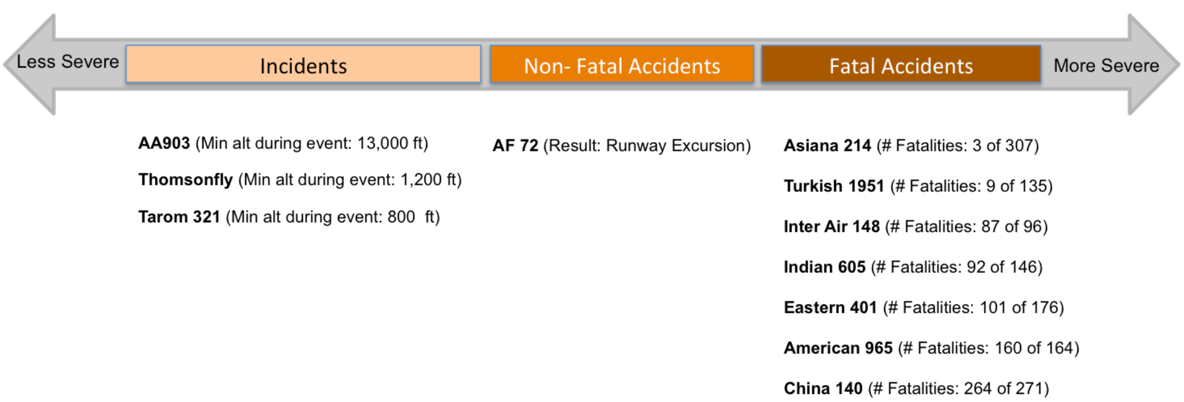

Figure D- 40. Severity of consequences of cases analyzed