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Problem Solving/Decision Making and Procedures for Unexpected Events: A Literature Review

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16. Abstract

The ultimate goal of this report is to provide the Federal Aviation Administration (FAA) with insight into how resilience engineering (RE) concepts can be used to help pilots better manage unexpected events [such as inflight loss of control (LOC-I), inflight upsets, and aerodynamic stalls]. Specifically, the objectives of this literature review are to (1) Identify the types of problem-solving/decision-making skills that could be applied in unexpected events to produce better outcomes; (2) Understand how RE concepts across safety-sensitive domains might apply to aviation, and (3) Suggest a future research path to develop procedures for pilots to use when facing unexpected events [including those with and without checklists and training guidance].

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Executive Summary

Unexpected events such as USAir Flight 1016, Colgan Flight 3407, and Swissair Flight 111 (NTSB, 1995; NTSB, 2010a; TSB, 1998) offer insight to the difficulties crews face in adapting plans and procedures under pressure and uncertainty. When faced with unexpected events, pilots are expected to evaluate the situation (sensemaking) and respond quickly. Unfortunately, these events do not always have guidance in written procedures or may not be experienced during training. Yet, some crews are still able to respond adaptively to unexpected events. The question is - why are some crews better able to respond to unexpected events than others?

One key factor that may distinguish between successful and unsuccessful responses is resilience, which is adaptive capacity in the face of adversity (Dekker & Lundstrom, 2006). We view resilience involving a set of skills or behaviors, rather than inherent characteristics about individuals or teams; resilience may also have a contextual/situational component. In other words, a resilient response is likely a combination of people armed with adaptive skills, plus a situation that is conducive to a successful response.

This concept is best represented by the emerging field called Resilience Engineering (RE), which seeks to promote safety through understanding and promoting resilient skills and behaviors that can be applied in a wide range of unexpected events (Dekker & Pruchnicki, 2013; Hollnagel, Woods, & Leveson, 2006; Woods, 2006a). By relying on the RE field and information from other safety-critical fields, we seek to clarify the skills and behaviors that enable adaptive responses to unexpected events on the flight deck.

Our research here examined several fields where professionals encounter unexpected events and are expected to respond quickly and appropriately. In total, we reviewed around 400 academic texts, journal articles, and books (2000+ pages total).

There have been numerous attempts to capture resilience in action from both within and outside of the aviation domain (Kaufmann, 2013; Saurin, Wachs, Righi, & Henriqson, 2014; Wachs, Saurin, Righi, & Wears, 2015). Perhaps the most widely discussed taxonomy of resilient characteristics is Hollnagel's (2009) four cornerstones of resilience - Anticipating (potential events), Monitoring (critical information), Responding (in unexpected events) and Learning (from past mistakes). Together with aircraft-specific knowledge, this taxonomy represents a basic framework of resilient actions.

The specific resilient skills and behaviors for flight crews are more difficult to pin down but could be observed via archival analyses of incident and accident reports and simulator training scenarios. Prior research has suggested looking at variability in responses (Casner, Geven, & Williams, 2013) or response time (Hoffman & Hancock, 2017) to measure resilience, with the hypothesis that resilient responses are quicker and more appropriate. However, the measurement of resilience is largely left unresolved, as previous attempts are not grounded in a measurement methodology.

This measurement gap presents a pressing challenge for future research to identify and test ways of measuring specific resilient behaviors. Moving forward, we recommend identifying and measuring specific behaviors and skills that contribute to successful responses during unexpected events. Only after doing so will we be able to test interventions designed to promote resilience.

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Acronyms

ATSB	Australian Transport Safety Board
ECAM	Electronic Centralized Aircraft Monitor
FAA	Federal Aviation Administration
ICAO	International Civil Aviation Organization
NTSB	National Transportation Safety Bureau
RE	Resilience Engineering
TSB	Transportation Safety Board of Canada
PARC/CAST	Performance-based Aviation Rulemaking Committee/Commercial Aviation Safety Team
PEGASAS	Partnership to Enhance General Aviation Safety, Accessibility, and Sustainability

Introduction to Unexpected Events

There are many examples of unexpected events in aviation, and oftentimes, the pilot(s) do not respond appropriately to the event and an incident/accident occurs. In one case, the pilot of a Beechcraft 95-B55 was surprised by the presence of a tow plane and glider on an intersecting runway in LaGrange, GA, and he reacted with excessive control inputs. This led to a subsequent aerodynamic stall, loss of control, and ground impact, killing all on board (NTSB, 2015). Unfortunately, both the tow and glider pilots reported that the Beechcraft pilot's actions were not required to prevent the perceived collision. There have been numerous other incidents/accidents due to unexpected events, such as USAir Flight 1016, Colgan Flight 3407, and Swissair Flight 111 (NTSB, 1995; NTSB, 2010a; TSB, 1998). These events offer the industry insight to the difficulties crews face in making trade-offs on adapting plans and procedures under pressure and uncertainty, and how our industry as a whole underprepares crews to face these challenges (Dekker, 2001).

The FAA (2015) defines an unexpected event[1] as any event that takes someone by surprise, which can "violate a pilot's expectations and can affect the mental processes used to respond to the event". When faced with an unexpected event, pilots must evaluate the operational circumstances and correctly respond, irrespective of the nature of the problem (e.g., mechanical malfunction, environmental factors, or security). Unexpected events can involve competing information and signal overload (which increases stress and cognitive workload) and can be ill-defined. Flight crews also experience constraints like time pressure, cognitive limitations, and teamwork/communication demands. Their ability to successfully respond to the unexpected event will decline as the complexity and time pressures increase. As the LaGrange, GA accident example showed, suboptimal responses to unexpected events can have serious consequences.

The concept of what it means to be surprised is important in understanding behaviors that are both observed and unobserved. As part of this psychological construct, other terms such as "sensemaking" and "staying ahead" play a role. For example, sensemaking is the process of continuously fitting data that are observed into a frame, and fitting the frame around the data (Klein, Wiggins, & Dominguez, 2010). This psychological process not only involves perception of one's environment but also matching the current experience to those experiences in both technical and non-technical environments. The commonly used phrase "staying ahead of the aircraft" describes a crew's awareness of the current state of the aircraft, their expectation and ability to respond to future events during flight (Rankin, Woltjer, & Field, 2016). There are cases where operators are pushed beyond their normal capacity to adjust to system demands, and these systems either suddenly fail or fail later after their attempts to deploy countermeasures. Typically, in these cases of failure, these countermeasures are discovered too late (Lanir, 1986; Rochlin, 1999; Woods, 2005; Woods, Johannesen, Cook, & Sarter, 1994).

As systems become more complex and unpredictable with time, new types of aviation

[1] Synonyms include sudden onset events, disturbances, anomalies, off-nominal events, extreme events

failures continue to emerge, and the major incidents or failures that occur in the aviation industry are increasingly due to unexpected events (Hassall, Sanderson, & Cameron, 2013). The aviation industry has made many efforts to mitigate incidents and accidents by providing more guidance (i.e. checklists) and training. For example, guidance helps pilots by providing aircraft states that have been deemed hazardous (off-nominal states during flight), but there is not always clear guidance about how pilots should respond in an unexpected event. Furthermore, when pilots encounter unexpected events, they are forced to assess and generate novel solutions both with and without the help of prescribed procedures (i.e., checklists) and training. The FAA recognizes that it is no longer possible to forecast all the different ways that aircraft mechanical systems might fail (Zuiderwijk, van der Vorm, van der Beek, & Veldhuis, 2016). These types of system failures are frequently unique (with no specific procedure or checklist to follow), and not specifically trained, therefore making it more likely that pilots will encounter what could be described as an unexpected event. Past events have shown that both individual pilots and crews did not always perform equivocally when confronted with these situations (NTSB, 1995; NTSB, 2010a; TSB, 1998). Some crews were unable to adapt to changes in the aircraft state (due to unexpected events), resulting in a loss of life and/or aircraft. However, not all surprising situations on the flight deck result in a total loss of life, such as United Flight 232 and US Airways Flight 1549 (NTSB, 1990; NTSB, 2010b).

For example, USAir 1549 lost power to both engines of an Airbus A320 after colliding with a flock of geese (NTSB, 2010b). Given the loss of power and time pressure, they chose to land the aircraft in the Hudson River, which they calmly communicated to air traffic control before losing connection with them. All 155 passengers and crew members survived the accident. Another example of a "successful disaster" is Apollo 13 (Lovell & Kluger, 1994). In this spaceflight accident, after leaving Earth orbit the spacecraft suffered an explosion that significantly crippled the vehicle. With insufficient oxygen to make it home by their original flightplan, the flight crew, NASA scientists, and associated personnel demonstrated how an entire space agency pulled together to successfully bring the crew home. As a final example, Qantas Flight 32 experienced a catastrophic engine failure and a cascade of system failure messages on the electronic centralized aircraft monitor (ECAM) (ATSB, 2013). The crew was unable to attempt every checklist/procedure before landing, so they established novel procedures to land safely. In all of these cases, the crews were not trained for these types of events, but they adapted and appropriately responded to the unexpected events, which prevented an adverse outcome.

The traditional response to incidents/accidents in aviation (as well as in other fields) for both unsuccessful and successful failures is to "blame and train" (Woods, 2005) but recently, the safety management field has moved toward asking the question: why are some individuals and crews better able to respond to unexpected events than others? This approach to safety is a component of what is known as "Safety-2", which leaves behind the outdated idea (Safety 1) that telling front line workers to "try harder" or "be more careful" will prevent incidents/accidents

(Hassler & Kohler, 2014; Hollnagel, 2017). One of the primary tenets of the Safety-2 approach is that accidents in most domains are so rare and unique that we cannot possibly train for every permutation. The real world is complex and unpredictable. To combat this challenge, we need to understand what makes people and systems better able to meet unique unexpected events by learning from past events. Every incident, whether the crew successfully responded or not, contains valuable information about the ideal response to future unexpected events. Many researchers have argued that one key skill to mitigate the unexpected events is resilience that can help to create robust solutions that can be applied to an unexpected event (even without having formally trained on that specific type of event) (Anders, Woods, Wears, Perry, & Patterson, 2006; Bhamra, Dani, & Burnard, 2011; Dekker & Pruchnicki, 2013; Hollnagel, 2017; Hollnagel et al., 2006).

Resilience as a concept is about enhancing people's adaptive capacity so that they can counter unexpected threats beyond their prepared abilities (Dekker & Lundstrom, 2006). This adaptability is so important that it is a hallmark skill of high-performing teams (Cannon-Bowers, Tannenbaum, Salas, & Volpe, 1995; Salas, Prince, Baker, & Shrestha, 1995). In particular, one study rated crew performance when faced with unexpected events and discovered that crews who engage in adaptive behaviors (e.g., information collection and transfer, task prioritization, and task distribution) had higher performance ratings (Waller, 1999). Additional studies have shown that not only does the demonstration of these behaviors affect outcomes, but perhaps more importantly, the timing of those outcomes (Eisenhardt, 1989; Gersick, 1988; Parks & Cowlin, 1995).

The field of resilience engineering (RE) is an emerging discipline which seeks to promote safety through understanding and promoting resilience of not only individuals but also of teams or organizations (Dekker & Pruchnicki, 2013; Hollnagel et al., 2006; Gao & Dekker, 2017; Sheridan, 2008; Vaughan, 2005; Wachs et al., 2015; Woods, n.d.,b; Woods, 1988; Woods, 2006a; Woods & Branlat, 2011). Because of growing complexity in our socio-technical systems such as aviation, we need resilience engineering to enable our systems to dynamically adapt to changing conditions beyond the normal level of preparedness (Thomas, Scharte, Hiller, & Leismann, 2016). The field of RE goes beyond the typical "blame and train" approach by attempting to understand the complexity inherent in nature and to engineer systems that are resilient in the face of complexity (see Task 2: The Need for Resilience Engineering). In short, the RE field believes that making pilots resilient in the case of unexpected events is essential to increase aviation safety.

The RE field posits that incidents/accidents occur because of disorder in the system via (a) interaction between several agents in the system, which is self-organized in a nonlinear fashion and (b) small fluctuations in safety compliance (Leveson, 2008). Adverse events are not necessarily the result of an initiating event or a root cause that triggers a linear series of events, but rather, adverse events emerge from (normal) interactions among many interdependent system components (Dekker & Pruchnicki, 2013; Leveson, Daouk, Dulac, & Marais, 2003). Analyses of actual accidents in a variety of domains (Pew, Miller, & Feeher, 1981; Reason & Mycielska, 1982; Woods, 1982) found that these adverse events, which can trigger a system-wide failure, emerge from breakdowns in the complex system (Pruchnicki & Dekker, 2017; Reason, 2016; Woods, 2006b). Although interactions in complex systems can yield negative results such as system collapse and an accident, positive aspects can also emerge such as resilience (Bracco, Gianatti, & Pisano, 2008; Day, 2005; Dekker, 2012; Dekker & Pruchnicki, 2013; Hollnagel et al., 2006; Leveson, 2008; Nemeth, Wears, Patel, Rosen, & Cook, 2011; Normandin & Therrien, 2016; Woods & Hollnagel, 2006).

The goal of this literature review is to identify a means to recognize and promote resilience in the face of unexpected events on the flight deck. Despite the proliferation of literature and global interest from numerous domains, both the scientific and operational community still grapple with: (1) how to define resilience within their own operations, (2) the need for the RE approach, (3) specific resilient skills/behaviors (4) how to observe and measure resilience in complex settings, and (5) promoting resilient responses to unexpected events. This literature review will offer potential answers to these five problems for the aviation field, specifically for unexpected events on the flight deck.

Review Methodology

Our research here examined several fields where professionals encounter unexpected events and are expected to respond in a timely and appropriate manner. We conducted an extensive search of the literature base in the fields of resilience engineering, crisis management, air traffic control, nuclear power, healthcare, cyber security, emergency response, complex systems and non-linear dynamical systems, crew resource management, and team training. In total, we reviewed around 400 texts, peer-reviewed journal articles, and several academic thesis or dissertations.

Document selection was accomplished in three steps. We started with numerous texts that represent some of the foundational work in the field of resilience engineering as exemplified in Ashgate’s Resilience Series. A review of these documents yielded numerous citations in other peer reviewed journal articles of interest. Next, the Ohio State search engine (which includes Web of Science, IEEE, PsycINFO, PubMed, and Scopus) and Google Scholar were searched with keywords such as “resilience”, “resilience engineering”, “resilience + aviation”, “resilience + flight operations”. This search yielded over 1.7 million hits for all of these keywords in the different combinations. Third, in consultation with colleague Dr. David Woods from The Ohio State University and two colleagues abroad (i.e., Dr. Sidney Dekker, Erik Van Der Lely) who are on the leading edge of resilience-engineering research, we identified approximately 157 usable sources of information. We drew from these different returns approximately 400 articles, totaling over 2,000 pages.

Although it could be said that resilience engineering is still in its infancy, numerous domains have explored the advantages of this approach to safety over older safety paradigms. The discipline of resilience engineering, including both research and operationalization perspectives, has increased significantly over the last 10 years. Because of the sheer volume of returns from our initial search, we had to establish a stopping rule since the extensive volume of literature returned would be impossible to review fully. With over 2,000 pages of literature reviewed, it appeared that we had in fact captured the major themes of resilience engineering. Our decision to stop was also based on two other factors – 1) the amount of repetition we were encountering; and, 2) our work on other related projects with many global leaders in the field allowed us to view our findings as sufficiently complete for the goals of this study.

Task 1: Resilience Defined

Resilience has always been a critical property of all human (and most other 'live') systems, but its more recent use in the safety literature has brought an old term to a new understanding and usage (Pruchnicki & Dekker, 2017). In one of the earlier uses of the term "resilience", Holling (1973) explained how different viewpoints (resilience and stability) on behavior within an ecological system can result in different strategies for the management of resources. This body of work is where the term resilience started to gain exposure, and other domains applied these ideas to their own operations beyond ecological systems. What it means to be resilient has been discussed extensively in literature. There are many definitions of resilience offered in the literature, and interestingly, even the office of the President of the United States released a definition of Resilience in Presidential Policy Directive 21 – "… the ability to 'prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions" (Office of the Press Secretary, 2013).

The varying definitions and nuances of the term resilience is not our focus here. Instead, we chose to emphasize the commonalities across domains. One common theme across domains is the notion that resilience is related to the capability of an element to return to a stable state after a disruption (Barnett & Pratt, 2000; Callister & Rethwisch, 2007; Dekker, 2012; Hamel & Valikangas, 2003; Hollnagel et al., 2006; Powley, 2009; Sheffi, 2005; Walker et al., 2002). Additional components include the ability to anticipate and adapt to the potential for surprise and failure (Hollnagel et al., 2006).

Systems are continually moving inside their safety envelopes between the various boundaries of safe operation, which is considered normal in resilience engineering (Dekker & Pruchnicki, 2013; Hollnagel, Nemeth, & Dekker, 2008; Nemeth, Hollnagel, & Dekker, 2009). An unexpected or surprising event pushes a system closer to its boundaries of safe operation. If the system does not know how to respond outside those boundaries, the system is brittle and adverse outcomes can result. A system that knows how to operate outside of the safe boundaries is resilient. Resilience in its truest sense is the system's ability to return itself to a stable system when, due to disruptions that are either foreseen or not, it operates outside of its normal capabilities as a whole. Contrast this with robustness, which is the ability of the system to operate within its normal operating boundaries when it is perturbed (Gluck et al., 2012; Hoffman & Hancock, 2017) and adaptiveness, which is a system's ability to create novel solutions to problems within the normal operating boundaries (Bhamra et al., 2011; Dalziell & McManus, 2004; Gallopin, 2006). For more information about boundaries, see Woods (2006b).

There may also be a situational component to resilience, such that a resilient response is likely a combination of people armed with adaptive skills, plus a situation that is conducive to a successful response. Or at the very least, some situations may be more likely to yield a resilient response (i.e., perhaps those that have written guidance or have been experienced by at least one crew member before).

Our working definition of resilience, as guided by experience and the literature base reviewed, is that: resilience is "the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions" (Hollnagel, 2017, p. 14). This level of challenge can be managed with other organizational skills (such as isolation, allocation of additional resources, etc.), or the ability to adjust its response to the challenge when the normal boundary conditions are surpassed. The true nature of resilient capabilities is the extensibility of resources to manage new challenges that create both opportunities and additional responses than originally planned - how people cope with complexity.

We view resilience as involving a set of skills that can help individuals in the system adapt and overcome unexpected events in a wide variety of situations. In particular, we are interested in identifying those skills so that we can train them or develop other interventions for promoting good responses to unexpected events.

Task 2: The Need for Resilience Engineering

Resilience engineering (RE) seeks to measure and enhance an individual's or organization's ability to successfully adapt to change and surprise (Woods, 2006a). More precisely, Woods and Hollnagel (2006, p. 6) offer us *"resilience engineering is a paradigm that focuses on how people cope with complexity under pressure to achieve success."* The relationship between complexity and surprise lies in the paradigm of emergent behaviors of the systems we control. Emergence, a tenet of complexity, describes the interaction of individual system parts such as ATC, aircraft system malfunctions and pilot reactions to challenges in unexpected ways. These interactions are non-linear and can manifest themselves in exaggerated ways (Leveson, 2008). Complex systems produce unexpected conditions and therefore can surprise and even overwhelm those agents involved, such as the pilots. Coping with complexity is an area of research examines adaptability and resilience of macrocognitive systems such as the human-machine work systems that require cognition in order to adapt to complexity (Klein et al., 2003). As explained by Woods and Hollnagel (2006, p. 3), "Success belongs to organizations, groups, and individuals who recognize, adapt to, and adsorb variations, changes, disturbances, disruptions, and surprises—especially disruptions that fall outside of the set of disturbances the system is designed to handle."

To better understand what the resilience engineering approach to safety is and why it is needed, a brief description of its predecessor is necessary. Resilience engineering is in stark contrast to the traditional Safety-1 approach of "looking back" on a failure and then changing the system to prevent future occurrences of that specific failure. The Safety-1 approach is limited in that it seeks to identify risks in hindsight but only makes use of a small portion of the available data (the system's failures) (Hollnagel, 2013). As Leveson (2008) put it, "Simply looking at past events in such systems will be as ineffective at attempting to catch a moving train by going to where it was previously" (p. 7).

In line with the Safety-1 approach, order and structure have been imposed on the aviation system since the inception of the FAA by preventing the types of failures that have already been observed in the past. There have been improvements in mechanical reliability, pilot training, increasingly capable automation devices, procedures, and advanced avionics in ATC centers and flight deck systems. As a result, the domain has seen a decrease in accidents (failures), particularly for the types of accidents that are more common and predictable (Amalberti, 2001; Boeing, 2017). However, accidents still occur, and the stable low accident rate is only populated now by the types of accidents that are exceptionally unique and multifactorial (as discussed in the landmark report by the PARC/CAST (2013) titled *Operational Use of Flight Path Management Systems*). Thus, the Safety-1 approach could not completely eliminate incidents/accidents, nor will it ever be able to—because the order that is imposed on a system will be counteracted by the disorder inherent to all complex systems. How does a system respond to disorder and challenges that are beyond the scope of structured boundaries (e.g., unexpected events)? Because the Safety-1 approach does not analyze why successes occur, it cannot help us prepare to be successful in unexpected events.

One of the primary principles of resilience engineering is that safety management cannot be based exclusively on failure, but should attempt to understand all outcomes (positive and negative) of everyday operations (Woltjer, Pinska-Chauvin, Laursen, & Josefsson, 2015). This Safety-2 approach to incident/accident investigation uses the available data (successes and failures) to determine what makes things go right. Because resilience engineers acknowledge that safety fields are a complex system, they can predict or "look forward" that there will be some successes and some unexpected events which might result in failure (Hollnagel, 2008a)[2].

The field of resilience engineering, just like complexity science, makes it clear that failures and successes are closely related phenomena and not opposites (Dekker & Pruchnicki, 2013; Hollnagel, 2008b; Hollnagel, 2017; Leveson, 2008; Woods, 2006a). In fact, both successes and failures emerge from the same set of preexisting conditions, and it is only the outcome that determines if it is considered, in hindsight, to be a failure or a success. The key to success and to failure is

[2] This approach is not without flaws. See Adler (2013); Amalberti (2013); Bergstrom, van Winsen and Henriqson, 2015; Eidelson, Pilisuk, Soldz (2011); and Wears and Vincent (2013) for critical discussions regarding the wisdom of the resilience engineering approach. Ideas such that the literature seems to imply that a lack of resilience will cause an accident. This direct correlation has not been proven scientifically. Additionally, the authors discuss that the literature is mostly non-peer reviewed thus potentially lacks a degree of rigor.

performance variability. The situations, people, behaviors, constraints, and unexpected events are all sources of variability in the system (Leveson, 2008). From this perspective, safety is the ability to succeed under varying conditions. If both performance outcomes result from the same system operations, how can one come to understand how human performance variability contributes to both? Hollnagel (2008a) offers this guidance:

"Since both failures and successes are the outcome of normal performance variability, safety cannot be achieved by constraining or eliminating that. Instead, it is necessary to study both successes and failures, and to find ways to reinforce the variability that leads to success as well as dampen the variability that leads to adverse outcomes."(Hollnagel, 2008a, pg. xii).

"Resilience is achieved both by damping variability that may lead to adverse events and by reinforcing variability that may have positive outcomes."(Hollnagel, 2008a, pg. xiii)

In order to develop and maintain such a low incident/accident rate, dynamic social-technical operations such as aviation require not only significant regulatory oversight, standardized training, and procedures, but also professionals that are able to recognize when the situation may not fit any prescribed procedures. Thus, another primary tenant of resilience engineering is that humans are adaptive problem solvers and, as such, add resilience to a system that might otherwise be brittle and fail in a challenging environment (Hollnagel, 2013). Planning such as training standard procedure can only take us so far when trying to operate in a dynamic hazardous environment where variability is the norm rather than the exception. We simply cannot prepare people for every single problem permutation, as operational life will contain situations where subtle infinite variations will mismatch the exact circumstances of training (Dekker & Lundstrom, 2006; Dekker & Pruchnicki, 2013).

Consider for a moment that a better way to prepare for these rare events is to ensure pilots have a skill set that can be applied to any unexpected event situation that they may encounter. This is because the focus is not on the specific technical details of the event, but rather a way that pilots can apply skills that can be used to face real-world variability. This approach suggests that the system should be designed to facilitate handling unexpected events that demand a shift of processes, strategies, and coordination (Woods, 2006a). Resilience engineering takes the opportunity to harness the well-established human ability to be adaptive, recognize when situations no longer fit expectations, and to respond accordingly. Crisis management researchers reached the same conclusion in the widely cited (487 citations, last accessed August 7, 2018) paper titled "Preparing for critical infrastructure breakdowns: The limits of crisis management and the need for resilience" (Boin & McConnell, 2007; see also Baer, Heron, Morton & Ratliff, 2005; Flin, 1996; Hermann, Preston, Korany, & Shaw, 2001; Longstaff, 2005; Wildavsky, 1988). In short, to dampen undesired variability in a system, we need to promote resilience.

Task 3: Specific Resilient Behaviors

There have been numerous attempts to capture resilience in action from both within and outside of the aviation domain (Kaufmann, 2013; Saurin et al., 2014; Wachs et al., 2015). For example, Anders et al. (2006) defined and assessed five characteristics of resilience in the trauma area of an Emergency Department: buffering capacity, flexibility, margin, tolerance, and cross-scale interactions, and Mendonca and Wallace (2006) mapped some of these characteristics onto power and telecommunications restoration after the attack on the World Trade Center in September 2001 (see also Woods, 2006a, who initially identified these 5 indicators of resilience). Perhaps the most widely discussed taxonomy of resilient characteristics is Hollnagel's (2009) four cornerstones (shown in Figure 1). These can be observed at both the individual and systems level. A brief description of each one follows.

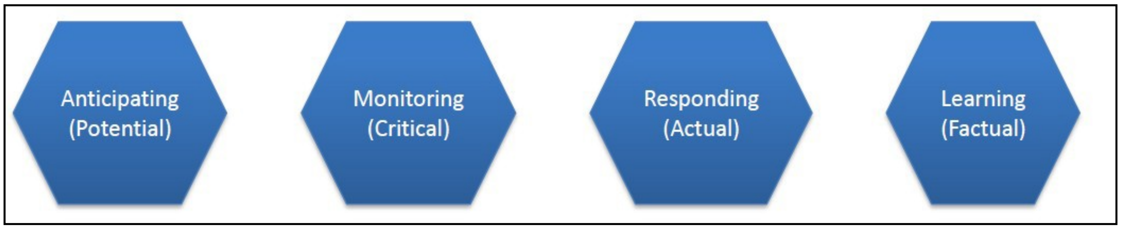

Figure 1. The Four Cornerstones of Resilience (Hollnagel, 2009)

Anticipating

Anticipating is about staying ahead, looking toward the future for possible failures, and sensemaking, or retrospective and prospective processes of data framing, re-framing and anticipatory thinking (Klein et al., 2010; Weick, Sutcliffe, & Obstfeld, 2005). Those that are successful in anticipation while engaged in safety-sensitive tasks can detect signals amongst the constant flow of information that signal a potential hazard, and this early recognition offers a head start on developing a course of action to resolve the emergency before it even happens. However, our expectations and use of heuristics (i.e., mental shortcuts) can create biases and blind spots in our understanding (Fischhoff, 2003; Tversky & Kahneman, 1974). Resilient individuals avoid this trap by frequent re-assessment of the cues provide to them.

Monitoring

Monitoring, or detecting early signs of a problem and taking appropriate actions to prevent further degradation, is a key element in preventing abnormal situations from occurring (Mumaw, Roth, Vicente, & Burns, 2000). The ability to monitor system states can be managed by either a single person, such as in general aviation flying, or with a more team-centered approach like a flight crew. The goal is to recognize, be flexible, and cope with that which could become critical in the near term (Hollnagel, 2009). What makes monitoring difficult is not the need to pick up subtle abnormal indications against a quiescent background, but rather the need to identify and pursue relevant findings against a noisy background (Mumaw et al., 2000). Monitoring is a cognitively challenging task for humans (Cuevas, Fiore, Caidwell, & Strater, 2007; Loukopoulos, Dismukes, & Barshi, 2003). Monitoring is a resilient skill because it helps to increase anticipation (early warning) and facilitate early response, hence improved allocation and use of resources (Lay, Branlat, & Woods, 2015).

Responding

The ability of a system to respond to risks or threats is a fundamental feature of any type of system, resilient or otherwise. In order to respond when something happens to a system, the system must be able to detect, identify the risk, and rate the level of seriousness of the risk (Hollnagel, 2009). What can make responding difficult is that we cannot predict or plan for some risk types.[3] The ability to steer our system's safety when encountering challenges depends on our perception of the cues we are using to determine the nature of the current threat or risk, and how we should best respond to it. Because humans have the capability to circumnavigate rules when required, it can actually lend flexibility and adaptability to the system. In fact, there are some cases where intentionally not following the prescribed procedure is a better option (Dekker, 2001). This was, in fact, one of the findings in the PARC/CAST Operational Use of Flight Path Management Systems (2013) – "*Pilots mitigate safety and operational risks on a frequent basis, and the aviation system is designed to reply on that mitigation*" (p. 2).

Learning

Learning, to be truly meaningful, requires planning in how to best understand what others have experienced and how those operations relate to the current situation. When considering learning as part of the four cornerstones of resilience, it should not be conceptualized as the last step in this process—learning forms the basis for the ability to anticipate, monitor, and respond (Hollnagel, 2009). A resilient system must be able to learn from experience. Learning can also take place on the flight deck when the event is in progress. However, to simply say that one should learn is not enough. To frame this in a meaningful way, Hollnagel (2009) suggested the following considerations when attempting to determine how to best learn and maybe more importantly, what to learn:

1. Which events should be investigated and which should not?
2. How should events be described?
3. When and how should learning take place?
4. What should the locus of learning be, individual or organizational?

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[3] Westrum (2006) made the distinction between various threats based on their frequency and whether it is possible to plan for them. *Regular threats* are described as occurring frequently which necessitates the need to have a planned response developed and readily available resources. These are the aircraft states that already have guidance—they are predictable and plannable. *Irregular threats* could be thought of as "one off" threats, which by are difficult to predict, but are somewhat plannable. And last, *unexampled threats*, which are so unexpected that they push the system's agents far outside their collective experience envelope. This makes prediction and planning all but impossible.

Any organization needs to answer these questions; this is one gap or area for future research.

In summary, the four cornerstones are:

1. **Anticipating –** Knowing what to expect. How to anticipate developments and threats further into the future, such as potential disruptions, pressures, and their consequences. This is about the potential as one moves forward in time.
2. **Monitoring –** Knowing what to look for. How to monitor that which is or could become a threat in the near term. Monitoring must cover both what happens in the environment and in the system itself.
3. **Responding –** Knowing what to do. How to respond to regular and irregular disruptions and disturbances by adjusting normal function.
4. **Learning –** Knowing what has happened. How to learn from the experience, in particular, to learn the right lessons from the right experience.

So far, resilience has been discussed at a theoretical, abstract level, with few attempts to operationally define specific resilience behaviors and skills. Four essential cornerstones of any resilient system were discussed at their most basic level, and this model seems to fit data from many safety domains better than other frameworks like the resilience marker framework developed by Rankin et al. (2016). However, a central preoccupation with the resilience science community is: how do these components show themselves as a specific skill set? This is, of course, an important part of this literature review – what are the identifiable resilience skills or behaviors that are supported in both the scientific literature and but also observable in unexpected event scenarios on the flight deck? What situational factors are there?

Resilient skills or behaviors, as well as situational factors, are still unknown for aviation and this presents a challenge for future research. The skills that emerge from multiple domains might be the most important skills that can apply to any unexpected event situation, including aviation. In other safety domains like healthcare (Carthey, de Leval, & Reason, 2001), emergency response (Kanno & Furuta, 2006), and air traffic control (Malakis & Kontogiannis, 2008), researchers have tried to identify specific resilient behaviors. In one study, flight crews' responses to an unexpected event clearly showed that crews who performed with sufficient leadership, teamwork, open communication, and decision making outperformed crews who did not utilize any of these when faced with surprise and could be considered more resilient (Field, Fucke, Correia Grácio, & Mohrmann, 2016). Other important behaviors include situational awareness, decision-making, and the management of stress, workload, and fatigue. These skills, already trained as part of Crew Resource Management (CRM), may be inherent in resilience of both individuals and teams (Martin, 2019).

As a starting point to identifying resilient aviation skills, we searched for commonalities across different safety domains that have identified resilient behaviors. Almost across the board, the resilience literature examined these concepts for both small teams and those of larger organizations, not specifically individuals. However, many of the concepts discussed are both team and individual concepts, thus they are quite usable for single-pilot capabilities or a crew environment. See Tables 1 and 2 for team-level and organizational-level resilience skills, respectively.

Table 1. Team-Level Resilient Skills and Behaviors

	Before UE	Onset of UE	Actions	After UE
The Four Cornerstones (Hollnagel, 2009)	Anticipating	Monitoring	Responding	Learning
	Ability to - See events that the current frame can't describe - Tracking anomalies - Evaluate surprise and plausibility - Evaluate data quality - Detect inconsistencies - Discover new relationships - Anticipate knowledge gaps - Anticipate resource gaps and needs - Support reflective processes of sense making	**Ability to** - Notice and track anomalies - Evaluate surprise and plausibility - Evaluate data quality - Detect inconsistencies - Discover new relationships - Anticipate knowledge gaps - Anticipate resource gaps and needs - Support reflective processes of sense making	**Ability to** - Shift goals & roles - Have critical resources - Perform critical tasks - Add buffers - Find critical resources including additional agents - Adjust capacity limits by removing stressors - Shed tasks & loads - Monitor agents approaching their limitations - Establish, repair and maintain	**Action to** - Identify which events should be investigated and which should not. - Document and describe the events in detail - Know when and how learning takes place - know what the locus of learning should be

	Before UE	Onset of UE	Actions	After UE
			common ground	
Alliger, Cerasoli, Tannenbaum, & Vessey, (2015)	Minimize	Manage	Manage, Mend	Mend
	Personal factors - A positive attitude - Forgive - Internal sense of control - Cognitive flexibility - Emotional ”toughness” - Realism - The courage to face one's own fears - Physical durability and fitness **Team ability to** - Anticipat e challenges - Plan contingencies - Understand current readiness - Identify early warning signs - Prepare to handle stressors	**Ability to** - Assess challenges quickly and accurately	**Ability to** - Address ”chronic” stressors - Maintain processes under stress - Seek guidance - Regain situation awareness	**Actions to** - Conduct team debrief - Address concerns or risk points - Express appreciation

	Before UE	Onset of UE	Actions	After UE
Normandin & Therrien (2016)	Keystone vulnerabilities Adaptive capacity	Access to resources	Situation awareness	
Jackson, Firtko, & Edenborough, (2007)	**Personal factors** - Building positive professional relationships and networks - Maintaining positivity - Developing emotional insight - Achieving life balance and spirituality - Becoming more reflective			

Table 2. Organizational-Level Resilient Skills and Behaviors

4 Cornerstones	------------
Alliger et al. (2015)	Social support by having ample, active sources of emotional and material support helps
Normandin & Therrien (2016)	• Strategies, Capacity development for resilience • Social, economic, institutional, infrastructure, community resilience • Financial slack, Relational slack, Coping competences • Cognitive capabilities, Organic structure; Attitudes • Trust, leadership, collective efficacy, social capital, social • cohesion, sense of community, community • involvement, existing norms/attitudes/values • communication and information, resource dependency • Organizational competences • Perception of environmental risk
Mallak (1998: p 6–8) version from Kendra and Wachtendorf (2003)	• "Goal-directed solution seeking", encompassing "goals and a vision to guide creative processes in seeking solutions to problems", which is comparable to "bricolage" • "Avoidance", or "approaching new situations with skepticism", which Mallak notes is related to wisdom, but somewhat contrary to the idea of "bricolage" • "Critical understanding" or "effective use of information … to make sense of the situation when chaos ensues" • "Role dependence" or "the ability to fill in for a missing team member", which Mallak associates with Weick's virtual role systems • "Multiple source reliance", which is the use of multiple sources of information to develop a coherent understanding of changing conditions

	• "Resource access", or the use of tools or supplies as needed, even without securing permission each time.
Huber, van Wijgerden, de Witt, & Dekker. (2009)	• Top-level commitment (e.g., Do you think your boss appreciates your work?) • Just culture (e.g., Do you feel comfortable reporting safety issues/problems to your boss?) • Learning culture (e.g., Do you feel the discussion about risk is kept alive in your company?) • Awareness and opacity (e.g., Do you know the major safety concerns the company has to deal with?) • Preparedness (e.g., Do you feel ahead of upcoming problems?) • Flexibility (e.g., Do you have any slack resources available to cope with sudden trouble?)
Grøtan, van der Vorm, & Macchi (2015)	• Defend o Watchfulness o Responsibility (every action counts) o Able to admit mistakes o Open for being corrected o Courage to challenge o Appreciate the work as imagined and work as described distinction • Build o Readiness to respond o Make fewer assumptions o Ignore less o Anticipation o Notice more o Curiosity

	o Awareness • Stretch o Sensemaking o Prepared to be surprised o Look beyond the obvious o Spot emerging patterns early o Hunt risks • Sustain o Improvisation o Mutually Supportive
Wachs et al. (2015)	• Collaborative work • Matching capacity and demand • Communication • Recognize the impact of small actions and decisions • Prioritize actions and decisions • Identify contextual factors that can hinder performance • Anticipation of the need for action • Managing the trade-off between time allocated • Re-plan the sequence of activities • Leadership • Workarounds involving the use of equipment and materials
Dekker & Lundstrom (2006)	• Resilience Indicators o How does the crew handle sacrificing decisions? o Does the crew take past success as a guarantee of future safety? o Is the crew keeping a discussion about risk alive when everything looks safe?

	o Has the crew invested in the possibility of role flexibility and role breakouts? o Does the crew distance themselves from possible vicarious learning through differencing? o Is the crew's problem solving fragmented? o Is the crew open to generating and accepting fresh perspectives on a problem?
Martin (2019)	• Monitor and report changes in systems' states • Acknowledge entries and changes to systems • Collect information about environment (position, weather, traffic) to identify problems • Share key information about environment with crew • Contact outside resources when needed • Discuss options, contingency strategies, and time constraints with crew • Identify possible future problems • State alternative options • Consider and share estimated risk of alternative options • Confirm and state selected option/agreed action • Check outcome against plan • Communicate • Use the tactic Aviate-Navigate-Communicate as a prioritization tool for how to respond to unexpected events • Make lifestyle changes to remediate the effects of stress • Manage fatigue through preduty rest, in-flight naps, and the appropriate use of caffeine

Yet another, but similar framework for structuring and capturing how resilience can best be understood, observed, and trained for comes from the Training for Operational Resilience Capabilities (TORC) now being used in numerous domains in Europe (Grøtan, van der Vorm, & Macchi, 2015). This work is designed to allow operators to examine their organizations so that their current resilient capabilities are better understood. As an extension of the four cornerstones of resilience (anticipate, monitor, respond and learn), they describe these concepts as 1) defend normalcy (preferred mode of operation), 2) build robustness to anticipated disturbance, 3) stretch and rebound in an (isolated) surprising situation/episode and 4) sustain resilient functioning over time (Grøtan et al., 2015). This work deserves serious merit in the effort to operationalize resilient concepts. The real advantage of this effort is evident in the descriptors of resilience as seen above in Table 2.

Other commendable work on identifying resilient skills and behaviors has been conducted by Wachs et al. (2015) for emergency medicine (Table 2), Dekker and Lundstrom (2006) for flight crews (Table 2), and Malakis and Kontogiannis (2008) for air traffic controllers (Table 2). Not all of these attempts to capture resilient behaviors and skills are mutually exclusive. Rather, they probably all play a role to some extent in our understanding of tools and techniques that pilots can use as leverage to better position themselves prior to experiencing an unexpected event. Furthermore, many of these also appear to be compatible with actions that can help pilots during these unexpected events in real time. Suggested work moving forward would be to consider bringing some or all of these actions and how they can be detected together while examining incidents or accident accounts and while observing simulator training. Finding commonalities across situations with successful versus unsuccessful responses to the unexpected event would also give us information about the situational factors that may be contributing to the ability to respond in a resilient way. Once complete, this will provide a solid foundation for the development of tools and strategies that can be incorporated into pilot training programs and tested empirically for effectiveness.

Task 4: Measuring Resilience in Complex Settings

To measure something in a scientific way, it is necessary to identify the behaviors of interest and then operationally define them within the specific operational context. This allows the behaviors to be observed, documented, and analyzed for general trends and conclusions (perhaps comparing across groups or some other variable, if relevant). The approach to measuring resilience should be no different. After identifying specific resilient behaviors and skills, we can observe them in archival analyses of incident/accident reports or in simulator training scenarios. The main hypothesis is that individuals and systems that are more resilient (i.e., display more resilient skills and behaviors) will be more likely to have a successful response to an unexpected event than those individuals and systems low in resilience. For example, Field and Lemmers (2014) discerned those behaviors that allowed crews to seem more resilient than others based on their performance when managing several different types of surprise events. This research showed that there is great variation in how the crews understand, prioritize, manage uncertainties and take action following the unexpected events introduced in the scenarios (Field & Lemmers, 2014). Casner et al. (2013) also found that pilots showed little variability when responding to events that they were expecting during training; however, when abnormal events were presented unexpectedly, pilots' responses were less appropriate and showed greater variability.

The field of RE seeks to measure resilience at a systems-wide rather than individual agent perspective. One must be mindful of what is defined as the “system”. That is, we decide how big the system will be when understanding resilient behaviors. For example, we can define the system in question to be just the interactions of the flight crews, or the entire national airspace system--two completely different systems in both size and complexity. To better understand these emergent processes when examining systems, one should ensure that the scope is large enough to capture those components of the system that interact. However, this still a very challenging task as explained by Woods (n.d., b) – “*Developing measures of the quality of macrocognitive work remains an outstanding challenge.*” Complex systems that are undergoing interactions and displaying emergent properties (i.e., large-scale reactions to small-scale changes) are dynamic and rich with context, which is just one of many factors that complicate this effort. Other obstructions to successful measurement are that not all parts of the system will contribute equally to the interactions, and resilience could look different across different contexts.

The measurement of resilience is left largely unresolved, as previous attempts are conceivably ungrounded in a measurement methodology. However, Hoffman and Hancock (2017) have suggested using time as a universal scale with which to measure successful resilient response to system challenges. For example, they have considered the following parameters for measurement:

1. How long it took the work system to recognize and characterize anomalies
2. How long it took to specify new goals
3. How long it took to identify and muster new resources

This measurement gap presents a pressing challenge for future research to identify and test ways of measuring specific resilient behaviors. Only after doing so will we be able to test interventions designed to promote resilience.

Task 5: Promoting Resilience

The literature regarding promotion of resilience is sparse. However, we believe that one of the most effective methods for promoting resilience is to train pilots to handle off-nominal events in simulators or other realistic settings. Casner et al. (2013) articulated some issues with current pilot training methods. Their work suggests that when entering training, pilots expect to encounter some off-nominal events. However, in real life situations, the off-nominal events will be unexpected and thus pilots can have more difficulty responding in real life situations. Indeed, they exposed pilots to off-nominal events in the circumstances that are familiar for training as well as in less-familiar circumstances. The pilots responded appropriately and with little variability in the familiar circumstances; their performance was much worse and variable in the unfamiliar circumstances. These results suggest that pilots should be trained to respond to off-nominal events in less familiar or unexpected ways so that they are able to face real life adversity. For example, in one study by Landman et al. (2018), pilots in one group practiced events in unpredictable and variable ways whereas a control group practiced the same maneuvers in a predictable and invariable manner. After the practice sessions, pilots in both groups were given a surprise scenario where they had to apply the knowledge learned from practice. The results showed superior performance and understanding of the surprise event in the group that practiced in an unpredictable manner as compared to the control group.

Casner et al. (2013) added that the nature of the training curriculum tended to result in pilots memorizing appropriate responses to situations that they expected to occur during simulated flight. This training concept is echoed in the 2013 ICAO document titled: *Manual of evidence-based training*. As such, it is proposed that rather than placing a strong focus on only technical performance, it would be better to offer crews training that is more generic in design. Other researchers concur; for example, Rankin et al. (2016) proposed – *"Findings in this study suggest the need for training programmes and pilot examiners to support pilots to identify the connection between system parts and identification of critical cues, rather than the specific procedures for specific incidents that have occurred recently" (p. 638).* That is, pilots need training that offers a skill set of useful strategies to use when faced with those events for which there is little to no guidance provided (e.g., how to be more adaptable when presented with conflicting information). Then as part of this training, offer scenarios via simulation that allow the crew to practice being resilient. Martin (2019) also advocates for training using unexpected scenarios to boost resilience. Casner et al. (2013) offered the following suggestions to help prevent this rote memorization during simulator training and the ability to practice for surprise events while flying the line:

1. "Change it up" – To abandon the idea of practicing and testing abnormal events in the same way every time. Offer many different types of surprise events.
2. "Train for Surprise" – Skills and experience are known to reduce a surprised reaction (Merk, 2010). In addition, at least one researcher has argued that the skills to manage surprise events are a specific competence area that deserves more research to see if it is teachable (Hilscher, Breiter, & Kochan, 2005).
3. "Turn off automation" – Although automation provides assistance in recognition to a surprise event, we should train so that the pilot is taught to recognize without any help from automation (Wiener, 1985).
4. "Reevaluate testing practices" – Move away from teaching to the test or dumbing down the grading of required skills (Herman, 1992)

These ideas offer some insight into training ideas that might better position pilots for a more meaningful simulator training experience and improved performance when facing unexpected events while flying theline[4]. In a similar fashion, Field and Lemmers (2014) provided the

[4] We thank an anonymous reviewer for pointing out that simulator time can be limited and widely spaced in time. There may be benefits to frequent discussion of off-nominal scenarios without the use of simulator (see de Jong, 2004 for a demonstration of this approach). As noted by Salas and colleagues (Salas, Bowers, & Rhodenizer, 1998; Salas & Burke, 2002; Salas, Wilson, Burke, & Priest, 2005), any method of training that maintains psychological

following recommendations to help crews function in a more resilient manner. Ideally, these will be considered in not only the training community, but also pilot groups that can consider their own actions and skill set when faced with surprise.

- “Improve crew abilities to carry out workload and information management and the processes of problem solving and decision making, by prioritizing information and identifying task relevant issues.”
- “Improve social awareness in pilots while at the same time building consciousness about focusing on the task at hand if necessary.”
- “Improve the efficiency of crew communication and cognitive offloading strategies within a socio-technical system.”
- “Put a greater focus on the role of the PM - i.e., how the pilot monitoring should be actively engaged in challenging situations.”
- “Improve leadership and teamwork by concentrating on when to use initiative and give directions, when to communicate relevant concerns and intentions, and when to tune into others for developing empathic accuracy; and put a focus on communication strategy (what, when, how) and on the application of non-verbal communication.”

These recommendations provide unique insight into how crews successfully manage surprise events and serve as a perfect complement to the discussed previous research by Wachs et al. (2015), Dekker and Lundstrom (2006), and Grøtan et al. (2015). This research generated procedural steps (listed below) that offer crews a framework to operate within as they face unexpected events (Field & Lemmers, 2014).

1. Manage time criticality, which includes:
    a. Stabilize the flight path
    b. Immediate threats
    c. Short term plan
2. Manage uncertainty which includes:
    a. Identify the situation
3. Plan for contingencies which includes:
    a. Perform appropriate actions
    b. Long term plan

However, maybe a more interesting question is: how do we as an industry or as

fidelity (even if it is low in physical fidelity) should be effective and may in fact be more efficient than training methods high in physical fidelity.

crewmembers, single or multiple pilot flight operations, handle those in-flight events that are beyond the scope of typical training programs? Here, we are referring to those events that could be categorized as unknown-unknowns. These events or situations are those that we were not able to imagine a priori to them becoming a reality. These are the types of events that as an industry we are unable to adequately prepare for with sharpened manual flying abilities or more time in the classroom. These are the events that no one ever conceived as possible, which bypasses typical training and other more informal pilot discussions. As such, preventing these types of events may not be possible with the traditional training methods and subjects utilized in the past.

Other limitations to training are that there will always be a gap between the real, dynamic, ambiguous (normal) world and what the procedures describe (Van der Lely, 2009). The number of situational possibilities that individual pilots or crews may encounter on any given flight is staggering. Any attempt to fully develop a sufficient knowledge base in both scope and depth in complex, dynamic systems such as commercial aviation are inherently imperfect (Rochlin, 1999). These limitations to training will need to be overcome in future research if we are truly going to be successful at promoting resilience.

Pilots can potentially face unexpected events on some scale during day-to-day operations. Many of these events do not have well-defined checklists or troubleshooting guidance. This research seeks to: (1) to identify the types of problem-solving/decision-making skills that could be applied in unexpected events—skills that could potentially result in better outcomes; and, (2) develop additional procedures for pilots to use in dealing with unexpected events including those beyond loss of control as based on the outcomes of this research. As part of the larger research goal, we carried out this review to identify problem-solving skills that have been successful across numerous safety-sensitive industries including aviation. These skills, steeped in the discipline of resilience engineering, have potential to aid flight crewmembers in perception and decision making during unexpected events.

The specialty of resilience engineering has seen amazing global growth in the research, operationalization, and measurement of resilience across these operations. To better understand the term *resilience,* we provided definitions from several researchers spanning multiple fields of study ranging from the environmental sciences to the process industry. We built on the discussions of different definitions to compare resilience to robustness. Next, to find commonality across industries, we reviewed resilience-engineering concepts in the context of safety-sensitive domains and the behaviors that support a successful resilience perspective. To support the discovered behaviors utilized across various practices, we briefly described the four cornerstones of resilience engineering— anticipating, monitoring, responding, and learning. Finally, we discussed research that focused on indicators of resilience within and outside the aviation domain.

Future Research

One goal of this research is to bring some or all of these actions and how they can be detected together while examining incident/accident accounts and while observing simulator training. Once completed, this provided a solid foundation for the development of tools and strategies that can be incorporated into pilot training programs and tested empirically for effectiveness. However, how we measure these tools and strategies remains a significant challenge. The goal is to identify and test ways of measuring specific resilient behaviors. Only after doing so will we be able to test interventions designed to promote resilience.

Moving forward, we recommend researching further the behaviors captured in this study in relation to action, and decision making in both successful and unsuccessful aircraft events. If a disparity between these outcomes is uncovered, one could hypothesize that these specific resilience behaviors are significantly beneficial when managing unexpected and surprise events. From here, it may then be possible to train pilots in resilience skills and behaviors to help further lower the incident/accident rate by improving these outcomes.

In closing, the value of a resilience-engineering perspective is just beginning to be understood globally across various safety-sensitive industries. We believe that there exists an opportunity to lower the global aviation incident/accident rate with the application of this new safety paradigm for managing risk, complexity and adaptation.

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