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Effects of Acute Stress on Aircrew Performance: Literature Review and Analysis of Operational Aspects

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Effects of Acute Stress on Aircrew Performance: Literature Review and Analysis of Operational Aspects

R. Key Dismukes[1], Timothy E. Goldsmith[2], and Janeen A. Kochan[3]

Situational stress can adversely affect the cognition and skilled performance of pilots, as well as experts in other domains. Emergencies and other threatening situations require pilots to execute infrequently practiced procedures correctly and to use their skills and judgment to select an appropriate course of action, often under high workload, time pressure, and ambiguous indications, all of which can be stressful. Our current study, consisted of three parts, starting with a critical review of the research literature on the effects of stress on skilled performance, going back to World War II and continuing to recent and more sophisticated studies of the cognitive effects of anxiety. In the second part we analyzed the specific ways stress may have impaired the performance of airline crews in twelve major accidents, selected for diversity of the situations the crews encountered. The third part examined the operational significance and practical implications of the findings from the first two parts, suggested specific ways to reduce the harmful effects of stress on flight crews, and identified aspects requiring further research. Even though this study focused on flight crews, the findings apply to the effects of stress on the skilled performance of experts in almost any domain.

In September 2014 we completed the last of a series of three reports on the effects of stress on pilot performance, which were sponsored by the FAA Division of Human Factors[4]. These reports examined the effects of acute situational threats, rather than chronic life stress, on pilot cognition and behavior. (For a review of the effects of chronic life stress, see Young, 2008.) Emergencies and other threatening situations require pilots to execute infrequently practiced procedures correctly and to use their skills and judgment to select an appropriate course of action, often under high workload, time pressure, and ambiguous indications.

The performance of even the most skilled experts can be impaired by situational stress. The research literature on the effects of stress goes back to World War II. Our first report reviewed the existing research literature, and the second reported our own study of the specific ways stress may have impaired the performance of airline crews in twelve major accidents. The third report examined the operational significance and practical implications of the first two reports, suggested specific ways to reduce the harmful effects of stress on flight crews, and identified aspects requiring further research.

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These three reports are collected in this NASA TM to provide ready access to both the human factors community and the aviation operational community. This overview summarizes our principle findings and highlights critical issues.[5] One might note that although we focus on flight crew performance, the issues and findings we report apply equally to the skilled performance of almost all experts, from surgical teams to firefighters.

1. What is Stress?

In everyday parlance the word stress is used in loose and varied ways to refer to almost any difficult situation humans encounter. Sometimes stress refers to a cause (the difficult situation) and other times to an effect (physiological and/or psychological responses). In this paper, we use the word *stress* to refer to effects and the term *stressful situations* to refer to causes.

The physiological literature provides a well-defined picture of two neural/hormonal systems that respond to threat with characteristic changes that prepare the body for 'fight or flight,' e.g., increased heart rate and hard breathing. The psychological literature, which is the focus of our study, is more murky. Diverse manipulations have been used in laboratory studies to induce 'stress,' for example, high workload, noise, temperature extremes, electric shock, and social threat. It is not clear that all of these manipulations work through the same psychological mechanisms, and processes other than stress may also be involved.

In most laboratory studies the effects of these manipulations were assessed with simple performance measures and the skilled performance of experts was not examined. Some more naturalistic studies have examined skilled performance but under less controlled conditions. Few studies have examined the skilled performance of expert pilots under well-controlled conditions. Consequently, caution is required in considering the implications of the research literature for skilled performance. Our reports focus on cognitive effects for which the research evidence seems strongest, and we tentatively connect this literature with what we know of the cognitive processes underlying the skilled performance of pilots, especially in threatening situations.

For the purposes of this study we used a focused and explicit concept of stress based on what is known as the *cognitive appraisal model,* for which there is considerable research support (Lazarus and Folkman, 1984). This model proposes that when individuals encounter challenging situations they orient both their cognitive and physiological resources to deal with the situation. Physiological responses, such as increased heart rate and force, faster breathing, and restriction of peripheral blood flow, prepare the body for 'fight or flight.' Cognitively, the individual focuses attention to the challenging situation, mentally preparing for whatever tasks may be required. Up to this point, the individual's resources are mobilized to deal with the challenge, but we choose not to call this stressful because the individual can manage the situation effectively and performance may actually improve. However, if the situation becomes threatening—physically or socially—and the individual is uncertain of his or her ability to manage the threat, anxiety arises. This anxiety is maladaptive, because it disrupts the individual's ability to manage the threatening situation, particularly by degrading attention and working memory, both of which are crucial for managing challenging situations effectively (Eysenck, Derakshan, Santos, and Calvo, 2007).

[5] Extensive literature citations are provided in our first report and, with a few exceptions, are not repeated in this overview.

2. Flightcrew Errors in Airline Accidents

In our second report (Appendix B) we identified 212 errors in 12 airline accidents chosen to represent a wide cross-section of aircraft types and situations. Readers should note that our study design did not allow us to differentiate effects of stress from high workload, time pressure, uncertainty, and unpracticed aspects of the accident situation. But to a large degree that does not matter for the purposes of this study. Flight crews experience some combination of all these factors in emergencies, and our goal is to find ways to reduce vulnerability to error in these highly difficult situations. We do not argue that stress necessarily directly caused the accident pilots' errors, but that the stressful conditions made these errors more likely to occur.

In the following sections we summarize findings from our review of the literature on the cognitive effects of stress and from our own study of accidents.

3. Attention and Working Memory

We all have an intuitive understanding of what attention is: the focus of one's mind on one task or thought or stream of sensory input from a myriad of other possibilities. Basically, we can only fully attend to one stream of information at a given moment. If we must deal with multiple tasks, we are forced to switch attention back and forth among them, somewhat like a spotlight.

Working memory is a very small subset of the vast store of an individual's long-term memory, momentarily activated so that it can be quickly accessed and manipulated. A classic example is looking up a telephone number and holding it in mind long enough to dial the number. Working memory consists of two components: the information stored and the control processes used to manipulate the information. For example, adding several numbers in one's head requires both storing information temporarily and manipulating that information. These control processes, known as *executive processes*, are also involved in directing attention.

The substantial literature on the effects of anxiety on attention and working memory is consistent with the *attention control theory* of Eysenck, Derakshan, Santos, and Calvo (2007). Attention is known to be controlled by two different brain systems: a top-down system that directs attention to support the individual's currently active goals, and a bottom-up system that draws attention to environmental stimuli, especially stimuli that are salient, abrupt, or threatening. Attention control theory posits that anxiety disrupts the balance between the two attentional systems, giving the bottom-up system more weight. Consequently, attention is less under the control of task goals, and is more easily pulled away by salient or threatening stimuli. Thus, the individual is more easily distracted from task goals. However, if the threatening stimuli are central to the task's goals, focus might actually be improved.

Individuals under stress are less able to manage their attention effectively. They are more likely to be distracted from a crucial task by highly salient stimuli, such as an alarm, or by threatening aspects of a situation. They may process information less fully and may have difficulty switching attention among multiple tasks in a controlled fashion, and consequently their management of the overall situation may become disjointed and chaotic.

Because anxious thoughts tend to preempt working memory's limited storage capacity, the individual may have difficulty performing computations that would normally be easy and have difficulty making sense of the overall situation and updating the mental model of the situation (i.e., situation awareness). In our study of accidents, by far the most common category of errors (50 out of 212) involved inadequate comprehension, interpretation, or assessment of the ongoing situation.

To understand how stress affects the skilled performance of pilots, especially in emergencies (which by their nature involve novelty, uncertainty, and threat), one must understand the distinction between automated performance of highly practiced tasks and effortful performance of less familiar tasks that draws heavily on attention and working memory. If the threat produces anxiety, pilots' performance is likely to be undermined in specific ways. Attention and working memory are essential for tasks involving novelty, complexity, or danger. Performing tasks requiring these two limited cognitive resources is typically slow and effortful. If all tasks depended primarily on these limited resources we could hardly function in the world. Fortunately, with highly practiced tasks, our dependence on these two limited resources diminishes considerably, performance becomes largely automatic, and we can perform these practiced tasks with minimum attention and effort, as, for example, when driving a car.

Highly practiced skills, such as manual operation of flight controls, are less vulnerable to stress because they are largely automated and are less dependent on attention and working memory. Inadequate execution of a physical action occurred only ten times among the 212 errors (<5%) identified in our accident study. However, emergencies almost always require interweaving highly practiced tasks with less familiar tasks, novel situational aspects, and uncertainty. Thus, in an emergency situation, overall demands on attention and working memory are very high at a time when these limited cognitive resources may be disrupted by anxiety; consequently, tasks such as decision-making, team performance, and communication that depend heavily on attention and working memory are likely to be impaired

4. Decision-Making

Research has shown decision-making under stress to become less systematic and more hurried, and that fewer alternative choices are considered when making decisions. However, in highly practiced situations experts make decisions largely by automatic recognition of the situation and retrieval of the appropriate response from long-term memory of previous experiences. This is why pilots are required to practice responding to some emergency situations. Thus, experts such as pilots are protected from impairment from stress under very familiar situations, at least to some extent. For example, airline pilots are often given an engine failure during recurrent simulator training, and so pilots are typically fairly reliable in executing the appropriate response when experiencing an actual engine failure emergency in flight, even though the situation is somewhat stressful.

Unfortunately, most emergency situations are not rehearsed. Even in cases where the emergency procedures are practiced, the decisions that the pilot needs to make to respond appropriately in a particular emergency may be unique, and thus the required decision-making is not rehearsed. For example, the immediate responses to an engine fire in flight are practiced in recurrent training and are likely to be fairly reliable. But, the decisions about the next steps to take depend on where the aircraft is, fuel remaining, weather, and many other variables. Consequently, deliberate thought is required about these aspects, and such necessary deliberation may be impaired by the stress that is induced during the emergency.

The decisions made by pilots involved in accidents are often criticized. Indeed it is easy to identify, after the fact, what the pilots could have done to avert the accidents. But, as we have previously argued (Dismukes, Berman, and Loukopoulos, 2007), that kind of assessment suffers from hindsight bias. In our current study of accident errors, we found relatively few examples of poor decision-making or poor choice of action (16 of 212 errors). We suspect that—at least in the case of experienced airline pilots—'poor decision-making' may be used as a catch-all category, and we suggest investigations would be better served by deeper analysis of underlying cognitive factors.

5. Team Performance and Communication

In many studies, researchers have found that under acute stress team members search for and share less information, tend to neglect social and interpersonal cues, and often confuse their roles and responsibilities. Stress hinders team performance, including decision-making, primarily by disrupting communication and coordination. Coordination, of course, lies at the heart of effective team performance. Stress significantly reduces both the number of communication channels used and the likelihood that teammates will be provided needed information. Poor communication and coordination can lead to downstream errors by team members. In our analysis of accidents, we found 30 of the 212 errors involved inadequate or improper communication.

We found 36 out of 212 errors involved poor management of competing task demands, and another 36 involved inadvertent omission of required actions. In laboratory studies, stress has been shown to impair prospective memory, that is, remembering to perform intended actions at the appropriate time.

We suspect that most of these 212 errors of all types may have resulted from an underlying cause already mentioned: disruption of pilots' executive control of attention and working memory. Although most of the research literature is based on laboratory studies *not* involving skilled experts, our analysis suggests that some critical aspects of skilled performance of pilots are vulnerable to disruption in emergencies and other challenging situations.

6. Ways to Reduce Error Vulnerability

The design of airline operating procedures, training, and cockpit interfaces have evolved and improved steadily over decades of operational experience. However, we suggest that there is a hidden vulnerability in the design of three crucial aspects of safety—operating procedures, training, and interfaces—when non-normal situations are encountered. There seems to be an implicit assumption by designers that experienced pilots in emergency situations will be able to perform 'normally:'that is to say pilots are assumed to process information, communicate, analyze situations, and make decisions as well as if they were sitting safely on the ground. That assumption is wrong.

We suggest that pilots' vulnerability to error in stressful situations could be reduced by developing tools to help flightcrews:

1. Recognize, interpret, assess and comprehend the full implications of a challenging situation that may change dynamically.
2. Keep track of where they are in a procedure or checklist.
3. Shift attention among competing tasks without becoming locked into just one task.
4. Identify and analyze decision options.
5. Step back mentally from the moment-to-moment demands of the flight situation to establish a high-level (meta-cognitive) mental model that guides action.

6. Continuously update that mental model as the situation unfolds.
7. Maintain the cognitive flexibility to abandon a previously selected procedure or course of action that has become inappropriate for the situation.

To a large degree, these seven objectives could be supported by revising existing flightdeck operating procedures, checklists, and training to reflect diminished attention control and working memory function in threatening situations. This would best be accomplished by collaboration between human factors experts and the operational community. In addition, a longer-range approach would be to support these objectives in the design of future flightdeck displays and automation interfaces.

Pilots' resilience to stressful situations could also be improved by stress exposure training. In its simplest form this training would explain the physiological and cognitive changes that occur in stressful situations, which might help pilots be less disconcerted when they experience the physiological effects and be on guard for the cognitive effects. More advanced training could be incorporated into existing Line Oriented Flight Training (LOFT), allowing pilots to examine their own performance in stressful scenarios.

7. Directions for Future Research

Research is needed to develop ways to evaluate the effectiveness of existing operating procedures and checklists used in threatening situations and to provide guidelines for making these procedures more robust. Similarly, research is needed to evaluate and enhance flightdeck interfaces to help flight crews manage their attention and their multiple concurrent tasks in emergency situations.

A very limited amount of research has been conducted suggesting that stress management training could reduce pilots' vulnerability in difficult situations, but this research has been conducted with novice pilots performing a limited range of tasks. Research is needed to develop practical and effective stress management training that could be incorporated into existing airline training, targeting highly experience pilots.

Targeted laboratory research could help us better understand basic cognitive functions affected by stress, for example:

- Individual differences
- Role of experience
- Situational context
- Role of uncertainty and/or novelty
- Role of pilots' mental perspective of threatening situations
- Judgment heuristics in decision-making
- Individual versus team effects

8. Implications for NextGen

The NextGen environment will present flightcrews with operating procedures and demands that could increase stress and the consequences of stress, especially in non-normal situations. Complexity and traffic density will increase in this environment, and thus margins for error and time to respond may decrease. Therefore, it is crucial to identify human factors challenges that may arise during implementation and to develop appropriate countermeasures.

The increased navigational precision and reduced aircraft spacing required for NextGen may sometimes reduce the time flightcrews have to interpret emergency situations and to select appropriate courses of action. The complexity of choosing an appropriate course of action may also increase for crews encountering emergencies because options may be constrained while conducting NextGen operations, such as closely spaced parallel operations.

New technologies will generate new failure modes that may increase stress and cognitive demands on flightcrews. Research would allow these failure modes to be characterized, well-anticipated, and thoroughly covered in training that is designed to mitigate stress effects on flightcrew performance in the NextGen context. Existing alerting features on flightdecks may not be adequate for NextGen procedures and failures.

As the airspace system evolves and grows more complex and crowded, the need for ways to help flightcrews deal with the heavy cognitive demands of non-normal situations becomes even more important. Transition to complex new technologies poses human factors challenges, and those in NextGen are particularly critical to its successful implementation. Difficulties will be worked out as they appear, but the transition period, including learning new procedures to proficiency, is likely to be especially cognitively demanding on flightcrews; thus realistic simulation research to characterize the human factors challenges and develop mitigations should be conducted before NextGen systems are fielded. After NextGen technologies are in operation, it will be important to carefully monitor operations for indicators of latent human factors problems, particularly related to the effects of stress in normal and non-normal operations.

References

Dismukes, R. K., Berman, B. A., and Loukopoulos, L. D. (2007). *The limits of expertise: Rethinking pilot error and the causes of airline accidents*. Aldershot, UK: Ashgate Publishing Limited.

Eysenck, M. W., Derakshan, N., Santo, R., and Calvo, M. G. (2007). Anxiety and cognitive performance: Attentional control theory, *Emotion, 7*, 336-353.

Lazarus, R.S., and Folkman, S. (1984). *Stress, appraisal, and coping*. New York: Springer.

Young, J. A. (2008). *The Effects of Life-Stress on Pilot Performance*. NASA/TM–2008–215375. NASA Technical Memorandum. Moffett Field, CA: NASA Ames Research Center.

Appendix A

Selective Review of Stress Literature: Implications for Pilot Performance

R. Key Dismukes[6]*, Timothy E. Goldsmith*[7]*, and Brenda Martinez-Papponi*[7]

November 15, 2013

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The stress literature is large and variegated. We have not attempted a comprehensive review; rather, we have focused on aspects of the literature that may shed light on how the acute stress of non-normal situations may affect the skilled performance of pilots. (Here we use the term 'non-normal' to include both emergency and abnormal situations, with emphasis on situations that threaten safe completion of a flight.) We started our literature search with existing, more extensive reviews (e.g., Driskell and Salas, 1996; Hamilton and Warburton, 1979; Hancock and Desmond, 2001; Hockey, 1986; Staal, 2004; Stokes and Kite, 1994), did forward searches to obtain more recent publications, and focused our discussion on papers most relevant to our concern. Our review includes a critical examination of the methodology of diverse empirical studies to better assess the extent to which findings could be extrapolated from laboratory settings and—in a few cases—from naturalistic settings to the challenges pilots face in the cockpit.

1. Stress: An Overview

Studies vary greatly in how stress is induced and manipulated, whether physiological, psychological or even social causes of stress are used, whether or not the stress manipulation is validated, the nature of the task performed, how performance is measured, the experience level of the participant, and so forth. Drawing conclusions across such a multifaceted set of research findings is difficult. Even the term 'stress' is not used consistently in this literature. Seyle (1956) conceptualized a 'general adaptation syndrome' as a common pattern of somatic responses to diverse noxious situations, and the physiological literature seems to provide a consistent picture of two neural/hormonal systems responding to threat: A pituitary/adrenal cortex system and a sympathetic/adreno-medullary system, both triggered by the cerebral cortex and hypothalamus (Biondi and Picardi, 1999; Seyle, 1956). These systems organize the body's response in 'fight or flight' situations. We were not able to find studies that explicitly characterize how these physiological systems interact with individuals' cognitive and behavioral responses to threat. (Some cognitive/behavioral studies have measured physiological responding to validate that the manipulations used actually induced stress.)

Hockey (1986), a prominent researcher in this field, stated that stress has come to be used to refer quite generally to any unusual state or conditions of work and the responses to those conditions. In that vein, a wide variety of manipulations have been used as stressors: workload, time pressure, noise, sleep deprivation, fatigue, social anxiety, threat of electric shock, heat, and cold, most commonly. This broad concept of stress and use of such diverse manipulations is problematic for our purposes. It is not at all clear that these manipulations affect performance through the same mechanisms and with the same outcomes as does the physical danger pilots might face in an emergency. Consequently we adopted a more focused model of stress, one with considerable support in recent literature: the cognitive appraisal model (Lazarus and Folkman, 1984). This model posits that when an individual perceives potential threat to his/her well-being, the individual assesses the nature of the threat and his/her ability to manage the situation successfully. As the challenge of the situation rises, the individual becomes increasingly anxious, and at some point is uncertain about managing a successful outcome. This anxiety plays a central role in altering the individual's cognitive processes and overall performance. Anxiety appears to pre-empt some of working memory capacity (see Memory section) and to divert attention (see Attention section).

Attention and working memory are known as limited cognitive resources; their capacity for processing information is quite small compared to the vast store of information in long-term memory. For the purpose of the review we ascribe to Cowan's (1997) model of attention and memory. The content of working memory (that is, short-term memory store) is generated by the interaction of perceptual input with activation of a very small portion of long-term memory. Central executive processes control movement of the spotlight of attention over this limited store and update its content, holding task-relevant information readily available and updating that information. (Involuntary processes, such as the startle reflex, also contribute to the direction of attention.)

Arousal is a concept bearing on many models of stress. This concept exists in both physiology and psychology, although more explicitly defined in the former, in which measures such as heart rate and EEG patterns are used. At the physiological level, arousal can be viewed as mobilization of the body's resources for 'fight or flight.'

Arousal at the cognitive level is thought to represent mobilization of resources to address task demands, although what these cognitive resources are is usually not spelled out. One wonders if, at a cognitive level, arousal is simply increased focus on the task at hand, directing attention, working memory, and cognitive processing in general to that task; however, there also seems to be an affective component, perhaps akin to excitement or fear, though that aspect has not been fully characterized. In the stress literature the relation of arousal to performance is often described as an inverted U, with performance increasing as a function of arousal to some point and then declining. But arousal is itself never directly measured, rather it is assumed to co-vary with some manipulation, such as task difficulty, and the inverted U is more often presented as an idealized figure rather than a curve of actual data points. (For critiques of the inverted U concept, see Stokes and Kite, 1994; Westman and Eden, 1996.)

For the purpose of the cognitive appraisal model, arousal may play in two different ways. First, when an individual becomes aware of and orients to a potential threat, cognitive resources may be re-directed to managing the threatening situation, improving performance capability. However, to the extent the individual is anxious over his/her ability to manage the situation, that anxiety will pre-empt limited cognitive resources, hampering performance, perhaps increasing anxiety further. Here the second aspect of arousal may come into play: The individual may become aware of the body's physiological responses, such as increased heart rate and force, labored breathing, and muscular trembling, further drawing attention away from task management and further increasing anxiety.

Most studies of the effects of stress on human performance have been conducted in laboratory studies in order to provide controlled manipulations and well-defined measures of effect. However, for multiple reasons, the limitations of laboratory studies make it difficult to extrapolate their findings to understanding the effects of stress on the skilled performance of pilots. One reason was already stated previously: It is not clear that some manipulations work primarily by inducing stress (as we have defined it in the cognitive appraisal model)—or even at all by this route. And to the degree that they do induce stress, it is not clear that the intensity of stress in laboratory manipulations can approximate the stress from threats to physical survival, given the different nature of the manipulations and ethical limits to how one must treat research participants.

Consider workload, a manipulation frequently used. Increasing workload may induce increased arousal (e.g., mobilization of resources), helping the individual focus on task demands. The individual may exert increasing effort to manage the rising workload, maintaining performance by improving efficiency (reducing the pauses between task steps and reducing the amount of time spent on each step). (Effort is a subjective feeling state evoked when one must concentrate on demanding tasks; Kahneman, 1973.)

At this point we are not dealing with deleterious effects, but as workload continues to rise, the individual faces a dilemma: It may not be possible to maintain an adequate level of performance. Two things may result, only one of which we consider a 'stress' effect per se. First, the individual may alter his performance strategy. In a simple laboratory task, the only adaptation possible may be to trade accuracy for speed, but in more complex tasks, as most in the real-world are, adaptation may involve giving priority to more important aspects of the task (or tasks) and attending less to less important aspects or abandoning them altogether. This strategic change may be deliberate and well controlled, allowing graceful decline in overall performance or it may be erratic and lead to catastrophic degradation of performance. The second effect of excessive task demands may be anxiety about the individual's ability to perform adequately, with the anxiety taking up critical cognitive resources, causing performance to deteriorate further. It is this second effect we are inclined to label stress. Both effects may operate together, and it is difficult to know which is causing what.

Still another aspect comes into play if the individual must maintain high levels of effort for prolonged periods: 'mental' fatigue, also a subjective feeling state, accompanied by declining performance. This decline often appears as erratic performance; periods with high error rates and/or low output, alternating with effective performance. How long individuals can maintain high effort presumably varies with the individual and the nature of the task, but at very high levels, it seems to be more a matter of minutes than hours.

This workload example illustrates the challenge of determining what aspects should be considered 'stress.' Of course, one could simply lump all of these effects of high workload together as stress—as many researchers seem to do—but this encounters an issue that has not been well addressed in the literature. The several effects may alter performance in fairly different ways, depending on the nature of the task and the characteristics of the individual. For example, individuals may be able to manage workload per se strategically, maintaining high levels of performance of the more crucial aspects of the situation, but anxiety pre-empts working memory capacity and misdirects attention, undercutting the individual's ability to work strategically. And if one wishes to find ways to ameliorate stress effects, the techniques that might work best for (what we define as) stress may not be the same as techniques for managing high workload. Time pressure as a stress manipulation raises many of the same concerns as workload.

An alternative view to that discussed above is that certain kinds of workload manipulation may mimic the effects of anxiety on working memory and attention. For example, giving an automobile driver a secondary mental computation task requires dividing attention and occupies a portion of working memory (Matthews, Sparkes, and Bygrave, 1996). This may closely mimic the effects of anxiety or may differ drastically, depending on exactly how anxiety and the secondary task operate. Unfortunately, we know of no studies directly comparing effects of the two kinds of manipulation.

We have no neat solution for the issue of what stress encompasses; we can only suggest that researchers think carefully about what it is they are manipulating and about how to interpret results of studies. It would be helpful if all studies included physiological measures and self-reports of stress. Research is needed to determine whether classic 'fight or flight' physiological indicators rise gradually with the challenge of a situation or appear only when anxiety occurs.

Noise seems to be the manipulation most commonly used in laboratory studies, and here also one must be concerned with the possibility of multiple effects, not all of which we are comfortable with calling stress. Obviously, noise may directly divert attention or interfere with processing of information by over-riding perceptual and attentional channels. And it is not clear how to categorize the irritation that noise produces, perhaps through the difficulty it causes in maintaining attention on task.

Some manipulations we feel should not be categorized as stressors at all, in particular, sleep deprivation and fatigue. Inadequate sleep has very direct physiological effects that in turn alter cognitive processing, in ways that may even be the opposite of stress effects. For example, fatigue tends to lower arousal, whereas stress tends to raise it (Stokes and Kite, 1994, pp. 235-268).

The manipulations that in many ways seem closest to, though much milder, than physical danger are social anxiety—induced, for example, by public speaking—and the threat of electric shock. Both produce anxiety that may capture limited cognitive resources.

Many laboratory studies have not included any verification that the manipulation in fact induced stress, apparently assuming that the manipulation works because manipulations of that general type have been generally accepted as appropriate in previous studies. Some studies use subjective reports from participants, but one should be cautious in accepting such reports because lay people seem to have broad and fuzzy concepts of what constitutes stress. We regard as most useful those relatively few studies that include a physiological measure, both because this provides a measure of validation and the possibility of assessing the degree of stress.

As will be apparent later in this review, stress studies have used a very wide range of quite diverse dependent measures of stress effects. See, for example the diverse tests assumed to measure selective attention (Attention section). These measures reflect quite different modes of information processing, and it is not at all clear that they share a common cognitive mechanism. We are aware of no studies that systematically compare the effects of a particular 'stressor' on multiple types of measures of a particular aspect of cognition, such as selective attention or working memory. Conversely we are aware of no studies that systematically compare the effects of multiple types of stressors on a particular cognitive function. (Needless to say, it would be difficult to devise such a study.)

The dependent measures used in laboratory studies of stress typically use very simple tasks, such as tracking one or more objects on a screen with a joystick. The tasks pilots perform are of course more complex and varied, generally requiring more skill. Further, pilots must manage multiple tasks concurrently, shifting priorities and timing of actions as a function of the current situation. Pilots are highly practiced at most of their normal tasks; thus execution involves a substantial degree of automaticity. However, some aspects, such as some kinds of decision making, depend heavily on controlled processing and make heavy demands on working memory. Non-normal situations can be challenging because they add additional tasks and procedures, and these must be integrated with normal procedures in ways that cannot entirely be predicted in advance. And non-normal procedures are much less practiced than normal procedures, thus these situations make heavy demands on limited cognitive resources such as attention and working memory. Few laboratory studies have examined the effects of stress on expert performance of complex tasks. All in all, extrapolation from typical laboratory studies to real-world flight operations is of necessity rather speculative and must be done with great caution.

Individual differences can play a large role in responding to stressful situations. Trait anxiety is the most commonly studied individual difference in laboratory studies. Individuals who score high on this trait may experience anxiety both in relatively low-demand situations and in more demanding situations in which they are otherwise quite competent, and this anxiety may undermine performance. (But, as an aside, performing artists and athletes debate whether some level of anxiety is good, enhancing performance.) Skill and experience performing combinations of complex tasks is a crucial individual difference; unfortunately, few studies have examined this aspect. (However, see the section of naturalistic studies, which sometimes compare two levels of experience.)

Two types of studies help close this gap between the laboratory and actual flight operations somewhat: Experiments with flight simulators and studies of human performance in real-world stressful situations, such as military training. The latter of these two, naturalistic studies, are discussed in a later section. Although these naturalistic studies provide valuable insights, they are limited in that the stressful situations are often rather complicated; for example a military training exercise may involve heavy physical exertion, sleep deprivation, threats to personal safety (and least simulated), potential social anxiety (performance evaluation), and even boredom interweaving over hours or days. In such an environment, it is hard to separate out the effects of stress from other factors affecting performance. On the other hand, such naturalistic studies have the potential to provide detailed assessments of alterations in performance of real-world tasks, combined with performance on standardized cognitive performance batteries.

We cite several studies using pilot performance in flight simulators in the respective sections on specific cognitive functions. This type of study has great potential for examining, in stressful conditions, pilots' performance of actual flight tasks and combining this with measures of performance on cognitive test batteries. Unfortunately, only a handful of these studies have been conducted, almost all in general aviation flight simulators, and these typically have looked at only a few aspects of pilot performance and have not combined these aspects with cognitive test batteries. Cost, of course, limits scientists' access to sophisticated transport category aircraft simulators and to professional pilots. Nevertheless, much could be learned from more extensive studies with general aviation simulators.

2. Attention and Stress[8]

Attention has multiple aspects, defined almost as much by experimental methods as by inherent cognitive processes. For our purposes we use the term 'attentive processing' to refer to a form of information processing required when tasks involve novel aspects, difficulty or danger. The capacity of attentive processing is quite limited—basically one can attentively process only one stream of information at a time; thus managing more than one task requiring attentive processing necessitates switching attention back and forth among the tasks. The moment-to-moment focus of attention corresponds roughly to the contents of our conscious awareness and in one view constitutes a subset of the contents of working memory (Cowan, 1997). Focused attention has been compared to a spotlight that moves about among sources of information, as a function of task demands and the individual's goals, and this movement is partly deliberate and partly unconscious/automatic. (Note

[8] This review does not attempt to describe the many and varied studies on this topic; rather it provides a representative sampling focused on the principle issues.

that the control of attention probably overlaps with the executive component of working memory, discussed in a later section.)

In contrast to attentive processing, performance of highly practiced tasks with few or no novel aspects becomes largely automatic, requiring little conscious control (Salings and Phillips, 2007; Schneider and Chein, 2003; Schneider and Shiffrin, 1977; Shiffrin and Schneider, 1977). However, real-world tasks (e.g., driving) probably require some small amount of attentive oversight, if only to check that automatic processing is achieving the individual's goals.

Almost all studies of the effects of stress on attention have addressed processing of visual information, rather than processing of other sensory modalities. Selective attention is one aspect of attention that scientists study, which is the ability to attend selectively to one source of information while ignoring other sources. One of the most frequently reported findings in the stress literature has been narrowing of perceptual scan, sometimes known as tunneling (Staal, Bolton, Yaroush and Bourne, 2008). Easterbrook (1959), in an often-cited review, asserted that under emotional arousal individuals narrow the range of cues utilized. Hockey (1970a; 1970b) used loud noise as a stressor in an experimental study in which participants were required to perform a centrally located tracking task and at the same time monitor for the occasional illumination of several lights placed peripherally in the visual field. In the presence of noise, performance on the central tracking task improved while monitoring of the peripheral lights decreased.

Weltman, Smith and Egstrom (1971) conducted a similar study using simulated dives in a pressure chamber to induce anxiety in novice divers. Increased heart rate and subjective ratings indicated the manipulation was effective, and detection of peripheral lights declined without a change in performance of the central task.

Baddeley (1972) suggested that this attentional tunneling might explain results of other studies in which individuals in real-world situations involving physical danger performed more poorly as a function of the degree of perceived danger. For example, Baddeley cited several studies in which divers performed worse in the open sea than on land in tasks such as transferring bolts from one set of holes to another set. Hammerton and Tickner (1968) had Army parachutists at three levels of experience perform a visual tracking task well before, just before, or after a jump and found that performance of the less experienced parachutists declined just before the jump, presumably due to anxiety. Experienced parachutists did not show this decline. Obviously, these several studies do not show whether the decrements in performance in the presence of danger-related anxiety resulted from attentional tunneling, but it seems likely that some form of disruption of attention played a role.

In a laboratory study, Bacon (1974) used the threat of electric shock to induce anxiety in participants and found impaired performance on a pursuit-rotor tracking task, apparently due to restriction of the range of perceptual cues used by the participants.

The mechanism by which stress narrows the spatial range of perceptual cues utilized is not known. The experimental paradigms used by Hockey (1970a) and by Weltmann et al. (1971) required participants to perform dual tasks, dividing their attention between the central task and the peripherally-cued task. Stress might impair performance on the peripheral task by disrupting or pre-empting the executive control processes necessary to switch attention between tasks. Since the central task was more continuously active than the peripheral task, lack of executive control might have left the central task as a default. Hockey (1979) proposed on the basis of several studies that stress increased attentional focus on the dominant aspects of a task, with reduced attention to less prominent aspects.

Several studies of eye-witness testimony (e.g., Loftus, Loftus, and Messo, 1987) have demonstrated 'weapons focus' in which crime witnesses pay increased attention to a weapon used in a crime and are less able to recall other aspects of the event, such as an assailants' face. In laboratory studies, this selective attention effect may be simply due to the fact that individuals' attention tends to favor emotionally valenced objects (Dijksterhuis and Aarts, 2003), although actual crime victims very probably experience stress as well.

Studies reporting attentional tunneling are not limited to narrowing of the spatial range of perceptual cues utilized. Several investigators have examined the effects of stressors on performance in the Stroop test. This test requires participants to ignore the intrusion of a highly automatic response to a stimulus cue while evaluating some aspect of that cue. For example, participants might be required to state the color of the ink of a word that spells out a color. When the spelled color is different than the color of the ink, responding is greatly slowed; participants must effortfully suppress the automatic tendency to say the name of the color spelled out. (Seeing a word naming a color automatically retrieves the name of that color from long-term memory into awareness.) Houston (1969) found that distracting levels of noise improved performance on the Stroop test, apparently reducing the distracting intrusion of the (irrelevant) word color name. Chajut and Algom (2003) reported that a combination of time pressure, task difficulty and noise also improved Stroop performance. Hu, Bauer, Padmala, and Pessoa (2012) reported two opposing effects of the threat of electric shock on Stroop performance: a general slowing of responding, and a lessening of interference from the irrelevant aspect of the stimulus cue.

The results of studies of Stroop performance under presumed stress have generally been interpreted as supporting the concept of attentional tunneling as a broad phenomenon (e.g., see Stahl, 2004). Yet some caution in interpretation is appropriate since the cognitive mechanism underlying these results is not known. Simple disruption of attentional control or pre-empting attentional capacity might have been predicted to impair Stroop performance, since correctly performing this test requires individuals to actively suppress a strong automatic response. Indeed, Keinan, Friedland, Kahneman, and Roth (1999) reported that socially-induced stress increased interference from non-relevant information in the Stroop task and several other Stroop-like tasks.

Morelli and Burton (2009) used exposure to disturbing photographs to stress participants who were then required to perform a multi-object tracking task in which several objects to be tracked were flanked by an array of moving distractors. Performance of stressed participants was lower than that of controls, presumably because stress increased interference from distractors. Thus, in contrast to previously discussed studies, this study found decreased selectivity of attention under stress. Obviously, the apparent conflict in findings may have resulted from the large differences in the 'stressors' and in the measures of performance used.

Still another laboratory paradigm, negative priming, has been used to explore the effect of stress on individuals' ability to ignore task-irrelevant information. In this paradigm, a cue is attended on one trial but is to be ignored in favor of a different cue on the next trial. Negative priming occurs when responding to the new to-be-attended cue is slowed in the presence of the old cue as a distractor. (Our description greatly simplifies a somewhat complex paradigm.)

Two studies have reported that stress increases negative priming, apparently by reducing participants' ability to inhibit task-irrelevant information. Skosnik, Chatterton, Swisher, and Park (2000) used a demanding video game as a stressor before the negative priming test, and Braunstein-Bercovitz (2003) used difficult-to-solve arithmetic problems as the stressor. These findings, like those of the discrepant Stroop test studies, suggest that whether stress decreases or increases interference from task-irrelevant information depends heavily on the nature of the task performed (and perhaps on the stressor used, not to mention characteristics of the individual).

Plessow, Schade, Kirschbaum and Rischer (2012) examined the effects of psychosocial stress on dual-task performance in which participants were to give priority to one of the tasks. Both tasks were very similar visual judgment tasks, thus interference to the higher priority task was expected from cross-talk with the lower order tasks. Stressed participants showed greater interference from the lower priority task.

In one of the few studies on selective attention to other than visual information, Al'Absi, Hugdahl, and Lovallo (2002) reported that stress induced by public speaking improved dichotic listening: Participants under stress were better able to ignore auditory input to the unattended ear.

In additional to the early studies of stress effects in naturalistic settings described above, several more recent studies have reported effects on attention. Lieberman, et al. (2005) gave Army officers a battery of cognitive tests after a 53-hour combat training exercise conducted in heat and allowing little sleep. Performance on a measure of attention and on all other cognitive measures deteriorated during the exercise. Morgan et al. (2006) reported that highly-trained special operations solders' ability to copy and recall the Rey Ostereith Complex Figure deteriorated substantially during survival training (an extremely demanding course). Performance on this test depends heavily on attention, although probably in a complex way.

Prospective memory refers to cognitive processes involved in remembering to perform tasks at the appropriate time without explicit prompting (Dismukes, 2012). The term is something of a misnomer, in that attentional processes are involved in addition to memory. To remember to perform a task at the appropriate time, an individual must notice some cue associated with the intended action, and that cue must trigger retrieval of the action from long-term memory. The more salient the cue and the more extensively it is attended and processed, the more likely retrieval will occur. No studies of effects of stress on prospective remembering have been reported, but almost certainly remembering is impaired when management of attention and depth of attentive processing are disrupted.

2.1 Implications for Pilot Performance in Non-Normal Situations

The great majority of studies of stress effects on attention have used laboratory paradigms, involving several types of stressor and diverse dependent measures of how attention is affected[9]. Thus it is clear that stress in laboratory settings alters attention, however it is not clear these effects follow any single, unifying pattern. Several studies report stressed individuals pay reduced attention to information spatially displayed peripherally to a centrally-displayed task, but the extent of this

[9] As noted in our introduction, one should be cautious in assuming that effects of some of these manipulations are primarily due to 'stress.' Manipulations such as workload may directly affect attention—and stress may or may not occur secondarily.

phenomenon has not been explored extensively: In what range of tasks does this occur and for what ranges of eccentricity and for what types of information?

Early hypotheses that stress increases focus on dominant or most relevant aspects of a task are not consistently supported by conflicting results in different laboratory paradigms. What one might conclude from diverse studies is that stress alters the relative amount or weighting of attention given to multiple sources of information as a function of the specific nature of the task and how those sources of information are used in the task. Depending on the specific task, processing might be improved or impaired. The several studies that used tracking of objects, especially multiple objects, in conjunction with all the other studies discussed here, suggest that individuals under stress are generally less able to manage effectively how they distribute attention as a function of task requirements.

Studies of naturalistic situations, such as highly stressful military exercises, show impairment of laboratory measures of attention, but so few measures of attention have been used that one can say little about how attention is affected other than it is impaired. Also, multiple factors, such as fatigue and sleep loss, may affect performance through multiple mechanisms in these studies.
Generally consistent with both diverse laboratory studies and naturalistic studies is a cognitive model of threat appraisal (discussed in the introduction) in which anxiety occupies working memory and disrupts executive control of attention.

Extrapolating from diverse laboratory studies and a handful of naturalistic studies with military personnel to the cockpit performance of pilots must be largely speculative. Pilots perform a wide range of tasks in which attention is critical, but those tasks are far more complex than the tasks of laboratory paradigms, and they draw upon the various aspects of attention in complex ways that have not been characterized to any great extent. Pilots must continually shift attention among tasks, whose priorities shift dynamically, and pilots sometimes must perform several tasks concurrently (Loukopoulos, Dismukes, and Barshi, 2009). Many of the tasks they perform are highly practiced and become largely automatic.

Non-normal situations impose new task requirements, and these tasks may have been practiced infrequently or not at all. Further, pilots must integrate these new task demands with normal procedures; multitasking and workload increase, as well as time pressure in some situations. Thus effective management of attention is vital.

Attentive processing may be either impaired or improved in simple laboratory settings, but effective management of attention in more complex real-world settings seems likely to be more or less universally impaired. One cannot predict with confidence how pilots' management of attention will be disrupted in a particular situation; indeed it seems likely the form of disruption will vary with the situation. A pilot might become fixated on one task or one aspect of a task and neglect other tasks, but might also become distractible, unable to focus adequately on any one task. Prioritizing and directing attention among competing task demands is likely to be vulnerable under stress. A pilot might not adequately process a source of information, such as an airspeed indicator, that normally he or she would process easily. Multitasking ability will very probably decline, sometimes drastically. Other than the stress management training discussed later in this report, few studies have explored specific countermeasures to help pilots avoid disruption of attentive processing under stress. In general, interfaces, procedures, checklists, and training should be designed to help pilots direct attention appropriately as a function of task demands of the moment and to help pilots keep track of where they are in tasks.

3. Startle and Surprise

Non-normal situations sometimes start with a sudden event such as a master caution warning, an uncommanded lurch of the aircraft, or a loud noise. Such salient sensory stimuli trigger a hard-wired response in individuals, who automatically orient to the stimulus, undergo physiological arousal, and experience an emotional state akin to fear; these responses are collectively called the startle response (Thackery, 1988). This response momentarily interrupts the individual's ongoing activity. If the individual recognizes the nature of the event, he may be able to quickly evaluate the situation and summon an appropriate response from memory. If the situation is not familiar and seems potentially threatening, stress may quickly follow.

Some non-normal situations evince themselves without a salient abrupt event; for example, gradually rising engine oil temperature. Unexpected events surprise pilots (or other professionals) because what happens in the environment does not match the individual's mental model of the situation and of what is supposed to happen (Kochan, Breiter and Jentsch, 2004). Here, too, if the situation seems threatening, and the individual cannot quickly recognize what to do, stress is likely to occur because of the uncertainty of outcome. Re-orienting attention to the startling or surprising event, combined with growing stress, may cause the individual to stop managing ongoing activities or to not evaluate the overall situation.

4. Memory

Scientists have identified many aspects of memory, defined in terms of both the presumed underlying function and the type of laboratory paradigm used. Most of these aspects fall beyond the scope of this study; here we focus on just three aspects: Acquisition of new information to be used in ongoing tasks (e.g., a flight clearance), processing of this new information, and retrieval of well-established information from long-term memory (e.g., the procedure for programming clearances into the flight computer). Working memory, discussed next, is involved in all three of these aspects.

4.1 Working Memory

"Working memory is so central to human cognition that it is hard to find activities where it is not involved" (Ericsson and Delaney, 1999, p. 259). Working memory is conceived as the active processing system in memory, serving as a kind of mental workspace. It temporarily keeps readily available a small set of information from the environment or from long-term memory so that that information can be manipulated and used in performing diverse tasks. It is working memory that allows one to focus on a central task and execute the required operations while excluding information not relevant to the task (Conway et al., 2007; Kane and Engle, 2000; 2002).

Working memory consists of two distinct components: a storage component, consisting of temporarily activated and readily available information, and a central executive system that supports goal-directed behavior by manipulating information, shifting attention within or between tasks, and selecting among competing responses (Baddeley, 1986; Conway et al., 2007). Thus the functions of working memory and attention overlap considerably. In contrast to the vast store of long-term memory, the capacity of working memory is quite limited; no more than handful of items can be actively maintained at one time.

4.2 Stress Effects on Memory

Eysenck and Calvo (1992) proposed that individuals under stress worry about the stressful situation and this worry reduces the availability of working memory storage and processing capacity for dealing with ongoing tasks by competing for these limited cognitive resources. Multiple lines of evidence in subsequent years support this view.

One line of research has used individual differences in math anxiety. Individuals high in math anxiety, independently of their level of math knowledge, perform computations more slowly and less accurately than individuals low in math anxiety (Ashcraft, 2002; Eysenck, 1997). Ashcraft and Kirk (2001) found that high math anxiety participants showed lower scores on several measures of working memory span, raising the question of whether anxiety lowered working memory scores. By partialling out the degrees of correlation of computational span (of working memory) and of language-based span (also working memory) with level of math anxiety (measured by questionnaire), Ashraft and Kirk (2001) determined that it was the computational span of working memory that was affected by math anxiety. On the basis of this finding and other studies, the authors concluded that math anxiety undercuts math performance by temporarily diverting limited working memory resources into worry and intrusive thoughts.

Similarly, Beilock (2008) studied the relationship between working memory capacity and math performance under stressful conditions. He found that although individuals who were high in working memory capacity were better equipped to manage the high demand situations that were working memory intensive, they were also the ones who were more likely to be adversely affected under stressful situations. Performance decrements were found only in high working memory individuals under high demand and high pressure situations. Beilock concluded that the worries that accompany a stressful situation consume the working memory resources that higher working memory individuals rely on for their superior performance.

Al’Absi, Hugdahl and Lovallo (2002) also drew upon individual differences in stress responding, by measuring cortisol secretion while participants were performing prolonged mental arithmetic. Participants who secreted higher levels of cortisol—presumably because they experienced higher levels of stress—made more arithmetic errors and performed more slowly.

An implication of these studies is that individuals with high working memory capacity might be less vulnerable to stress because they would have more spare capacity even when some of their working memory is occupied by worry. A study by Johnson and Gronlund (2009), drawing on individual differences in both trait anxiety and working memory span, supports this conclusion. Participants performed a highly demanding dual task, and correlations among trait anxiety, working memory span, and task performance were examined. Participants with average to low working memory span performed the dual task much more poorly if they were also high in trait anxiety, but participants with high working memory span were to a large degree buffered against the effect of anxiety.

A study by Luethi, Meier, and Sandi (2009) illustrates another approach in studying the effects of stress on memory. Social anxiety/stress was induced by the Trier Social Stress Test (TSST), which participants are told simulates a job interview. Participants are required to deliver a free speech and perform mental arithmetic before an audience that appears to evaluate performance. TSST has been shown to produce the physiological[10] and subjective manifestations of stress reliably. Immediately following the 25-minute exposure to the TSST, participants were given a series of different memory tests that examined aspects of working memory, explicit verbal and spatial memory, implicit memory (priming), and classical conditioning[11]. Working memory performance (measured by reading span) of TSST participants was significantly lower than that of controls. (Effect size was not reported, but appears to be modest.) Explicit verbal memory was not affected, however the authors suggest that a negative effect of stress on memory retrieval may have cancelled out a positive effect on acquisition/consolidation of memory, since both acquisition and retrieval occurred in a few minutes after the TSST. (Previous studies have reported that stress has opposite effects on consolidation and retrieval.) TSST participants showed improved spatial memory (here, too, acquisition and retrieval both occurred under residual stress) and increased classical conditioning of negatively-valenced stimuli.

A similar study by Schoofs, Preuss, and Wolf (2008) also found working memory impairment after the TSST, with both reduced accuracy and increased reaction time on the n-back paradigm, which emphasizes monitoring and updating of working memory. An interesting aspect is that the size of the working memory effect and the physiological measures of stress (salivary cortisol and alpha-amylase) declined roughly in parallel over time.

Still another approach in the neuroscience literature has been to administer corticosteroids to participants to mimic at least some of the physiological manifestations of stress (see Het, Ramlow, and Wolf, 2005, for a review). An obvious issue with this approach is whether this physiological manipulation produces a subjective experience of stress comparable to that caused by threat or anxiety. Lupien, Gillin and Hauger (1999) infused participants with several levels of hydrocortisone and examined working memory and declarative memory performance. At the highest dosage, working memory, as measured by an item recognition task that taps central executive function, was impaired, but declarative memory was not.

Lupien et al (1999) measured declarative memory by recall of learned paired word associates, in such a way that potential effects on acquisition and recall, 15 minutes later, could not have been disambiguated. However, de Quervain, Roozendaal, Nitsch, McGaugh and Hock (2000) administered cortisone immediately before learning, immediately after learning, or shortly before testing for recall and recognition of paired word associates. Acquisition (learning) was not affected, nor was recognition memory, but recall was substantially reduced. Newcomer et al. (1999) also observed a decrease in declarative memory performance in participants administered a cortisol dose corresponding to high levels of stress over one to four days, but no decrease was observed in participants given a lower dose corresponding to mild stress. It is not clear to what extent this extended elevation of cortisol would mimic the effects of acute stress that might be experienced in a cockpit emergency.

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[10] Increased activity in the sympathetic nervous system followed by increased activity in the hypothalamic-pituitary-adrenal axis.

[11] A methodological limitation with this study is that testing of memory effects occurrd after the psychological manipulation of anxiety ended. (Testing took about 56 minutes overall.) Physiological manifestations of stress remained high, but the social threat was over, and we do not know how long participants may have perseverated in thinking about this social threat.

Diverse studies strongly support the argument that stressful situations engender worry and intrusive thoughts that pre-empt working memory functioning to some degree. This finding has strong implications for the performance of pilots (and other professionals) in non-normal situations because those situations typically confront the individual with multiple task demands that, in aggregate, make heavy demands on working memory.

Several studies also suggest that declarative memory is also impaired under stress, but because most of these studies manipulate cortisol levels directly rather than by using psychological manipulations, some caution is required in extrapolating to cockpit situations. Also, the extent to which performance on the dependent measure of declarative memory (e.g., recall of a recently read paragraph) would parallel pilots' recall of long-term declarative memory (e.g., recalling memory items from an emergency checklist) is not known. Nevertheless, in part because recall from long-term declarative memory itself depends on working memory to some degree, it would be reasonable to assume that in an emergency pilots' ability to draw upon long-term memories to deal with the situation would be impaired to some degree.

Individual differences in cognitive abilities and traits are potentially quite relevant to performance issues in non-normal situations. It is reasonable to assume as a working hypothesis that pilots high in working memory span might be somewhat less susceptible to stress impairment and pilots high in trait anxiety somewhat more susceptible. However, this hypothesis should be directly tested in a pilot population, and we might suspect that as a group pilots may tend to be a bit higher than average in working memory capacity and less likely to have trait anxiety. Also, it may be worth noting that the executive component of working memory is highly correlated with measures of fluid intelligence (Engle, 2002), thus the often-repeated pilot's statement, "Under stress my IQ goes way down" may be literally true.

These research findings have strong implications for the design of interfaces, training and procedures to help pilots deal with non-normal situations. Designers should assume that, in addition to facing unusual combinations of task demands, pilots may be cognitively impaired to some degree, less able to seek out, process and assess information; manage concurrent tasks, and reliably recall all that they know. Checklists can be designed to provide the stressed pilot more explicit guidance in executing procedures and in navigating through long checklists. Similarly, cockpit systems displays can be designed to better help pilots keep track of where they are in procedures and what remains to be done and the status of multiple systems.

5. Skilled Performance

Surprisingly, little of the empirical literature explores how stress might affect performance of highly practiced skills. Much—perhaps most—of what pilots and other skilled professionals do consists of performing highly practiced tasks. As discussed in the introduction, non-normal situations impose novel conditions and novel combinations of tasks, yet even when dealing with emergencies pilots are largely performing practiced tasks, albeit under unusual conditions.

Hancock (1986) reviewed early studies on the effects of high environmental temperatures (a condition relevant to some military operations and a manipulation used in some laboratory stress studies) on skilled performance of Morse code operators, navigation and piloting performance, and laboratory tasks. He concluded that more skilled operators showed less decrement of performance than less skilled operators, presumably because greater expertise allows tasks to be performed through automated processing, making fewer demands on limited cognitive resources required for controlled processing.

Although caution is required in extrapolating from thermal stress to anxiety/threat-based stress, Hancock's conclusion is consistent with what is known about automated processing. Schneider and Chein (2003) found that automatic processing is more resistant to stressors, such as fatigue and high workload situations, than controlled processing. In general, highly practiced skills are more robust than skills drawing heavily on limited cognitive resources, presumably because over-learning causes more elaborate representation in brain circuits (Schneider and Detweiler, 1988).

In their study of pilot judgment, Wickens, Stoke, Barnett and Hyman (1991) found judgments requiring direct retrieval of facts from long-term memory to be relatively unimpaired by stress. However, retrieval of information that is not well learned is apparently much more vulnerable to stress effects than deeply learned information (Eysenck, 1976). Stokes (1995) reported that the flight simulation performance of novice pilots deteriorated under stress but the performance of highly experienced pilots did not. The non-flying domain performance of both groups declined equally under stress, supporting the interpretation that it is expertise that protects against stress effects. In a similar vein, Smith and Chamberlin (1992) found that requiring soccer players to perform a cognitively demanding task impaired the soccer performance of experienced players less than that of players with more modest experience.

In one kind of situation the skilled performance of experts may be especially vulnerable to disruption by stress. Skilled performers sometimes 'choke' when they focus intently on a highly practiced task, inadvertently replacing the highly automated sensory-motor routines with less efficient controlled processing of the task (Svoboda, 2009). This would seem to be more of an issue for athletes and musical performers than civil aviation pilots, but one could imagine a stressful situation, such as landing a crippled airplane, in which over-thinking could impair execution of task aspects requiring precise sensory-motor performance.

Although it seems probable that highly-practiced, highly automated skills are per se less vulnerable to disruption of stress than are tasks drawing more heavily on controlled processing, in reality skilled performance may be more negatively affected than one might expect from the automated/controlled processing perspective. In real-world settings, such as aviation, performance of practiced tasks does not take place in isolation; the human operator must decide when/whether to initiate a skilled task, evaluate how well it is working, perhaps modify how it is employed, and integrate it with performance of other tasks. All this draws heavily on controlled processing, so in stressful non-normal situations how automated skills are deployed might well be impaired. This crucial aspect has not been well addressed in previous studies, but should be considered in future research.

6. Human Decision Making under Stress

Formal investigations into the cause of aviation accidents often conclude that pilot error in judgment or decision making was a contributing factor. The normally good decision making of pilots failed in some respect, perhaps due to the stress of an unusually demanding operation or a non-normal situation. Our goal in this section is to review the effects of stress on judgment and decision making and try specifically to better understand how and when decision processes fail under stress. We begin by briefly reviewing the scientific study of human judgment and decision making, how it is defined and studied in laboratory settings, and the basic research findings on human judgment. We then examine what is known about the effects of stress on decision making. Our interest lies specifically in the sort of judgment and decision making that occur in the cockpit, and so throughout this review we attempt to relate research findings back to the cockpit situation

Several sources of data exist for studying the effects of stress on decision making. NTSB accident reports offer a rich source of information about the details of the events along with carefully analyzed accounts and explanations of their causal factors. However, they do not serve well as a primary source of research information about human decision making because they are limited by the small numbers and uniqueness that necessarily accompany case studies. Instead, we have used laboratory studies of stress and decision making as a primary source. Although not without their own limitations, such as small sample sizes, small effect sizes, and limited realism (Wickens, 1996), laboratory studies are more likely to offer generalizable findings.

6.1 What is Decision Making?

Judgment and decision making are broad category labels that include cognitive processes such as reasoning, selecting, diagnosing, inferencing, prioritizing, integrating, predicting, etc. The study of human decision making by behavioral scientists has occurred within several different frameworks or paradigms, where each one defines differently the questions of interests, appropriate methods of investigation, and theoretical perspectives. One way to see the breadth of the field is to consider the reviews of judgment and decision making in the Annual Review of Psychology over the last several decades (Edwards and Fasolo, 2001; Einhorm and Hogarth, 1981; Gigerenzer and Gaissmaier, 2011; Hastie, 2001; Mellers, Schwartz and Cooke, 1988; Pitz and Sachs, 1984; Weber and Johnson, 2009). These seven reviews cover a broad spectrum of topics ranging from classical decision theory to cognitive processes in decision making, judgmental heuristics, and more recently mindfulness in decision making. The subtopics in one review rarely overlap with subtopics in other reviews.

Even more disheartening for the current review, the term stress occurs only about a half dozen times across all seven reviews, primarily limited to a single review, where the topic is given only cursory coverage. Clearly the topic of stress and human decision making has not been given much attention in the basic psychological literature.

Although the terms judgment and decision making have been distinguished, where judgment is sometimes viewed as more subjective and dependent on experience, knowledge or even wisdom, and decision making as the more objective selection of an action, this distinction is not common in the scientific literature and so in this review we will primarily use the term decision making. Decision making is a higher-order cognitive process as opposed to more elementary cognitive activities such as perception, memory, and attention. However, this distinction is nonexclusive because higher-order processes necessarily rely upon elementary processes for their completion. Hence, decision making cannot be studied independently of these more primitive cognitive processes.

In practice, decision making corresponds to certain intellectual tasks that occur in real-world contexts. Medical diagnosis, predicting stock prices, and reading and interpreting x-rays are all prototypical decision tasks. In the cockpit is a host of flight-related tasks that are decisional in nature: diagnosing the cause of a hydraulic failure, recognizing the consequences of a shorted circuit, prioritizing tasks during an emergency, evaluating alternative airports, judging the severity of a thunderstorm, etc.

A central feature of decision making is uncertainty (Arkes and Hammond, 1986). The source of this uncertainty can be unreliable information cues, a probabilistic relationship between cues and a predicted criterion, an uncertain state of the world, etc. Traditionally, it is uncertainty that distinguishes decision making from other higher-order cognitive processes such as problem solving. Uncertainty is clearly an element of decision making in the cockpit, particularly during the occurrence of non-normal events.

6.2 Laboratory Tasks Used to Study Human Decision Making

Decision making, as with any cognitive process studied scientifically, becomes operationally defined by the laboratory tasks used to study it; decision making is what subjects do in decision-making tasks. Various laboratory tasks have been created over the years to study human decision making, including gambling, predicting odds, answering questions about hypothetical scenarios, estimating correlations between variables, solving deductive reasoning tasks, and so forth (Hogarth, 1987). At times these tasks have obvious face validity to realistic decisions, but rarely are they formally validated by correlating performance on a laboratory task to a real-world situation. In any case, the bulk of the scientific study of human decision making has occurred with such laboratory tasks.

One characteristic of most decision tasks studied in the laboratory is that they can be performed by the typical study subject, a college student, after only a few minutes of instruction. In addition to convenience, tasks that allow decision processes to be studied independently of subjects' knowledge might have the advantage of focusing on basic, generalizable processes. But knowledge-lean tasks have a clear shortcoming. Most real-world decisions are made by experts using their domain knowledge to make decisions. This is certainly true for commercial flying. Further, studies of the effects of stress on decision making that have used artificial laboratory tasks raise the question of whether similar results would occur in real-world contexts where domain knowledge is crucial. The naturalistic decision-making perspective (Lipshitz, Klein, Orasanu and Salas, 2001) has studied expert decision makers in real-world tasks to counter these criticisms.

A second characteristic of laboratory decision tasks is that they are typically framed so that formal methods, such as mathematics or logic, specify correct solutions. When asked to revise the likelihood of some event based on new incoming information, combine multiple sources of information into a single quantitative judgment, or answer an implication question, Bayes' theorem, multiple regression, and propositional logic specify the correct answers, respectively. Using such tasks that allow the outcomes from normative rules to be compared to human behavior has characterized much of the research in psychology (Arkes and Hammond, 1986). Unfortunately, people routinely fail to answer these decision problems correctly, and instead show systematic biases and errors in their judgments.

6.3 Stress and Human Decision Making

There is a surprising paucity of research on how the decisions made by flight crews are affected by stress, especially the type of stress that may occur in non-normal situations.

6.4 General Effects of Stress on Deciding

Considerable evidence indicates that stress deteriorates human performance in general and judgment and decision making in particular (Welford, 1976). Although the specific deficits that result from stress may vary across different manipulations and laboratory tasks, there are is general agreement that the effects of stress are negative. Janis and Mann's (1977) early work on stress and decision making showed that decisions under stress become less systematic and more hurried, and that fewer alternative choices are considered while deciding under stressful conditions.

6.5 Rational-Analytic Decision Making

A common framework for thinking about how decision making occurs is the rational-analytic model (Edwards and Fasalo, 2001). Here the decision maker is assumed to carry out a sequence of cognitive operations including such actions as weighting attributes of information cues, combining multiple sources of information, assessing probabilities, forming subjective utilities, and evaluating outcomes. The final decision comes out of a sequence of these operations performed in a thoughtful, deliberate manner. But because stress is known to have detrimental effects on fundamental cognitive processes of memory, attention, perception, etc., it is reasonable to expect rational-analytic decisions to suffer also.

The rational–analytical system is vulnerable to stress because it draws heavily on limited cognitive resources that are themselves disrupted by stress, as discussed previously Numerous studies show that stress interferes with basic cognitive functioning such as recall and executive control. Working memory capacity decreases, the scope of information attended to narrows, our ability to selectively focus on a set of information cues decreases, and we have more difficulty processing visual information in working memory. (However, as previously discussed, some of these putative effects are less rigorously established than others, and some effects may be due to manipulations other than stress per se—e.g., workload.)

There is a general consensus in the literature that stress negatively affects rational decision making by degrading both the quality of the processing of alternative actions and the actual number of alternatives considered (Stokes and Kite, 1994). In a study of college students performing a multiple-choice analogies test, Keinan (1987) manipulated stress by threatening electric shock. The results showed that under induced stress subjects failed to consider all available alternatives before choosing an alternative (premature closure), and scanned and evaluated alternatives in a disorganized manner (nonsystemic scanning). Although similar findings were reported in previous work (e.g., Janis and Mann, 1977; Sieber, 1974; Wachtel, 1967; Wright, 1974), these previous studies typically manipulated stress through time pressure. In contrast, Keinan's study demonstrated a degradation of alternative processing through an acute stressor unrelated to time, demonstrating that hurried processing of choice alternatives was the result of stress per se and not simply lack of time.

6.6 Naturalistic Decision Making

Another prominent model of human decision making is the naturalistic framework (Klein, 2000; Lipshitsz, Klein, Orasanu, and Salas, 2001). The basic idea behind naturalistic decision making is that people make decisions by recognizing patterns in a quick, intuitive manner rather than the deliberate sequence of activities carried out under the rational-analytic approach. Decision problems evoke previously learned response patterns that have been stored in long-term memory, and it is these evoked knowledge patterns that provide the choices and actions called for in the current situation. Naturalistic decision making has close ties to the work in cognitive psychology on human expertise, which argues that expert performance comes primarily from storing large numbers of domain-specific patterns in long-term memory (Chase and Simon, 1973; Ericsson and Charness, 1994);

One feature of naturalistic decision making particularly relevant for commercial pilots is its emphasis on expert judgment. Most studies within the framework use participants who have been highly trained and considered to be performing at an expert level. One finding with such experts, particularly responders to emergency situations such as fire fighters or emergency room doctors, is that they choose a course of action within a short time (Klein, Calderwood, and Clinton-Cirocco, 1986). Obviously the time constraints of the situation dictate such quick responses, but more importantly these decisions are often the right decision and they occurred outside of a deliberate, analytical decision process. The responses seemed to be automatically activated by the features of the problem situation. Further, this type recognition-primed decision making is thought to underlie much of decision making by human experts.

To what extent does pilot decision making rely on recognition-primed deciding and so stress is less likely to interfere with this type of decision making than the rational-analytic method? Unfortunately, we could not find studies providing definitive answers to these questions. Stokes and Kite (1994, pp 102-111) report the results of several studies on pilots aimed at testing a decision model that integrates pattern recognition deciding with analytic strategies; unfortunately, the results were mixed.

6.7 Judgmental Heuristics

A final major framework for investigating human judgment and decision making has been defined by Kahneman, Tversky and their colleagues (Kahneman, Slovic, Tversky, 1982; Kahneman and Tversky, 1983; Tversky and Kahneman, 1974). Often referred to as judgmental heuristics, this research perspective is characterized by describing the often simplified strategies people use in making decisions and forming judgments. The basic finding is that people use simple heuristics, rather than optimal rational processes, in making decisions. A heuristic is a way of deciding that requires less mental effort from the decision maker than would be needed if a more formal process were used. Heuristics typically ease the burden of deciding by reducing the amount of information considered. For example, fewer information cues may be examined, information cues may be weighted and combined in a simplified fashion, or fewer alternatives are considered during action selection. These simplifications often produce acceptable and at times even good outcomes, but they routinely result in biases or errors that prevent optimal outcomes.

An obvious connection between the research in judgmental heuristics and decision making under stress is the common use of simplifying strategies. Are the heuristics and biases that occur in normal human judgment similar to the simplification strategies used by decision makers under stress? To our knowledge researchers within the judgmental heuristics framework have not explicitly studied the effects of stress on decision making. However, research outside of this framework does show that people change decision strategies under stress, particularly when imposed by time pressure. For example, Payne, Beuman and Johnson (1988) studied decision maker’s adaptation to changing environmental conditions in gambling decisions. They found that under time pressure decision makers accelerated their processing of information and tended to focus their attention on a subset of information available. Maule, Hockey and Bdzola (2000) found similar results with time pressure imposed on students making decisions about everyday risk scenarios. In the following sections, we briefly review some of the common judgmental heuristics, and attempt to relate them to scenarios that might occur with flight crews.

Representativeness. When predicting an unknown object's class or an event's origin, there are three types of information that should be considered for optimal performance: the base rate or prior probability of the category or process, the specific evidence presented by the object or event, and the predictive validity of this specific information. For example, when estimating the likelihood of windshear at an arrival airport, a flight crew should consider the overall likelihood of windshear at this airport, the specific weather information presented, and how predictive this specific information is to windsheer at time of arrival. A large body of research shows that when faced with decisions of this type people tend to use a judgmental heuristic called representativeness (Kahneman and Tversy, 1972). Here a judge predicts likelihood simply based on how similar (i.e., representative) the current object or event is to the category's prototypical occurrence. Both base rate information and the information's predictive validity are ignored.

In the windsheer example, a crew using representativeness would estimate the likelihood of windsheer at arrival by simply noting how similar the current conditions are to previously encountered windsheer events. Although we are not suggesting that crews do a formal probabilistic analysis for every potential windsheer occurrence, which for practical reasons would be quite impossible, it might be possible for the crew to consider at a general level the base rate likelihood of windsheer at this particular airport when making such a decision, assuming of course they had prior experience or knowledge about the frequency of windsheer at the location. Similarly, some general sense of the validity of the presented weather information could also be considered.

Availability. The availability heuristic occurs when the judged likelihood of an event is influenced by how easily instances of the event can be brought to mind (Tversky and Kahneman, 1973). For example, people tend to judge the likelihood of their being in a car accident higher after witnessing a car accident than otherwise. The recently observed accident is salient and easily remembered. The bias arises because a person's ease in recalling an event is usually not a valid index of the objective likelihood of the event's occurrence. Assume a pilot experienced a fire in an electrical panel during recurrent training the previous week. When the smell of smoke is detected in the cockpit on an actual flight, her judgment of the likelihood of an electrical panel fire will be heightened, relative to other possible events.

Anchoring. People sometimes estimate the likelihood of an event by starting with an initial value and then later adjusting this value to arrive at a final judgment. In a phenomenon known as anchoring, studies show that our final estimates of likelihood are unduly influenced by our initial judgments (Epley and Gilovich, 2006; Kassam, Koslov, and Mendes, 2009). We fail to move away from these initial estimates even when the data suggest we should. For example, on an international flight, flight attendants report to the crew a sick passenger; the crew judges the passenger's condition to be sufficiently minor so as not to require diverting the flight for medical attention. Anchoring would cause this initial judgment of low probability of need for medical attention to mitigate a subsequent estimate of the seriousness of the patient's condition, perhaps even resulting in taking no action when a diversion for medical attention was warranted.

Conservatism. Conservatism occurs when people fail to revise their probability estimate of some event enough in light of new data (Edwards, 1961). Conservatism is related to anchoring, but here the fault is not tied to an initial estimate, but rather to failing to recognize the significance of new data. Bayes' theorem provides the normative model for revising probabilities based on new, incoming information. The decision situation entails making an initial probability estimate of some event, and then subsequently receiving new information and revising the estimate. The central finding of conservatism is that people revise their estimates in the right direction but not as strongly as the data warrant. That is, the new data are not seen to be as diagnostic as they really are. Using the earlier example of windshear, a crew might estimate the likelihood of windshear at arrival at .50. Subsequently, they receive data suggesting an increased likelihood of windshear. Whereas Bayes' theorem might compute the new conditional probability at .80, the flight crew would estimate the likelihood of windshear at say .65.

Illusory Correlation. At times people perceive two variables co-varying when in fact they do not (Chapman, 1967). This idea of illusory correlation has been studied primarily in social psychology where people falsely recognize relationships between certain classes of people (e.g., race) and traits. Our propensity to see relationships between events no doubt facilitates our discovering true causal connections, but it can also lead to false positives. For example, during the course of a non-normal event a pilot might perceive evidence of an electrical problem as co-varying with a hydraulic failure when in fact the two events are independent. The hypothesized relationship between these events could lead the pilot astray in making an accurate diagnosis of the problem.

Confirmation Bias. In making decisions we sometimes form a hypothesis about the state of the world and then seek subsequent information to support our hypothesis. Such confirmatory evidence may be consistent with the hypothesis, but rarely does it prove it. In contrast, a single negative fact could disconfirm the hypothesis and thus allow us to consider other viable hypotheses. There is a strong propensity for people to seek confirmatory evidence rather than disconfirmatory evidence (Nickerson, 1998). For example, a crew may believe that a particular hydraulic system is functional and seek multiple pieces of evidence to confirm its normal operation, but none would be definitive. However, a single negative indicator might reveal that the system had indeed failed, allowing the crew to now deal effectively with the situation.

Framing Effects. There is a large body of research showing that how a problem is framed can affect people's decisions (Tversky and Kahneman, 1981). For example, people tend to be risk averse when an outcome is stated in terms of gains but risk seeking when the outcome is stated as a loss, even though formally the problems are identical. Slight changes in the wording of a problem can produce significant differences in people's estimates of event likelihood or selections of alternatives. In laboratory studies, the framing information is often manipulated along a gain/loss or positive/negative dimension. Although, to our knowledge framing effects have not been considered in flight decisions, how certain flight information is framed (e.g., from ATC or dispatch) could perhaps affect pilots' decisions.

In summary, the judgmental heuristics framework for studying human decision making has identified and described specific ways in which humans fail to carry out optimal decisions. These heuristics are general cognitive strategies or biases that reduce the cognitive effort of the decision maker and are often appropriate in everyday situations. However, the strategies may also lead to systematic errors and biases resulting in poor decisions. Obviously more research is needed to determine how often pilots use these judgmental heuristics in flight decisions and whether stress increases their use. It seems likely that when stress reduces limited cognitive resources, dependency on heuristics would increase, but this is an empirical question requiring research. To the extent that heuristics are used, airlines could incorporate them into their training to help pilots become better aware of their existence and less vulnerable to their detrimental effects.

7. Decision Making, Team Performance, and Stress

Commercial flying is undoubtedly a team effort; cockpits contain multiple crew members and others outside the cockpit (e.g., ATC, dispatch, maintenance) can contribute to crew decision making and problem solving, especially during non-normal events. The FAA (FAA, 2004) has long recognized the importance of training and assessing crews above and beyond the performance of individual pilots. Further, negligence in crew resource management (CRM) has been noted by the NTSB as probable causes of multiple accidents (NTSB, 1994). In particular, failures of decision making, communication, and coordination have been identified as leading causes. Our goal in this section of the report is to examine the performance of team decision making under acute stress. What are the specific effects of stress on team performance and what can be done to counter the deleterious effects of stress?

7.1 The Nature of Team Decision Making

We first consider how team decision making differs from decisions made by individuals. With respect to the actual decisions made there is little, if any, difference. In the cockpit, the same decisions about flying the aircraft need to be made whether an individual or crew is flying; the same environmental inputs, available alternatives, and goals exist. What does differ, however, is the added interaction among crew members. Team decision making differs fundamentally from individual decision making because of the need to communicate and coordinate activities. And to anticipate the effects of stress on team decision making, the primary hindrances to deciding seem to occur through disruptions to communication and coordination among team members.

Although our specific focus in this section of the report is on team decision making, it is worth noting that the relevant research literature rarely addresses decision making by itself but rather team performance more generally. Hence, most of the studies we review here are about team performance. This is not an issue, however, because the tasks used to study team performance are most often complex, cognitive tasks where deciding, planning, and problem solving all occur in an integrated manner.

Much of the research on teams presents specific models of team performance or decision making. These models can be helpful by identifying the specific mechanisms of deciding that are affected by stress. As discussed in an earlier section of the report, a common way of characterizing individual decision making is the information processing model. Here a decider receives inputs, carries out mental operations of encoding, storing, and retrieving information, and then finally transforms the information into an appropriate output, typically a selected action (Hogarth, 1987). Team models are most often types of information processing models.

Various models have been used to explain team performance (Salas, Cooke and Rosen, 2008), but the predominant view in the literature is shared cognition (although see Cooke et al., 2013 for a recent alternative model). Shared cognition is fundamentally a mental model and so has similarities to the information processing models of individual decision makers. The critical difference lies in its postulating states and processes corresponding to the shared activities that occur in team decision making. In addition, team mental models are sometimes assumed to have an emergent cognitive state. As a type of validation of the concept of shared cognition, research has shown that more similar mental models among team members supports team performance (e.g., Marks, Sabella, Burke, and Zaccaro, 2002; Mathieu, Heffher, Goodwin, Salas, and Cannon-Bowers, 2000).

Team members are assumed to have internal representations of the task situation, including task environment, possible actions, goals, methods for achieving those goals, and roles of teammates. To the extent that team members share similar cognitions, the coordinating and communicating of task relevant information is facilitated. The shared cognition model of team performance seems particularly relevant to tasks carried out by air crews, and evidence exists that shared models among team members aids decision making in complex task environments like flying (Klein, 1999).

Finally, Cooke, Salas, Cannon-Bowers, and Stout (2000), along with other researchers, have created methods for empirically eliciting and formally representing mental models of teams. These methods allow researchers to compare the similarity of mental models of team members, compare a team's mental model to a goal standard or referent model, and show how team models change as a function of training. These tools are important for carrying out empirically sound studies of team performance from a mental model perspective.

7.2 The Effects of Stress on Team Decision Making

The research literature on team performance clearly shows negative effects due to acute stress (e.g., Cannon-Bowers and Salas, 1998; Driskell and Salas, 1991; Driskell et al., 1999;). Earlier studies occurring within personality and social psychology showed that under acute stress team members search for and share less information, tend to neglect social and interpersonal cues, and fail to recognize situations that require interpersonal interaction (Cohen, 1980; Janis, 1982). Further, individuals find it more difficult to differentiate among people with differing areas of expertise (Rotten, Olszewski, Charleston, and Soler, 1978) and often confuse their roles and responsibilities (Torrence, 1954).

Stress hinders team performance, including decision making, primarily by disrupting communication and coordination (Driskell and Salas, 1996; Stokes and Kite, 1994). Coordinated action lies at the heart of effective team performance (Orasanu and Salas, 1993). Acute stress significantly reduces both the number of communication channels used (Gladstein and Reilly, 1985) and the likelihood that they will provide needed information to their teammates (e.g., Isen and Levin, 1972; Mathews and Canon, 1975), thus compromising their ability to retrieve and update information and coordinate its allocation to others.

Ellis (2006) examined the effects of stress on specific cognitive and behavioral mechanisms of team performance within a study of several hundred subjects engaged in a command and control simulation task. Stress was induced through time pressure and threats. He investigated the effects of stress on both team mental models and team member's transactive memory, which is knowledge about other member's specializations, ability to work together efficiently, and reliability of knowledge and skill. Team interaction mental models primarily serve to integrate team members' perceptions, while transactive memory primarily serves to capitalize on differences among team members' roles and responsibilities. Ellis found that both mental models and transactive memory suffered from acute stress, and argued that these components represent the cognitive and behavioral mechanisms through which acute stress affects team performance.

7.3 Ways of Decreasing the Stress Effects on Team Performance

Here we examine studies that have attempted to ameliorate the negative effects of stress on team performance and decision making more specifically. One widely touted method for improving team performance under stress is cross-training, essentially the idea of teaching team members about the duties and responsibilities of their teammates. Cross training assumes that knowing another's roles and understanding how one's own tasks and responsibilities relate to others, will improve communication and coordination. The method acts primarily through improving communication and coordination, and its effectiveness seems to be maximized under periods of high stress. There is now considerable research supporting the benefits of cross-training on team performance.

Cannon-Bowers, Salas, and Volpe (1996) investigated cross-training on team performance in a flight simulation with two pilots engaged in an air combat task. They found that teams given cross-training were rated higher on teamwork processes, used more efficient communication strategies, and achieved better task performance, than control teams not receiving cross-training. The study manipulated world-load, which indirectly affected stress. The researchers hypothesized that cross training would be more beneficial under high than low workload. Although their hypothesis was not supported, the authors noted that even the low workload condition was quite demanding, and so the difference between the two conditions was most likely insufficient to allow for an interaction to occur.

In a related follow-up study, Blickensderfer, Bowers, Cannon-Bowers, and Salas (1998) used a three-person command and control simulation task to investigate the benefits of cross training. They found that cross-trained teams were rated higher on teamwork processes, volunteered more information to teammates, and achieved higher task performance scores than teams without cross training. And now with a stronger manipulation of workload, they did find that the benefit of cross training was significantly higher under high than low workload. Further, their research design allowed them to identify the mechanism by which cross-training improved team performance. Here they concluded that cross-trained teams used implicit strategies that allowed better team communication and coordination, and this was particularly true under severe task demands.

Entin and Serfaty (1999) studied naval officers performing a realistic command and control task under conditions of high stress. They found that teams given adaptation and coordination training performed significantly better than control teams, and the advantage was greatest under conditions of high stress. Training consisted of adapting to high stress situations by shifting from explicit to implicit modes of coordination. Implicit coordination required team members to use shared mental models of their teammates. Team members who knew about the mental models of others could fulfill their teammate's requirements before explicit requests were made. The authors concluded that the implicit coordination of actions became more efficient and thus reduced communication and coordination overhead.

Coordination generally refers to the sequencing and timing of events, managing workload, and exchanging information with other team members. Communication and coordination go hand in hand, and these two processes are often treated together as an integrated unit in research on team performance. Coordination and communication processes are central to team decision making. Hence, not only is cross-training beneficial to team performance generally, its advantages occur through processes that are instrumental in decision making.

Marks et al. (2002) examined the specific role of coordination in cross-training using a three person team operating a simulated Apache attack helicopter. Participants were naïve college students. The effects of cross training were evident in higher levels of shared team-interaction knowledge and better overall task performance for cross trained compared to a control team. A significant correlation was found between team performance and coordination processes, and further regression analyses showed that coordination served to mediate the relationship between shared mental models and team performance.

More recently, Gorman, Cooke and Amazeen (2010) investigated a new type of training to aid team performance. Perturbation training has its roots in motor and verbal learning where it has been shown that varying practice conditions during learning results in better subsequent performance especially when the learner is faced with novel or difficult conditions. Presumably the varied practiced conditions create more elaborate encoding and retrieval processes, which in turn benefits later performance. Gorman, et al. extended perturbation to team processes by perturbing team coordination activities, requiring team members to accommodate to the changes.

Gorman, et al. had three-person crews fly an uninhabited air vehicle simulator to photograph stationary ground targets. A total of 32 teams were randomly assigned to cross training, procedural training, or perturbation training. Task performance was a composite of number of missed targets, time to process targets, and time spent on warnings and alarms. The results showed that teams trained with perturbation training performed better under novel situations than either cross-trained or procedurally trained teams, but cross-trained teams performed significantly better on a measure of shared knowledge. The researchers concluded that perturbation training allowed teams to better respond to actual task demands of changing requirements for team coordination, and that it will likely produce more adaptive teams in novel, real-world settings.

Grote, Kolbe, Zala-Mezö, Bienefeld-Seall, and Künzle (2010) investigated team performance from the perspective of organization theory. Their study aimed specifically at examining the relationship between heedful interrelating and task load. Heedful interrelating occurs when all team members make deliberate efforts to reconsider the effects of their actions on current goals. It purportedly helps teams to adapt to novel situations by breaking away from stereotypical or highly-learned responses (Gersick and Hackman, 1990).

Grote et al.'s study consisted of 42 A320 flight crews, returning for recurrent training, performing a predefined flight scenario requiring the execution of a clean approach. Various measures of performance were obtained including team coordination (both implicit and explicit) and actual performance on the maneuver graded on a 1 to 6 scale.

The results indicated that heedfulness training was generally effective in producing better team processes, and under certain conditions improved actual task performance. Crews given heedfulness training adapted their coordination processes in response to increased task load, however under high levels of standardization, implicit coordination increased and heedfulness interrelating decreased. Assuming that heedful interrelating requires a certain amount of shared cognition, the study's results also relate to research showing the relevance of shared mental models for team performance (Salas et al. 2005, Burke et al. 2006).

7.4 Summary of Decision Making and Stress

Research clearly shows that acute stress disrupts processes underlying team performance, primarily through affecting communication and coordination, and so reduces actual task performance. Studies have used tasks that are for the most part complex and realistic, such as simulations of military command and control or flight simulators, and participants have been either experts in the field or students undergoing training in the field. The tasks have been complex and cognitively demanding and generally included numerous subtasks that would fall into the category of decision making. On occasion, subjects are college students engaged in PC based task simulations. Acute stress has most often been manipulated by task difficulty, time pressure, increased workload of secondary task elements, and threats. The stress manipulations are typically validated through observing overall decreased task performance in high stress conditions, post study self-ratings of stress by participants, or on occasion by physiological measures such as cortisol.

Most of the research investigating stress and team performance has not been focused simply on demonstrating how and when stress affects team performance, but rather on examining methods for reducing the negative effects of stress. In a nutshell, the results of these studies have been encouraging showing that teams can be trained to better adapt to the difficulties that arise during stressful situations.

These studies most often examined specialized training that focused on helping members better communicate and coordinate during novel situations that occurred during times of high stress. Often these training methods were couched within a theoretical framework of team mental models such as shared cognition. Cross-training and perturbation training have both been shown to be effective at reducing the deleterious effects of stress on team performance. It is particularly encouraging to see that their benefits occur primarily during times of high stress. These and other methods aimed at helping teams adapt to stress, such as heedful training, could be implemented in real-world contexts such as commercial aviation.

In complex tasks with a potential for high risk, such as commercial flying, training typically focuses on the execution of routine tasks using standardized operating procedures. Crews are trained until their execution of standardized tasks occurs flawlessly, or at least close to it. Performance on routine tasks becomes automatized. This type of procedural training to perfection makes perfect sense given the importance of executing these tasks at a high level of performance. And even for some non-normal tasks deemed more probable (e.g., rejected takeoffs, v1 cuts) a similar level of training is required. High level of standardization achieved through procedural training has been the core element of the remarkable safety record that exist today in high risk environments such as commercial flying.

However, it is now clear from the research on stress and team performance that this type of procedural training does not prepare crews well for the novel situations that occur during truly non-normal events. The acute stress that often co-occurs during unexpected, difficult-to-manage events disrupts team processes, particularly communication and coordination, resulting in poor task performance.

Airlines operating under AQP have a mandate to carry out some form of CRM training. However the extent and scope of this training varies greatly and is under the airline’s discretion. Further, there is a necessary tension between normal procedural training and training aimed at preparing pilots for the type of non-normal event that will most likely never occur during their careers. Although there is ample empirical evidence showing the effectiveness of training crews to adapt to the stress of unexpected events, the contingencies for allocating more training resources to prepare crews to for highly improbable non-normal events are simply not in place.

8. Naturalistic Studies

Investigators have taken advantage of real-world situations in which individuals are exposed to stressors, including physical danger, to study stress reactions. Reid (1948) extracted data on errors in wind calculation by navigators on WWII bombing missions and found errors increased during operational segments of flights, reaching a maximum during enemy opposition. As mentioned previously, Hammerton and Tickner (1968) found that trainee parachutists performed a visual tracking task more poorly shortly before a jump, presumably due to anxiety. Performance by experienced parachutists did not show this impairment.

Weltman et al. (1971, previously discussed) used simulated dives in a pressure chamber to induce anxiety in novice divers, and found narrowed spatial attention. Mears and Cleary (1980) collected physiological data from experienced Scuba divers and measured performance on the Raven Progressive Matrices, a test of reasoning ability, during shallow (6 m) and deep (30) dives. Anxiety was assessed on a standard scale after the dives. Anxiety and heart rate decreased during shallow dives but increased during deep dives, and cognitive performance decreased on the deep dives. Several studies have examined the effects of military survival, escape and evasion training and similar exercises on cognitive performance. These studies must be interpreted cautiously because the training combines prolonged physical demand, sleep deprivation, and fatigue with emotional stress, but they are worth discussing because investigators have used informative cognitive test batteries.

Lieberman, Bathalon, Falco, Georgelis, Morgan, Niro, and Tharion (2002) reported two studies of demanding military exercises and found reaction time, vigilance, memory, and logical reasoning impaired relative to individuals' baselines shortly after the training. The degree of impairment was greater than alcohol intoxication. Morgan, Hazlett, Wang, Richardson, Schnurr, and Southwick (2001) reported increased evidence of dissociative symptoms (from an inventory scale) after similar training. Harris, Hancock, and Harris (2005) administered cognitive batteries after week-long Navy survival training, and found no impairment on the first few trials of the batteries. However, on later trials, seconds into testing, trainees showed impairments in reaction time, information manipulation, and logical reasoning. Apparently, they could maintain performance only for very brief periods. Trainees reported difficulty concentrating.

Morgan, Doran, Steffian, Hazlett, and Southwick (2006) had special operations soldiers undergoing survival school perform the Rey Ostereith Complex Figure (POCF) test while they were confined in a mock POW camp, 15 min. after a grueling interrogation. The POCF requires participants to copy a very complex figure of many line segments and to try to re-draw it from memory later. Compared to pre-stress and post-stress soldiers and to POCF norms the stressed soldiers' copy of the POCF was substantially altered; copying was piecemeal, resembling the copying done by children rather than the gestalt approach taken by adults. This suggests impaired ability to integrate visual information. Recall of the ROCF one minute later was also reduced, suggesting impaired working memory.

From these few naturalistic studies one may tentatively conclude that anxiety does increase with perception of danger, though this may be tempered by experience, and that this anxiety may impair performance of simple tasks such as visual tracking and may undermine logical reasoning. Extreme conditions in which emotional stress is combined with prolonged physical challenge substantially impair many aspects of cognitive functioning, especially if functioning has to be sustained. Non-normal situations in commercial aviation do not place such extreme demands on pilots, thus we cannot conclude whether danger, workload, and uncertainty are in themselves sufficient to produce such a broad spectrum of deficits.

9. Stress Management Training

Stress impairment of performance can be reduced through training designed to help individuals understand and cope with the effects of stress. Driscoll and colleagues (Driskell and Johnston, 1998; Driskell, Salas and Johnston, 2006) have developed a general approach, *stress exposure training,* that can be adapted to various training environments[12]. It consists of three phases: (1) preparatory information, in which trainees are given information about the physiological and emotional experiences they are likely to encounter during stress and how their performance may be affected; (2) skill training, in which trainees are told how to maintain performance under stress; and (3) application, in which trainees practice performing under stress. The specific content of the phases is tailored to the particular type of work performed and the nature of particular stressful situations.

Stress exposure training has been shown to reduce stress impairment of performance of both simple laboratory tasks (Driskell, Johnston and Salas, 2001) and more complex tasks, such as team performance (Johnston, Driskell, and Salas, 1997). Driskell et al. (2001) reported that this training generalized from one type of laboratory stressor to another and from a trained task to an untrained task, however this result must be interpreted with caution because in both tasks the stress-coping skill required was simply to ignore distraction from the stressor (noise or time pressure).

Stress exposure training has not, to our knowledge, been tested with experienced pilots, but two studies examined its effect on inexperienced or trainee pilots. McClernon, McCauley, O'Connor, and Warm (2011) gave a treatment group participants without flight experience brief instructions on avoiding distraction from stress: Maintain normal breathing, focus on the task at hand, and focus on flight performance parameters. This group then practiced a basic flight maneuver in a simulator for 10 minutes while their left foot was immersed in cold water. The control group, which did not receive the stress training and performed the same flight maneuver without the cold pressor. When tested in an actual aircraft and performing the same basic maneuver, the treatment group performed the maneuver more precisely than did the control group.

Fornette, Bardel, Lefrancois, Fradin, Massiouri, and Amalberti (2012) gave much more extensive cognitive adaptation training (six two-hour sessions) to a group of military pilot cadets. This training emphasis metacognitive reflection upon how one manages emotional situations such as stress. In the treatment group, cadets who had performed below average in initial flight training improved their flight performance during the remainder of their flight training, but cadets initially above average and cadets in the control group did not improve. Although suggestive, this study suffers from a methodological flaw: The control group did not receive any intervention at all; thus the improvement may have resulted from a Hawthorne effect (non-specific intervention).

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[12] For a meta-analysis of the broader area of stress management training techniques see Saunders, Driskell, Johnston, and Salas (1996).

Taken together, the stress management training literature suggests it might be worthwhile to adapt it to the training of experienced pilots and study its potential. It could be used, for example, with CRM and Line Oriented Flight Training (LOFT). The preparatory phase might inform aircrew about the physiological affects they may experience under stress (e.g., elevated heart rate, rapid breathing,), emotional effects (e.g., anxiety), cognitive effects (e.g., narrowed attention, confusion), and team effects (e.g., impaired communication). This information would help the crewmembers to be prepared for these effects, to reduce distraction from these effects, and to be alert for alterations in their performance.

The skill-training phase could provide specific techniques such as making communications more explicit and periodic review of what the crew members understand about an emergency situation. Then, a challenging non-normal situation could be presented in the realistic LOFT flight simulation (as is sometimes done anyway).

10. Summary and Conclusions

We have reviewed a fairly extensive research literature on how stress affects human performance, particularly cognitive performance. Our specific interest was with the type of stress that commercial pilots might encounter during a flight emergency or under severely challenging 'normal' operations. In these situations, pilots, who are highly trained and skilled operators, may experience substantial acute stress while performing complex, demanding cognitive tasks under conditions in which errors can have drastic consequences. Unfortunately, none of the stress studies we were able to find was performed under these exact conditions. Consequently, our conclusions regarding stress effects on pilots were derived in part through inference or speculation from the studies that were available.

Much of the stress research suffers from methodological weaknesses. Most studies used laboratory situations with relatively naïve subjects performing rather simple tasks. Stress was artificially induced by manipulating a task characteristic (e.g., difficulty level or time pressure), environmental factor (e.g., noise), or social situation (e.g., embarrassment). The nature and intensity of these stressors was much less than the level of stress encountered in life-threatening emergencies. Further, researchers often failed to validate the physiological and psychological effectiveness of the stressor or failed to consider that the stress induction could influence task performance in ways separate from stress per se. Although there were a few naturalistic studies of stress on performance, they rarely approximated our intended piloting situation. Nevertheless, some general conclusions can be derived from these diverse studies.

Research showed that stress negatively affects some of the core cognitive mechanisms of attention and memory. With respect to attention, stress can decreases people's ability to (a) manage and distribute their attention as a function of task requirements, (b) prioritize and direct attention among competing task demands, (c) manage multiple tasks concurrently, and (d) perform normal perceptual scanning of environmental cues. Stress affects memory by decreasing working memory storage and processing capacity and inhibiting retrieval of declarative information. However, long-term procedural memory (e.g., motor schemas) may be less affected by stress. We remind the reader that these conclusions are largely, though not entirely, based on studies using naïve participants performing simple tasks. Research is needed to determine to what extent similar effects occur with experts performing practiced tasks.

Research on stress effects on higher-order cognitive processes, such as decision making, also shows general decrements in performance both at the individual level and team or crew level. (Some of these studies did use experienced teams.) Stress causes decision makers to be more disorganized in their scanning and evaluating of alternatives and to consider fewer alternatives when deciding. Acute stress disrupts processes underlying team performance, primarily through undercutting communication and coordination, and so reduces overall task performance. Under stress, team members search for and share less information, tend to neglect social and interpersonal cues, and fail to recognize situations that require interpersonal interaction.

These findings show that stress degrades human performance in many ways, and we now know some specific cognitive structures and processes that are disrupted. During emergency and other highly challenging situations pilots may be cognitively impaired so that they are less able to seek out information, process and assess it; manage concurrent tasks, recall facts from memory, and communicate and coordinate with other crew members.

This is not to say that one should expect experienced pilots to fall apart when experiencing a life-threatening emergency; on the contrary, pilots have often shown remarkable ability to manage such situations, though not always successfully. The highly practiced skills of experienced pilots provide considerable protection in such situations; nevertheless, given the extreme demands of some emergencies and the inherent vulnerability of some aspects of cognition to stress, it is crucial to devise countermeasures to the effects of stress. Some success has already been demonstrated in using stress exposure training to fortify performance of individuals and teams. Other countermeasures could be implemented in the design of cockpit interfaces, training, and operating procedures, based on what we now know about the specific ways stress affects cognitive processes. In particular, designers should consider that cognitive capabilities of pilots under stress are likely to be impaired, thus performance should be supported by measures to reduce workload, to prompt pilots to perform required tasks, to help them keep track of where they are in a procedure or checklist, to shift attention among tasks without becoming locked into just one task, to maintain situation awareness, to identify and analyze decision options, and—perhaps most important—to step back mentally from the moment-to-moment demands of the flight situation to establish a high-level (meta-cognitive) mental model that guides action as the situation unfolds. However empirical research using experienced pilots and realistic challenging flight situations is required to develop such countermeasures that will be both practical and effective.

In a follow-up to this report we will examine commercial aviation accident reports to explore how the cognitive effects of stress manifested in laboratory settings may affect pilot performance in real-world situations.

References

Al'Absi, M., Hugdahl, K., and Lovallo, W. R. (2002). Adrenocortical stress responses and altered working memory performance. *Psychophysiology, 39,* 95–99.

Arkes, H. R and Hammond, K. R. (1986). *Judgment and decision making: An interdisciplinary reader*. Cambridge University Press: London.

Ashcraft, M. H. (2002). Math anxiety: Personal, educational, and cognitive consequences. *Current Directions in Psychological Science, 11,* 181–185.

Ashcraft, M. H., and Kirk, E. P. (2001). The relationships among working memory, math anxiety, and performance. *Journal of Experimental Psychology: General, 130*, 224–237.

Bacon, S. J. (1974). Arousal and range of cue utilization. *Journal of Experimental Psychology, 102*(1), 81-87.

Baddeley, A.D. (1972). Selective attention and performance in dangerous environments. *British Journal of Psychology, 63*(4), 537–546.

Baddeley, A. D. (1986). *Working Memory*. Oxford, U.K.: Oxford University Press.

Bearman, C., Paletz, S. B. F., Orasanu, J., and Thomas, M. J. W. (2010). The breakdown of coordinated decision making in distributed systems. *Human Factors, 52*, 173-188.

Beilock, S. L. (2008). Math performance in stressful situations. *Current Directions In Psychological Science, 17*(5), 339-343.

Biondi, M., and Picardi, A. (1999). Psychological stress and neuroendocrine function in humans: the last two decades of research. *Psychotherapy and Psychosomatics, 68,* 114-150.

Blickensderfer, E., Bowers, C. A., Cannon-Bowers, J. A., and Salas, E. (1998). Impact of cross-training and workload on team functioning: A replication and extension of initial findings. *Human Factors, 40*, 92–101.

Braunstein-Bercovitz, H. (2003). Does stress enhance or impair selective attention? The effects of stress and perceptual load on negative priming. *Anxiety, Stress, and Coping, 16*(4), 345–357.

Burke, C. S., Stagl, K. C., Klein, C., Goodwin, G. F., Salas, E., and Halpin, S. M. (2006). What type of leadership behaviors are functional in teams? *The Leadership Quarterly, 17,* 288-307.

Cannon-Bowers, J. A., and Salas, E. (1998). *Making decisions under stress: Implications for individual and team training*. Washington, DC: American Psychological Association.

Cannon-Bowers, J. A., Salas, E., and Volpe, C. E. (1996). The impact of cross-training on team functioning: An empirical investigation. *Human Factors, 38*, 87–100.

Chajut, E., and Algom, D. (2003). Selective attention improves under stress: Implications for theories of social cognition. *Journal of Personality and Social Psychology, 85*(2), 231–248.

Chapman, L. J. (1967). Illusory correlation in observation report. *Journal of Verbal Learning and Verbal Behavior, 6,* 151-155.

Chase, W.G.; Simon, Herbert A. (1973). Perception in chess. *Cognitive Psychology 4*: 55–81.

Cohen, S. (1980). Aftereffects of stress on human performance and social behavior: A review of research and theory. *Psychological Bulletin, 88,* 82–108.

Conway, A. R. A., Jarrold, C., and Kane, M. J. (2007). *Variation in working memory*. New York, NY, US: Oxford University Press.

Cooke, N. J., Gorman, J. C., Myers, C. W., and Duran, J. L. (2013). Interactive team cognition. *Cognitive Science, 37*(2), 255-285.

Cooke, N. J., Salas, E., Cannon-Bowers, J. A., and Stout, R. J. (2000). Measuring team knowledge. *Human Factors, 42,* 151-173.

Cowan, N. (1997). The development of working memory. In N. Cowan (Ed.) , *The development of memory in childhood* (pp. 163-199). Hove England: Psychology Press/Erlbaum (UK) Taylor and Francis.

de Quervain, D. J.-F., Roozendaal, B., Nitsch, R. M., McGaugh, J. L., and Hock, C. (2000). Acute cortisone administration impairs retrieval of long-term declarative memory in humans. *Nature Neuroscience, 3*, 313–314.

Dijksterhuis, A., and Aarts, H. (2003). On wildebeests and humans: The preferential detection of negative stimuli. *Psychological Science, 14*(1), 14–18.

Dismukes, R. (2012). Prospective memory in workplace and everyday situations. *Current Directions In Psychological Science, 21*(4), 215-220.

Driskell, J. E., and Johnston, J. (1998). Stress exposure training. In J.A. Cannon-Bowers, and E. Salas (Eds.), *Making decisions under stress*. Washington, D.C.: American Psychological Association.

Driskell, J. E., Johnston, J., and Salas, E. (2001). Does stress training generalize to novel settings? *Human Factors, 43*(1), 99-110.

Driskell, J. E., and Salas, E. (1991). Group decision making under stress. *Journal of Applied Psychology, 76*, 473-478.

Driskell, J. E., and Salas, E. (1996). *Stress and human performance*. Mahwah, NJ: L. Erlbaum.

Driskell, J. E., Salas, E., and Johnston, J. (1999). Does stress lead to a loss of team perspective? *Group Dynamics: Theory, Research, and Practice, 3*, 291-302.

Driskell, J. E., Salas, E., and Johnston, J. H. (2006). Decision Making and Performance under Stress. In T. W. Britt, C. Castro, A. B. Adler (Eds.) , *Military life: The psychology of serving in peace and combat (Vol. 1): Military performance* (pp. 128-154). Westport, CT: Praeger Security International.

Easterbrook, J. A. (1959). The effect of emotion on cue utilization and the organization of behavior. *Psychological Review, 66,* 187–201.

Edwards, W. (1961). Behavioral decision theory. *Annual Review of Psychology, 12,* 473-498.

Edwards, W. and Fasolo, B. (2001). Decision technology. *Annual Review of Psychology, 52*, 581-606.

Einhorm, H. J. and Hogarth, R. M. (1981). Behavioral decision theory: Processes of judgment and choice. *Annual Review of Psychology, 32,* 53-58.

Ellis, A. P. (2006). System breakdown: The role of mental models and transactive memory in the relationship between acute stress and team performance. *Academy of Management Journal, 49,* 576-589.

Engle, R. W. (2002). Working memory capacity as executive attention. *Current Directions in Psychological Science, 11*, 19-23.

Entin, E. E., and Serfaty, D. (1999). Adaptive team coordination. Human Factors, 41, 312-325.

Epley, N. and Gilovich, T. (2006). The anchoring-and-adjustment heuristic: Why the adjustments are insufficient. *Psychological Science, 17*, 311-318.

Ericsson, K. A. and Charness, N. (1994). Expert performance: Its structure and acquisition. *American Psychologist, 49*, 725-747.

Ericsson, K. A., and Delaney, P. F. (1999). Long-term working memory as an alternative to capacity models of working memory in everyday skilled performance. In A.Miyake, and P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 257–297). New York: Cambridge University Press.

Eysenck, M. W. (1976). *Arousal, learning, and memory*. Psychological Bulletin, 83(3), 389-404.

Eysenck, M. W. (1997). *Anxiety and Cognition: A unified theory*. Hove, UK: Psychology Press.

Eysenck, M. W., and Calvo, M. G. (1992). Anxiety and performance: The processing efficiency theory. *Cognition and Emotion, 6*, 409–434.

Federal Aviation Administration (2004). *Crew resource management training*. Advisory Circular 120-51E.

Fornette, M., Bardel, M. Lefrançois,C., Fradin, J., Massioui, F., and Amalberti, R. (2012). Cognitive-adaptation training for improving performance and stress management of air force pilots. *The International Journal of Aviation Psychology, 22*, 203-223.

Foushee, H. C. (1984). Dyads and triads at 35,000 feet: Factors affecting group process and aircrew performance. *American Psychologist, 39*, 885-893.

Gersick, C. J., and Hackman, J. (1990). Habitual routines in task-performing groups. *Organizational Behavior and Human Decision Processes, 47*(1), 65-97.

Gigerenzer, G and Gaissmaier, W. (2011). Heuristic decision making. *Annual Review of Psychology., 62*, 451–482.

Gladstein, D. L., and Reilly, N. P. (1985). Group decision making under threat: The tycoon game. *Academy of Management Journal, 28,* 613–627.

Gorman, J. C., Cooke, N. J., and Amazeen, P. G. (2010). Training adaptive teams. *Human Factors, 52,* 295-307.

Grote, G., Kolbe, M., Zala-Mezö, E., Bienefeld-Seall, N., and Künzle, B. (2010). Adaptive coordination and heedfulness make better cockpit crews. *Ergonomics, 53,* 211-228.

Hamilton, V., and Warburton, D. M. (1979). *Human stress and cognition: An information processing approach*. New York: John Wiley and Sons.

Hammerton, M., and Tickner, A.H. (1968). An investigation into the effects of stress upon skilled performance. *Ergonomics, 12,* 851–855.

Hancock, P. A. (1986). The effect of skill on performance under an environmental stressor. *Aviation, Space, And Environmental Medicine, 57*(1), 59-64.

Hancock, P. A., and Desmond, P. A. (2001) *Stress, workload, and fatigue*. Mahwah, NJ: L. Erlbaum.

Harris, W. C., Hancock, P. A., Harris, S. C. (2005). Information processing changes following extended stress. *Military Psychology, 17(2),* 115-128.

Hastie, R. (2001). Problems for judgment and decision making. *Annual Review of Psychology, 52,* 653-683.

Het, S. S., Ramlow, G. G., and Wolf, O. T. (2005). A meta-analytic review of the effects of acute cortisol administration on human memory. *Psychoneuroendocrinology, 30(8),* 771-784.

Hockey, G. R. J. (1970a). Effect of loud noise on attentional selectivity. Quarterly *Journal of Experimental Psychology, 22*, 28-36.

Hockey, G. R. J. (1970b). Changes in attention allocation in a multicomponent task under loss of sleep. *British Journal of Psychology, 61(4),* 473-480.

Hockey, G. R. J. (1979). Stress and the cognitive components of skilled performance. (pp. 141–177) In V. Hamilton and D. M. Warburton (Eds.) *Human stress and cognition: An information processing approach*. New York: John Wiley and Sons.

Hockey, G. R. J. (1986). Changes in operator efficiency as a function of environmental stress, fatigue, and circadian rhythms. In K. R. Boff, L. Kaufman, and J. P. Thomas (Eds.), *Handbook of perception and human performance,* Vol. 2: Cognitive processes and performance. (pp. 1-49). Oxford, England: John Wiley and Sons.

Hogarth, R. M. (1987). *Judgment and Choice: The Psychology of Decision*. Wiley and Sons, New York, NY.

Houston, B.K. (1969). Noise, task difficulty, and Stroop color-word performance. *Journal of Experimental Psychology, 82*, 403–404.

Hu, K., Bauer, A., Padmala, S., and Pessoa, L. (2012). Threat of bodily harm has opposing effects on cognition. *Emotion, 12(1),* 28-32.

Ilgen, D. R., Hollenbeck, J. R., Johnson, M., and Jundt, D. (2005). Teams in organizations: From I-P-0 Models to IMOI models. In S. T. Fiske, A. E. Kasdin, and D. L. Schacter (Eds.), *Annual review of psychology,* vol. 56: 517-543. Palo Alto, CA: Annual Reviews.

Isen, A. M., and Levin, A. F. (1972). Effect of feeling good on helping: Cookies and kindness. *Journal of Personality and Social Psychology, 21*, 384–388.

Janis, I. L., (1982). *Groupthink* (2nd ed.). Boston: Houghton Mifflin.

Janis, I. L., and Mann, L. (1977*). Decision making: A psychological analysis of conflict, choice, and commitment*. New York, NY: Free Press.

Johnston, J. H., Driskell, J. E., and Salas, E. (1997). Vigilant and hypervigilant decision making. *Journal of Applied Psychology, 82(4),* 614-622.

Johnson, D. R., and Gronlund, S. D. (2009). Individuals lower in working memory capacity are particularly vulnerable to anxiety's disruptive effect on performance. *Anxiety, Stress and Coping, 22(2),* 201-213.

Kahneman, D. (1973). *Attention and effort*. Englewood Cliff, NJ: Prentice-Hall.

Kahneman, D., Slovic, P. and Tversky, A. (1982). *Judgment under uncertainty: Heuristics and biases*. Cambridge University Press, London.

Kahneman, D., and Tversky, A. (1972). On prediction and judgment. *ORI Reserch Monograph, 12(4)*. (10)(a).

Kahneman, D., and Tversky, A. (1973). On the psychology of prediction. *Psychological Review, 80,* 237-251.

Kane, M.J., and Engle, R.W. (2000). Working memory capacity, proactive interference, and divided attention: Limits on long-term memory retrieval. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 26,* 336–358.

Kane, M. J., and Engle, R. W. (2002). The role of prefrontal cortex in working-memory capacity, executive attention, and general fluid intelligence: An individual differences perspective. *Psychonomic Bulletin and Review, 9,* 637-671.

Kassam, K. S., Koslov, K. and Mendes, W. B. (2009). Decisions under distress: Stress profiles influence anchoring and adjustment. *Psychological science, 20,* 1394-1399.

Keinan, G. (1987). Decision making under stress: scanning of alternatives under controllable and uncontrollable threats. *Journal of Personality and Social Psychology, 52,* 639-644.

Keinan, G., Friedland, N., Kahneman, D, and Roth, D. (1999). The effect of stress on the suppression of erroneous competing responses. *Anxiety, Stress, and Coping: An International Journal, 12,* 455–476.

Klein, G. (1999). *Sources of power: How people make decisions*. Cambridge, MA: MIT Press.

Klein, G. (2000). Naturalistic decision making. *Human Factors, 50,* 456–460.

Klein, G. A., Calderwood, R., and Clinton-Cirocco, A. (1986). Rapid decision making on the fireground. *Proceedings of the Human Factors and Ergonomics Society 30th Annual Meeting, 1,* 576–580.

Klein, G., Orasanu, J. M., Calderwood, R., and Zsambok, C. E. (Eds.). (1993). *Decision making in action: Models and methods*. Norwood, NJ: Ablex.

Kochan, J.A., Breiter, E.G., and Jentsch, F. (2004). Surprise and unexpectedness in flying: Database reviews and analyses. *In Proceedings of the Human Factors and Ergonomics Society 48th Annual Meeting*. New Orleans, LA: Human Factors and Ergonomics Society.

Lazarus, R.S., and Folkman, S. (1984). *Stress, appraisal, and coping*. New York: Springer.

Lieberman, H.R., Bathalon, G.P., Falco, C.M, Georgelis, J.H., Morgan, C.A., Niro, P., and Tharion, W.J. (2002). The "fog of war": Documenting cognitive decrements associated with the stress of combat. In the *Proceedings of the 23rd Army Science Conference, December*.

Lieberman, H. R., Bathalon, G. P., Falco, C. M., Morgan, C. A., III, and Niro, P. (2005). Severe decrements in cognition function and mood induced by sleep loss, heat, dehydration, and undernutrition during simulated combat. *Biological Psychiatry, 57(4),* 422-429.

Lipshitsz, R, Klein, G, Orasanu, J., and Salas, E. (2001). Taking Stock of Naturalistic Decision Making. *Journal of Behavioral Decision Making, 14*: 331-352.

Loftus, E. F., Loftus, G. R., and Messo, J. (1987). Some facts about 'weapon focus'. *Law and Human Behavior, 11(1),* 55-62.

Loukopoulos, L.D., Dismukes, R.K., and Barshi, I. (2009). *The Multitasking Myth: Handling Complexity in Real-World Operations*. Aldershot, U.K.: Ashgate.

Luethi, M., Meier, B., and Sandi, C. (2009). Stress effects on working memory, explicit memory, and implicit memory for neutral and emotional stimuli in healthy men. *Frontiers In Behavioral Neuroscience, 2(5),* 1-9.

Lupien, S.J., Gillin, C.J., and Hauger, R.L. (1999). Working memory is more sensitive than declarative memory to the acute effects of corticosteroids: A dose-response study in humans. *Behavioral Neuroscience, 113(3),* 420–430.

McClernon, C. K., McCauley, M. E., O'Connor, P. E., and Warm, J. S. (2011). Stress training improves performance during a stressful flight. *Human Factors, 53(3),* 207-218.

Marks, M. A., Sabella, M. J., Burke, C. S., and Zaccaro, S. J. (2002). The impact of cross training on team effectiveness. Journal of *Applied Psychology, 87*, 3-13.

Mather, M, and Lighthall, N. R. (2012). Risk and Reward Are Processed Differently in Decisions Made Under Stress. *Current Directions in Psychological Science, 21*: 36-41.

Mathieu, J. E., Heffher, T. S., Goodwin, G. F., Salas, E., and Cannon-Bowers, J. A. (2000). The influence of shared mental models on team process and performance. *Journal of Applied Psychology, 85,* 273-283.

Matthews, K. E., and Canon, L. K. (1975). Environmental noise level as a determinant of helping behavior. *Journal of Personality and Social Psychology, 32*, 571–577.

Matthews, G, Sparkes, T. J., and Bygrave, H. M. (1996). Attentional overload, stress, and simulated driving performance. *Human Performance, 9,* 77–101.

Maule, A. J., Hockey, G. R., and Bdzola, L. (2000). Effects of time-pressure on decision –making under uncertainty: changes in affective state and information processing strategy. *Acta Psychologica, 104,* 283-301.

Mears, J.D., and Cleary, P.J. (1980). Anxiety as a factor in underwater performance. *Ergonomics, 23(6),* 549–557.

Mellers, B. A, Schwartz, A., and Cooke, A.D.J. (1988). Judgment and decision making. Annual *Review of Psychology, 49,* 447-477.

Morelli, F., and Burton, P. A. (2009). The impact of induced stress upon selective attention in multiple object tracking. *Military Psychology, 21(1),* 81-97.

Morgan, C., Doran, A., Steffian, G., Hazlett, G., and Southwick, S. M. (2006). Stress-induced deficits in working memory and visuo-constructive abilities in special operations soldiers. *Biological Psychiatry, 60(7),* 722-729.

Morgan, C., Hazlett, G., Wang, S., Richardson, E. r., Schnurr, P., and Southwick, S. M. (2001). Symptoms of dissociation in humans experiencing acute, uncontrollable stress: A prospective investigation. *The American Journal Of Psychiatry, 158(8),* 1239-1247.

National Transportation Safety Board. (1994*). A review of flight crew-involved major accidents of US air carriers 1978 through 1990.*

Newcomer, J.W., Selke, G., Melson, A. K., Hershey, T., Craft, S., Richards, K., and Alderson, A. L. (1999). Decreased memory performance in healthy humans induced by stress-level cortisol treatment. *Archives of General Psychiatry, 56,* 527–533.

Nickerson, R. S. (1988). Confirmation bias: A ubiquitous phenomenon in many guises. *Review of General Psychology, 2*, 175-220.

Orasanu, J. M. (1993). Decision making in the cockpit. In E. Wiener, B. Kanki, and R. Helmreich (Eds.), *Cockpit resource management* (pp. 137-172). San Diego, CA: Academic Press.

Orasanu, J. M., and Salas, E. (1993). Team decision making in complex environments. In G. A. Salas, E., Driskell, J. E., and Hughes, S. 1996. Introduction: The study of stress and human performance. In J. E. Driskell and E. Salas (Eds.), *Stress and human performance: 1-46*. Mahwah, NJ: Erlbaum.

Payne, J. W . , Beuman, J. R . , Johnson, E. J . (1988) . Adaptive strategy selection in decision making. *Journal of Experimental Psychology: Learning, Memory and Cognition, 14,* 534-552.

Pitz, G. F. and Sachs, N. J. (1984). Judgment and decision: Theory and practice. *Annual Review of Psychology, 35,* 139-163.

Plessow, F., Schade, S., Kirschbaum, C., and Fischer, R. (2012). Better not to deal with two tasks at the same time when stressed? Acute psychosocial stress reduces task shielding in dual-task performance. *Cognitive, Affective and Behavioral Neuroscience, 12(3),* 557-570.

Reid, D.D. (1948). Fluctuations in navigator performance during operational sorties. In E.J. Earnaley and P.B. Warr (Eds.), *Aircrew stress in wartime operations*. New York: Academic.

Rotton, J., Olszewski, D. A., Charleton, M. E., and Soler, E. (1978). Loud speech, conglomerate noise, and behavioral aftereffects. *Journal of Applied Psychology, 63,* 360–365.

Salas, E., Cooke, N. J., and Rosen, M. A. (2008). On teams, teamwork, and team performance: Discoveries and developments. *Human Factors, 50(3),* 540-547.

Salas, E., Sims, D. E., and Burke, C. S. (2005). Is there "big five" in teamwork? *Small Group Research, 36(5),* 555–599.

Salas, E., Prince, C., Bowers, C. A., Stout, R. J., Oser, R. L., and Cannon-Bowers, J. A. (1999). A methodology for enhancing crew resource management training. *Human Factors, 41,* 161-172.

Saling, L. L., Phillips, J. G. (2007). Automatic behaviour: Efficient not mindless. *Brain Research Bulletin, 73*(1-3), 1-20.

Saunders, T., Driskell, J.E., Johnston, J.H., and Salas, E. (1996). The effect of stress inoculation training on anxiety and performance. *Journal of Occupational Health Psychology, 1,* 170–186.

Schneider, W., and Chein, J. M. (2003). Controlled and automatic processing: behavior, theory, and biological mechanisms. *Cognitive Science, 27,* 525-559.

Schneider, W., and Detweiler, M. (1988). The role of practice in dual-task performance: Toward workload modeling in a connectionist/control architecture. *Human Factors, 30(5),* 539-566

Schneider, W., and Shiffrin, R. M. (1977). Controlled and automatic human information processing: I. Detection, search, and attention. *Psychological Review, 84,* 1-66.

Schoofs, D., Preuß, D., and Wolf, O. T. (2008). Psychosocial stress induces working memory impairments in an n-back paradigm. *Psychoneuroendocrinology, 33(5),* 643-653 .

Selye H. (1956). *The stress of life*. New York: McGraw-Hill.

Shiffrin, R. M., and Schneider, W. (1977). Controlled and automatic human information processing. II. Perceptual learning, automatic attending and a general theory. *Psychological Review, 84(2),* 127–190.

Sieber, J. E. (1974). Effects of decision importance on ability to generate warranted subjective uncertainty. *Journal of Personality and Social Psychology, 5,* 688-694.

Skosnik, P. D., Chatterton, R. T., Swisher, T., and Park, S. (2000). Modulation of attentional inhibition by norepinephrine and cortisol after psychological stress. *International Journal of Psychophysiology, 36,* 59–68.

Smith, M.D., and Chamberlin, C.J. (1992). Effect of adding cognitively demanding tasks on soccer skill performance. *Perceptual and Motor Skills, 75,* 955–961.

Staal, M. A. (2004). *Stress, cognition, and human performance: A literature review and conceptual frame-work* (Rep. No. TM-2004-212824). Moffet Field, CA: Ames Research Centre.

Staal, M. A., Bolton, A. E., Yaroush, R. A., and Bourne, L. E., Jr. (2008). Cognitive performance and resilience to stress. In B. J. Lukey and V. Tepe (Eds.), *Biobehavioral resilience to stress* (pp. 259-300). Boca Raton, FL: CRC Press.

Stokes, A. F. (1995). Sources of stress-resistant performance in aeronautical decision making: The role of knowledge representation and trait anxiety. *39th Human Factors and Ergonomics Society Annual Meeting,* San Diego, CA, Oct., 1995, Proceedings. Vol. 2 (A96-13001 02-54, p. 887–890.

Stokes, A.F., and Kite, K. (1994). *Flight stress: Stress, fatigue, and performance in aviation.* Burlington, VT: Ashgate.

Stout, R. J., Cannon-Bowers, J. A., Salas, E., and Milanovich, D. M. (1999). Planning shared mental models, and coordinated performance: An empirical link is established. *Human Factors, 41(1),* 61-71.

Svoboda, E. (2009). Avoiding the big choke. *Scientific American Mind,* February/March, 36-41.

Thackray, R.I. (1988). *Performance recovery following startle: A laboratory approach to the study of behavioral response to sudden aircraft emergencies.* FAA Office of Aviation Medicine Report No. FAA-AM-88-4.

Torrance, E. P. (1954). The behavior of small groups under the stress conditions of 'survival'. *American Sociological Review, 19,* 751-755.

Tversky, A. and Kahneman, D. (1973). Availability: A heuristic for judging frequency and probability. *Cognitive Psychology, 4,* 207-232.

Tversky, A. and Kahneman, D. (1974). Judgment under Uncertainty: Heuristics and Biases. *Science, 185,* 1124-1131.

Tversky, A. and Kahneman, D. (1981). The Framing of decisions and the psychology of choice. *Science, 211,* 453–458.

Urban, J. M., Weaver, J. L., Bowers, C. A., and Rhodenizer, L. (1996). Effects of team workload and structure on team processes and performance: Implications for complex team training. *Human Factors,* 38,300-310.

Wachtel, P. L. (1967). Conceptions of broad and narrow attention. *Psychological Bulletin,* 68,417-429.

Weber, E. U. and Johnson, E. J. (2009). Mindful Judgment and decision making. *Annual Review of Psychology,* 60, 53-85.

Welford, A. T. (1976). *Skilled performance*. Scott, Foresman and Company, Glenview, Ill.

Weltman, G., Smith, J. E., and Egstrom, G. H. (1971). Perceptual narrowing during simulated pressure-chamber exposure. *Human Factor,* 13, 99-107.

Westman, M., and Eden, D. (1996). The inverted-U relationship between stress and performance: A field study. *Work and Stress,* 10(2), 165-173.

Wickens, C. D. (1996). Designing for stress. In Driskell, J. E., and Salas, E. *Stress and human performance* (pp. 279-295). Mahwah, NJ: L. Erlbaum.

Wickens, C. D and Hollands, J. G. (2000). *Engineering psychology and human performance*. Prentice Hall, London.

Wickens, C.D., Stokes, A., Barnett, B., and Hyman, F. (1991). The effects of stress on pilot judgment in a MIDIS simulator. In O. Svenson and A.J. Maule (Eds.), *Time Pressure and Stress in Human Judgment and Decision Making* (pp. 271–292). New York: Plenum Press.

Wright, P. (1974). The harassed decision maker: Time pressures, distractions, and the use of evidence. *Journal of Applied Psychology,* 59, 555-561.

Appendix B

Stress and Flightcrew Performance: Types of Errors Occuring in Airline Accidents

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Executive Summary

The Federal Aviation Administration (FAA) has embarked on an ambitious NextGen program to improve the safety, efficiency, and capacity of the National Airspace System. Planned NextGen operational capabilities call for new and enhanced flight deck automation. These flight deck technologies will require special attention to development of effective flightcrew operations as well as updated design requirements for flight deck controls, automation, and alerting mechanisms. Such efforts will ensure that flight deck design and operating procedure changes do not induce pilot stress and error that would limit the ability to successfully conduct NextGen operations.

This report is the second of three documents aimed at better understanding of how acute stress affects the performance of pilots. The first document reviewed the research literature on stress and human performance; the majority of studies that we reviewed were conducted in laboratory settings with artificially induced stress and, for the most part, using novice participants. The current study examined the errors made by experienced airline pilots in accidents involving substantial levels of acute stress, high workload, time pressures, uncertainty, and unfamiliar situations in various combinations. The third report will examine the operational implications of our findings and explore ways of lessening pilots' vulnerability to stress-related errors by improving design of procedures, training, and interfaces. Taken together, the three reports offer a foundation for better understanding of the nature of human performance under acute stress and for ways to lessen stress-related human error through improved design of procedures, training, and equipment.

Two subject matter experts (SMEs—current authors KD and JK) applied their expertise in aviation human factors and commercial flight operations to perform a detailed analysis of twelve major airline accidents. The focus was on errors that appeared to be associated with the demanding events of the flight. In all of these accidents pilots made errors while dealing with high levels of threat-induced anxiety, workload, time pressure, uncertainty, etc. Through studying the formal investigation reports of the accidents, the SMEs identified and characterized 212 distinct flightcrew errors. The errors were identified without use of a pre-existing taxonomy in an attempt to let the behavioral data drive the results. Each error was described by a clear statement of a failure in communication, action, or deviation from established procedures. Additional flight context information (e.g., phase of flight, crew position) was recorded for each error. These error statements then served as the basis for all subsequent analyses.

Next, the SMEs grouped the 212 individual errors into 49 error types based on similarity of error statements. The error types abstracted across the individual errors eliminated much of the contextual information specific to the particular error, but were still sufficiently detailed to preserve small, yet significant distinctions in the nature of the flight tasks. Each individual error was assigned to only one error type. The error types varied in frequency from 12 error statements (Failure to provide input to another crewmember) to 1 (Lack of planning).

In a final step of abstraction, the SMEs created eight still higher-order error categories to capture similarities across the error types and to integrate the cognitive and human factors aspects of the errors. The stress literature discussed in the first report guided the SMEs as they analyzed how challenges during the accident flights could make experienced pilots vulnerable to error. The cognitive appraisal model of stress that we also reviewed in the first report influenced the development of these eight categories. Each of the 49 error types was assigned to only one of the eight categories, producing a hierarchical structure of categories, types, and individual errors. The most common category (Inadequate comprehension, interpretation, and/or assessment of the situation) contained 50 error statements and 11 error types and the least common category (Failure to acquire information) contained 10 error statements and 4 error types.

The distribution of the errors and error types among the eight higher-order categories appears to support a cognitive appraisal model of error in which anxiety disrupts executive control of attention and pre-empts some of the limited capacity of working memory. Attention and working memory are crucial resources for managing situations that involve novelty, difficulty or danger. The stress-induced impairments of cognitive functioning we observed in our database of errors help explain errors such as poor management of competing tasks, inadequate communication, as well as several other categories of error. Also consistent with the cognitive appraisal model of stress is the low frequency of errors in the category of 'inadequate physical execution of action.' For experienced pilots, physical execution of tasks is largely automatic, and makes fewer demands on the limited resources of attention and working memory; thus this aspect of pilot performance is less vulnerable to stress.

In addition, we found that over two-thirds of the 212 errors committed by pilots were errors of omission, many of which occurred because of prospective memory failures[16]. Forty-two percent (90 out of 212) of the errors involved both pilots, but when an error was attributed to a single pilot that pilot was most often the captain rather than the first officer. Errors were more frequent for both pilots in the flying role, but this may only reflect that the duties of the flying pilot are enumerated in more detail in written procedures.

In summary, this report describes a systematic analysis of pilot errors that occurred during accident flights. The database of errors and the resulting categorization schemes demonstrated specific ways flightcrew performance falls short in accident flights and offers more general categories of pilot errors occurring under highly challenging conditions. The results should prove useful for developing countermeasures to reduce vulnerability to error in these conditions and to improving training, operating procedures and flight deck systems for use in NextGen operations.

The ultimate objective of this work is to develop actionable guidance for use by the industry with regard to flightcrew workload management and response to non-normal situations under NextGen. This guidance will be suitable for incorporation into (a) FAA Order 8900.1, the Flight Standards Information Management System (FSIMS); (b) new and existing FAA Advisory Circulars; (c) air carrier training curricula, and supporting materials; and (d) non-normal checklist system designs and development across the industry.

[16] A prospective memory failure has occurred when someone forgets to perform a planned action or intention at the appropriate time.

1. Overview

The Federal Aviation Administration (FAA) has embarked on an ambitious NextGen program to improve the safety, efficiency, and capacity of the National Airspace System. Planned NextGen operational capabilities call for new and enhanced flight deck automation. These flight deck technologies will require special attention to development of effective flightcrew operations as well as updated design requirements for flight deck controls, automation, and alerting mechanisms. Such efforts will ensure that flight deck design and operating procedure changes do not induce pilot stress and error that would limit the ability to successfully conduct NextGen operations.

The ultimate objective of this work is to develop actionable guidance for use by the industry with regard to flightcrew workload management and response to non-normal situations under NextGen. This guidance will be suitable for incorporation into FAA Order 8900.1, the Flight Standards Information Management System, into new and existing Advisory Circulars, into air carrier training curricula, and similar materials as well as for use by non-normal checklist system designers and developers across the industry.

Stress often impairs human performance in challenging or threatening situations. This report is the second of a three-part series examining how stress affects the performance of pilots and how vulnerability to stress effects might be reduced[17]. In the first report we reviewed the research literature on stress and human performance and described human limitations and errors that occur when people experience acute stress. Much of this research was conducted in laboratory settings in which stress was artificially induced and the participants were novice performers. Diverse manipulations, such as high workload, time pressure, social anxiety, electric shock, and exposure to heat or cold, were used in these studies; consequently, different kinds of effect—both physiological and behavioral—may have been confounded. Only a few studies have been conducted in realistic operational settings or used experienced pilots as participants. Consequently, although we extrapolated the implications of these studies to the performance of pilots encountering emergencies and other threatening situations, our conclusions were necessarily somewhat tentative and incomplete.

The current report extends the literature review by identifying and analyzing the errors made by cockpit crews in twelve major airline accidents. Our focus is on errors likely to be associated with the stress induced by the challenges and threats in the accident scenarios[18]. We used the earlier literature review to aid our analysis of the errors experienced pilots made in these accident flights.

Because the term ‘stress’ in everyday parlance is used in reference to diverse situations, in this study, we use a more specific definition based on a widely accepted cognitive appraisal model, which posits that individuals confronted by potentially threatening situations assess their ability to manage the situation adequately. If individuals feel reasonably confident in their ability to manage

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[17] This study considers only the *acute stress* arising in reaction to immediately threatening situations and does not address the effects of more prolonged life stressors such as divorce and job loss.

[18] The third report of this study, examines the operational implications of the literature review and explores ways to reduce vulnerability to stress-related errors by improving design of procedures, training, and interfaces.

the situation, they perceive it as a challenge, but if they doubt their ability, they perceive the situation as threatening, and this causes anxiety. The anxiety, in turn, distorts the normal cognitive processes of attention and working memory, impairing the individual's performance in specific ways discussed under Results.

It should be noted that multiple factors in the accidents we analyzed probably combined to increase vulnerability: stress itself (i.e., threat-induced anxiety), high workload and time pressure, uncertainty, and limited practice in dealing with the specific accident situations. However, for the purposes of our study, it does not matter too much which factors were most at play in a given accident. The central goal of this report is to identify specific types of errors experienced pilots often make in extremely demanding situations, so that ways of reducing vulnerability to those types of error can be developed.

Taken together, the three reports of this study provide a foundation for improving performance under stress through better design of procedures, training, and equipment. The results should prove useful for developing countermeasures to reduce vulnerability to error in stressful conditions and to improving training, operating procedures and flight deck systems for use in NextGen operations.

2. Method

We first identified a small set of airline accidents in which the flightcrew[19] had likely experienced high levels of stress in reaction to the events of the flight. Then through a series of steps involving reading, coding, and analyzing the full accident reports including the cockpit voice recorder transcripts, we created a list of flight-crew errors. We limited the errors to ones that occurred during periods in which the flightcrew was dealing with substantial challenges and threats to safety.[20] These errors were grouped into more generic types, based on the kind of task being performed and when the error was made. An example of a type of error is 'Inadvertent omission of a checklist item when executing a checklist.' Drawing upon our review of the stress literature, we analyzed the cognitive factors that may have precipitated pilots being more vulnerable to making each type of error in the stressful conditions present. To help organize the fairly long list of error types for discussion, we grouped them into eight more general categories defined around human factors dimensions.

2.1 Subject Matter Experts

Two subject matter experts (SMEs) with extensive experience in aviation human factors, flight safety, and commercial flight operations identified candidate accidents, read the accident reports, and identified specific errors. These SMEs (JK and KD) were already familiar with the investigations and reports from a wide range of commercial aviation accidents over the previous several decades.

[19] The term 'flightcrew' includes the captain, first officer, and (when present) flight engineer and relief pilot positions. We use 'flightcrew' when referring to the pilots as a group and use 'pilot' to refer to an individual in one of these positions.

[20] Errors made by the crew before stressful conditions were encountered were not included in this analysis.

2.2 Selection of Accidents

The primary criterion for selecting the specific accidents analyzed was that even highly experienced pilots would regard the events and conditions encountered by the accident crew as stressful. Our inference of acute stress is based on the accident reports, transcripts of the cockpit voice recordings (CVR), and the specific actions and errors committed by the crew. Obviously, the mental and emotional state of the accident pilots cannot be determined with the certainty and objectivity with which mechanical systems are evaluated, but we are reasonably confident that the challenges these flightcrews struggled with contributed to the errors they made, whether due to stress (threat-induced anxiety), high workload, time pressure, uncertainty, less familiar procedures, or some combination of these factors.

To be considered for selection in this study a full investigation and report from the investigating authority, including CVR transcript, had to be available. Further, crew errors contributed to the cause or consequences of the accident. All of the accidents included in our analysis were major accidents involving hull loss or loss of life. The SMEs identified an initial set of 32 candidate accidents for review, and of these, 12 were selected for full analysis. This set of 12 accidents was chosen because they: (a) were reasonably certain to involve flightcrews who experienced stressful conditions, (b) involved a diverse range of conditions (e. g., some scenarios played out very quickly, some slowly), and (c) involved both older and newer generation aircraft. Table B1 lists the final set of 12 accidents used in the study along with some basic descriptive information about each flight. A synopsis (page B-36) provides a short narrative description of each of these accidents.

Table B1. The Twelve Accidents Analyzed in the Current Study

ID #	*Accident Flight*	*Accident Title*	*Date*	*Location*	*Aircraft Type (Generation)*	*# of Errors*[1]
1	Fed Ex 1406	In-Flight Fire/Emergency Landing	09/05/1996	Newburgh, NY	Douglas DC-10-10 (Generation 2)	20
2	American 1420	Runway Overrun During Landing	09/01/1999	Little Rock, AR	McDonnell Douglas MD-82 (Generation 3)	26
3	TWA 843	Aborted Takeoff Shortly after Liftoff	07/30/1992	Jamaica, NY	Lockheed L-1011 (Generation 2)	9
4	Continental 795	Runway Overrun Following Rejected Takeoff	03/02/1994	Flushing, NY	McDonnell Douglas MD-82 (Generation 3)	9
5	Pinnacle 3701	Crash	10/14/2004	Jefferson City, MO	Bombardier CL-600 (Generation 3)	23
6	China 006	In-Flight Upset	02/19/1985	300 Miles NW of San Francisco, CA	Boeing 747-SP (Generation 2)	19
7	Air France 447[2]	Stall and Loss of Control	06/01/2009	351 Miles NE of Brazil	Airbus A330-203 (Generation 4)	20
8	Swiss 111[3]	In-Flight Fire Leading to Collision with Water	09/02/1998	5 Miles SW of Peggy's Cove, Nova Scotia	McDonnell Douglas MD-11 (Generation 3)	19
9	Empire 8284	Crash During Approach to Landing	01/27/2009	Lubbock, TX	ATR 42-320 (Generation 3 Turboprop)	23
10	Simmons (dba American Eagle 4184)	In-Flight Icing Encounter and Loss of Control	10/31/1994	Roselawn, IN	ATR-72 (Generation 3 Turboprop)	3
11	American 1400	In-Flight Left Engine Fire	09/28/2007	St. Louis, MO	McDonnell Douglas DC-9-82 (Generation 2)	23
12	Luxair[4] LG 9642/ LH 2420	Loss of Control on Approach	11/06/2002	Luxembour g	Fokker 27 Mk050 (Generation 2 Turboprop)	18

Note: All reports are U.S. NTSB unless noted otherwise.
[1] Number of flightcrew errors identified in the current study.
[2]Bureau d'Enquêtes et d'Analyses.
[3] Transportation Safety Board of Canada.
[4] Le Gouvernement Du Grande–Duche' Luxembourg.

2.3 Analysis

2.3.1 Identification of Flightcrew Errors

We approached the analysis of the accidents in a bottom-up manner rather than using a top-down analysis, aiming to let the behavioral data drive the subsequent analyses and conclusions. Thus, we did not use any pre-existing taxonomy to characterize or categorize the errors.

The first step in analyzing the accidents was to generate a list of errors committed by the flightcrew, beginning at the point (in our judgment) at which flight conditions became sufficiently challenging and threatening that typical pilots would experience significant stress. The formal national aviation authority investigation reports served as the primary source of information about the accidents. Each SME worked independently to identify specific errors made by the crew. Many of these errors were explicitly identified by the investigation report; the SME's also identified and listed as errors any deviation from widely accepted air carrier flight deck practices.

Each individual error was described by a short sentence or statement (e.g., "the First Officer [FO] did not prompt the Captain [CA] to run the evacuation checklist"). Enough detail was provided in the statement of each error to allow someone familiar with the accident to understand what had happened. These statements reflected various types of errors including communications, actions, failures to act, and deviations from established procedures.

Our aim here was to focus on errors that were induced--or at least made more likely--by the demanding events and situations of the accident flights. To help determine that the situations were sufficiently difficult that the crews were likely to have been experiencing stress we drew upon supporting information such as the nature of the threatening situation, environmental factors, state of the aircraft, and work climate within the flight deck.

Beginning with the first accident, each SME generated a list of error statements for each accident independently of the other SME. The two separate lists of errors were then placed side by side in a spreadsheet and differences in the error statements or disagreements about the nature of the errors were discussed and reconciled. This procedure was then repeated for each of the 12 accidents. The generation and reconciliation of the error statements was the most time-demanding part of the analyses. Finally, a single list of errors was compiled across the 12 accidents. The resulting list of 212 error statements is shown in Table B9 (page B-30). This list of errors served as the basis for all subsequent analyses.

In addition to the error statements, we also coded (a) which pilot made the error and whether that pilot was the designated flying pilot or the monitoring pilot, (b) phase of flight, (c) whether the error was one of commission or of omission, and (d) whether deviations from formal procedures were deliberate or inadvertent (when it could be determined). Tables B2 through B5, respectively, show the frequency of occurrence for these aspects across the 212 errors.

Table B2. Number of Errors by Crew Position/Function	
Crew Position/Function	*Frequency*
Crew	90
Captain as pilot flying	39
Captain as pilot monitoring	27
First Officer as pilot flying	20
First Officer as pilot monitoring	14
Flight Engineer	10
Captain (not in flight)	5
First Officer as pilot monitoring	3
Relief First Officer	2
First (not in flight)	1
Captain on relief	1
Total	212

Table B3. Number of Errors by Phase of Flight	
Phase of Flight	*Frequency*
Approach	77
Cruise	56
Descent	45
Take-off	11
Ground evacuation	10
Climb	7
Landing	6
Total	212

Table B4. Number of Inadvertent and Deliberate Errors

Failed to Follow Procedure	*Frequency*
Undetermined	150
Inadvertent	46
Deliberate	16
Total	212

Table B5. Number of Errors of Omission and Errors of Commission

Error Type	*Frequency*
Omission	144
Commission	64
Unknown	4
Total	212

2.3.2 Categorization of the Errors: Error Types and Error Categories

The error descriptions at this point were statements characterizing each specific error that occurred during the stressful portions of the accident flights. In the next stage of the analysis the SMEs grouped the individual errors into clusters based on similarity of the task being performed or that should have been performed (e.g., when executing a checklist, a checklist item may have been omitted). This grouping of the errors into clusters was done informally and without using any predetermined categories. The SMEs attempted to let the similarity of the tasks performed and the errors made drive the clustering in a bottom-up fashion, rather than using a predetermined taxonomy. The clustering of the error statements was performed independently by each SME.

The SMEs then compared their two sets of clusters, discussed advantages and disadvantages of the various clusters, reconciled differences, and finally agreed upon a set of 40 groupings which we called error types. Each of the 212 errors was assigned to a single error type. For example, error statement number six in Table B9, “Flight engineer failed to accomplish step six of checklist: Pull T handle” was one of nine errors placed under the error type ‘Omit checklist items.’ The 49 error types and their frequency of occurrence across the 212 errors are shown in Table B6. Readers may note that some of the error types are rather similar. We allowed these similar sounding error types to remain in order to keep track of small but important distinctions in the nature of the tasks the pilots were performing.

Table B6. The 49 Error Types and their Frequency across the 212 Errors

Error Type	*Frequency*
Fail to provide input to another crewmember	12
Fail to communicate completely or explicitly	11
Fail to recognize gravity of situation and respond appropriately	11
Fail to comprehend/interpret situation	11
Poor task prioritization	10
Omit checklist item(s)	9
Fail to notice event or status of item	9
Fail to properly execute checklist	8
Fail to properly execute procedure	8
Fail to recognize threat and alter plan	7
Fail to use available resources	6
Fail to direct/guide crewmember	6
Decide in reactive/non-strategic manner	5
Fail to choose appropriate response to situation	5
Fail to initiate checklist	5
Fail to adequately assess situation	5
Fail to consider relevant aspects of situation	5
Fail to initiate procedure	5
Slow to assess and respond to situation	4
Fail to call for checklist	4
Fail to consider alternatives	4
Fail to seek information	4
Fail to make correct physical response	4
Fail to initiate checklist in timely manner	3
Fail to monitor and supervise	3
Action slip	3
Fail to resolve issue	3
Fail to understand communication	3
Fail to make required callout(s)	3
Misinterpret aircraft state	3
Fail to properly control aircraft	3
Fail to discuss situation	3
Fail to coordinate actions among crew	3
Fail to initiate correct checklist	2
Fail to distribute duties effectively	2
Fail to appropriately use automation	2
Fail to appropriately manage systems	2
Fail to comprehend checklist	2

continued on next page

Table B6. The 49 Error Types and their Frequency across the 212 Errors (cont.)	
Error Type	*Frequency*
Poor timing	1
Fail to integrate information	1
Discourage seeking information	1
Fail to use standard terminology	1
Fail to call for checklist item	1
Fail to call for correct checklist	1
Fail to timely interpret situation	1
Fail to monitor flying pilot	1
Fail to take charge of situation	1
Direct crewmember to make inappropriate response to situation	1
Fail to control airspeed	1
Fail to sufficiently respond to situation	1
Fail to retrieve knowledge from long-term memory	1
Lack of planning	1
	212

The final step in the analysis was to group the 49 error types into still higher-order categories. The goal here was to use cognitive and/or human factors aspects of the errors to derive the categories rather than the kinds of tasks the pilots were performing. For example, 'Poor management of competing task demands' is one of the broad error categories that resulted from this stage of the analysis. Drawing upon the research literature as summarized in our previous report on the effects of stress on human performance, we analyzed how the events and challenges of the accident flights may have made experienced pilots vulnerable to each of the types of error defined in the higher-order categories. In particular, these categories allow one to examine how frequently the kinds of error predicted by a cognitive appraisal model of stress occur in air carrier accidents.

As before, the SMEs worked independently at grouping the error types into categories, and then subsequently settled differences by discussion. A final set of eight categories resulted. Each of the 49 error types was assigned to a single higher order category. The categories and their corresponding error types are shown in Table B7.

Table B7. The Eight Error Categories and their Corresponding Error Types	
Category (# of Errors)	*Error Type(# of Errors)*
Inadequate Comprehension, Interpretation, and/or Assessment of the Ssituation (50)	Fail to adequately assess situation (5) Fail to comprehend checklist (2) Fail to comprehend/interpret situation (11) Fail to consider relevant aspects of situation (5) Fail to integrate information (1) Fail to recognize gravity of situation and respond appropriately (11) Fail to recognize threat and alter plan (7) Fail to timely interpret situation (1) Misinterpret aircraft state (3) Slow to assess and respond to situation (4) Fail to coordinate actions among crew (3)
Poor Management of Competing Task Demands (36)	Fail to coordinate actions among crew (3) Fail to direct/guide crewmember (6) Fail to distribute duties effectively (2) Fail to initiate checklist in timely manner (3) Fail to monitor and supervise (3) Fail to monitor flying pilot (1) Fail to take charge of situation (1) Fail to use available resources (6) Poor task prioritization (10) Poor timing (1)
Inadequate or Improper Communication (30)	Fail to communicate completely or explicitly (11) Fail to discuss situation (3) Fail to provide input to another crewmember (12) Fail to understand communication (3) Fail to use standard terminology (1)
Inadequate/improper Execution of Tasks (23)	Fail to appropriately manage systems (2) Fail to appropriately use automation (2) Fail to call for correct checklist (1) Fail to properly execute checklist (8) Fail to initiate correct checklist (2) Fail to properly execute procedure (8)
Poor Decision-making or Choice of Actions (16)	Decide in reactive/non-strategic manner (5) Direct crewmember to make inappropriate response to situation (1) Fail to choose appropriate response to situation (5) Fail to resolve issue (3) Fail to sufficiently respond to situation (1) Lack of planning (1)
Inadequate Physical Execution of Action (11) (Assumption here is pilot was trying to execute appropriate physical action but could not make it happen properly.)	Action slip (3) Fail to control airspeed (1) Fail to make correct physical response (7)
Failure to Acquire Information (10)	Fail to retrieve knowledge from long-term memory (1) Fail to consider alternatives (4) Fail to seek information (4) Discourage seeking information (1)

3. Results and Discussion

3.1 Error Types and Categories

In this section of the report we present the frequencies of each error type within each error category along with illustrative examples. For each of the eight error categories we examine the ways in which the events and challenges of the flight may have contributed to these kinds of error, and we discuss the cognitive factors underlying vulnerability to these errors.

3.1.1 Error Category 1: Inadequate Comprehension/Interpretation/Assessment (50 Errors; 24% of Total)

Twenty-four percent of all error statements occurred in this category. The most common error types in the category were failure to comprehend or interpret the situation (11 instances) and failure to recognize the gravity of the situation and respond appropriately (11 instances). Respective examples of these two error types are failing to recognize that the aircraft was stalled and the flying pilot decreasing throttle settings into the beta range while in flight, a prohibited action that puts the aircraft into a dangerously high rate of descent.

In the first example, the autoflight system was engaged at cruise altitude, and the crew was deviating around an area of convective weather. Weather conditions caused the pitot tubes to block with ice, degrading operation of the air data system. Consequently the autopilot and then the autothrust system disconnected. The airplane rolled to the right, at which time the pilot flying took the controls and rolled left and pulled up, whereupon, the stall warning briefly activated. Although the aircraft automatically changed from normal to an alternate control law because of these events, the appropriate recovery procedure from a stall warning would have been the same (reduce the angle of attack) in either condition. Confused by the discrepancies in the airspeed indications and numerous warning, caution, and advisory messages, the crew was unable to interpret the information, determine the aircraft state, and recover from the stall.

The second example was a deliberate failure to follow procedures, and this resulted in an unrecoverable sink-rate on approach. Since it was an intentional action, it appears that the captain did not comprehend the risk associated with removing a propeller lock safety feature designed to prevent inadvertently putting propellers into beta range in flight. In this configuration, the aircraft could not remain airborne.

In seven instances a crew failed to recognize a specific threat and alter their plan to avoid the threat, for example, continuing an approach to an airport under a thunderstorm. The accident sequence unfolded in a series of decisions to attempt to beat the weather to the destination airport. Accepting a short turn onto the approach course to try to avoid the worst of the weather induced time pressures on top of the already high workload.

In nine instances crews either failed altogether to correctly assess their situation or were slow to assess it and respond appropriately; for example, one crew allowed speed to bleed off to the point of a full stall. In five instances pilots considered some but not all relevant aspects of the situation, such as the need to increase speed for icing, and in three instances, the pilots simply misinterpreted the aircraft state, for example, mistaking a false stick-shaker warning for an actual stall. In this example the accident unfolded very quickly with an unexpected and unannounced transfer of the flight controls from the first officer to the captain. The stick-shaker malfunctioned, causing it to activate on take-off, and the first officer felt that the aircraft would not fly. The first officer unexpectedly transferred control to the captain, who elected to land the aircraft without runway remaining. In two instances pilots were unable to comprehend the meaning of a non-normal checklist item, and in another instance the crew failed to integrate the implications of a series of weather reports.

These errors have much in common with the concept of situation awareness (Endsley and Jones, 2013), often discussed in operational communities. Situation awareness is characterized as having three levels: perception of relevant information from diverse sources in the environment, integration of that information into a mental model, and projection of the implications of that information for continued operation. Situation awareness has not been directly related to specific underlying cognitive processes, which makes it difficult to relate to studies of the effects of stress and other aspects of non-normal situations on pilot performance. Indeed, it seems likely that the cognitive processes involved in situation awareness vary as a function of the tasks, goals, strategies, and training of the individual human operator.

However, it is not hard to see how the cognitive challenges of non-normal situations might increase vulnerability to errors involving comprehension, interpretation, and assessment of non-normal situations. Stress tends to disrupt individuals' management of attention, sometimes causing them to fixate on one threatening aspect to the neglect of other relevant aspects and sometimes making them more distractible.[21] Thus pilots under stress might not notice or fully process some sources of information. This appeared to be the case when a crew focused on a split flap abnormal condition, and then neglected to consider the effects of icing, allowing the aircraft to stall on approach.

Stress also tends to pre-empt working memory, reducing ability to keep track of multiple pieces of information and to integrate that information into a coherent mental model. If a non-normal situation is highly practiced, pilots might recognize it and respond appropriately through the process of recognition-primed decision-making, which makes limited demands on the scarce cognitive resources of attention and working memory. However, many non-normal situations involve uncertainty, and novel aspects with which pilots have limited or no prior experience, and in such situations the flightcrew must draw heavily on limited cognitive resources. Pilots may fail to comprehend the combined implications of multiple partial cues occurring at different moments if the associated attentional and information processing demands exceed their cognitive capabilities.

Beyond threat-induced stress, non-normal situations often engender high workload and time pressure and increase demands for managing multiple tasks concurrently. This creates competing demands on working memory while also requiring more frequent shifts of attention among tasks. Up to a point, pilots may be able to manage workload strategically, delaying or deleting lower priority tasks in order to keep control of more urgent and important tasks. But at some point, the pilot's ability to manage strategically may be overwhelmed. One of the most important tasks of pilots in non-normal

[21] See Dismukes, Goldsmith, and Martinez-Papponi (2013) for a detailed analysis of stress effects on cognition.

situations is to establish and update a high-level mental model of the dynamic situation.[22] But, although instructors may urge pilots to take this high-level perspective, in practice little actual training is given in how to do it. Lacking such formal training, and seldom experiencing actual emergencies, when an emergency does occur pilots may quickly fall into a reactive mode of responding to individual events as they occur without developing an adequate mental model of the overall situation.

3.1.2 Error Category 2: Poor Management of Competing Task Demands (36 Errors; 17% of Total)

This error category was one of the larger categories containing 17% of the error statements. The most frequent error type within this category was poor prioritization of tasks, which occurred 11 times. For example, when ATC requested information from a crew during an emergency, the first officer, who was handling communications, did not tell ATC to standby until he could complete the checklist being run. In this accident, the captain had originally been the pilot flying and the first officer was performing the ‘Engine Fire/Damage/Separation’ checklist in response to a left engine fire warning. He had only completed the first two items (disconnecting the autothrottles and placing the left engine throttle to idle) when the captain interrupted him to take the controls so he could brief the flight attendants. There was no specific transfer of control; consequently, the first officer was flying the aircraft, running a checklist, and talking to ATC. Although this was an emergency requiring an immediate return to the airport due to an engine fire indication, the priorities were out of place. All passengers and flight attendants would still be seated since the aircraft had just departed, so securing the cabin was not a concern. Even with an immediate return, the correct flow of tasks would be to complete the emergency checklist(s), minimizing interruptions, and postponing less important tasks.

The next most common error type was failure to use all available resources (six instances). For example, a crew flying an aircraft in which both engines flamed out failed to ask ATC for landing alternatives. In this case, the crew may have believed that they would be able to restart an engine and did not consider the consequences if they could not get a restart.

In six other instances the captain failed to explicitly assign responsibilities to the first officer, who was the monitoring pilot. A closely related error type was failure to distribute duties (two instances). For example, a captain who was the flying pilot failed to transfer control of the aircraft to the first officer or delegate any other duties to the first officer. In this loss-of-control accident, initially due to an engine failure at altitude, the captain remained the pilot flying while working with the flight engineer on the engine malfunction.

Three instances of captains’ failing to monitor and supervise other crewmembers occurred; for example, a captain failed to recognize that the flight engineer had become overloaded during an emergency descent and was not performing his tasks well. A new flight engineer, in the midst of

[22] This high-level mental model should include not only the pilot’s understanding of the situation but also what scientists call ‘metacognition,’ which refers to the individual’s understanding of how well he or she understands the situatioin. For example, a pilot might think the crew will have time to land at the destination airport before an approaching stom arrives, but with a good metcognitive model would recognize that the crew’s assumptions about the weather might be flawed and that more information is needed.

performing the ‘Fire and Smoke’ checklist and then the ‘Cabin Cargo Smoke Light Illuminated’ checklist was confused by some of the checklist items and overwhelmed with in-range duties (he could not find the three-letter identifier for the diversion airport). The pressure to accomplish all of his tasks resulted in his missing critical items on the checklist.

In another instance in which a fire occurred on the flight deck, the captain failed to monitor the first officer’s execution of an emergency descent, resulting in the aircraft being too high during approach to the airport intended for landing. In this same accident the crew failed to take charge of the situation, relying on ATC to tell them when to dump fuel. Particularly in an onboard fire, the task demands are immense. In this case, the crew did not know the extent of the fire, originally assuming it to be air conditioning smoke, which would not have been a threat. The failures to (a) make a plan to execute an emergency descent to the landing surface, (b) monitor the progress of the descent being flown by the first officer, and (c) decide to make an overweight landing were most likely an artifact of the pilot’s training for smoke isolation. When overwhelmed by workload, confusion, and stress, pilots—like all individuals—may revert to a reactive mode of operation because they cannot keep up with the cognitive demands.

Coordination among pilots failed in three instances; for example, in one accident a reserve first officer, who was the monitoring pilot, took control of the aircraft (an Airbus) without discussion with the first officer, who was the flying pilot. Transfer of control of the aircraft is a basic, crucial procedure required in all of flying. However, it must be coordinated and reinforced consistently. In this loss-of-control accident, the Captain who was going on break had not clarified pilot flying assignments and coordination for the reserve pilot. Subsequently, control transferred between the pilot flying (from the right seat) and the pilot monitoring several times, all without proper communication and coordination. At times, both pilots were on the controls, making recovery of the airplane even more doubtful.

In three instances pilots failed to initiate a critical checklist in a timely manner. For example, after a crew landed a burning aircraft, the crew did not execute the evacuation checklist and did not shut down the engines. After a high-speed rejected take-off (RTO) due to blocked pitot tubes and unreliable airspeed, the crew appeared confused and removed from the situation. Stress resulting from the subsequent crash at the end of the runway may have prevented them from retrieving from memory relevant knowledge as to what to do next: shutdown the engines and perform the emergency evacuation checklist.

In almost all of these accidents the crews experienced heavy workload and time pressure was sometimes high. However, from our reading of the accident investigation reports, we believe that in most of these accidents the crews had enough time to complete the most essential tasks, had they been able to manage their work effectively. It seems likely that the way stress disrupts the human attentional system undercut the crews’ efforts to manage their tasks. We do not think that, in general, poor judgment or lack of understanding caused the pilots to mismanage or neglect competing task demands, although in one accident we studied, the flightcrew’s terrible judgment was cited as the accident cause.

Research indicates that under stress humans tend to focus predominately on the salient or most central aspect of a threat, failing to notice or attend to more subtle or peripheral cues even though those cues provide critical information. Conversely, individuals under stress may sometimes become too easily distracted from the most crucial task. In general, stress seems to interfere with individuals' executive control of attention. This effect is especially problematic in non-normal situations, which impose high demands for the pilot to judiciously switch attention back and forth among multiple tasks.

Stress may also undermine the depth or quality of attention available to process and comprehend information that is received. During an emergency descent with a cargo fire, the flight engineer attempted to find the three-letter identifier for the diversion airport. Even though he was given the identifier three times, he continued to request the same information. Surely he would not have had any difficulty processing this information in a calm situation.

Poor management of competing task demands is probably also strongly linked to the way stress pre-empts working memory, leaving less capacity for managing tasks. Multitasking actually involves rapid switching among tasks, and therefore makes heavy demands on working memory. As stress diminishes working memory, multitasking ability is also impaired. Further, working memory is required to maintain and update a mental model of the crews' situation; thus with diminished working memory capacity a pilot may be simply unable to keep track of the overall situation. What appears to be poor prioritization or to be neglect of some tasks might actually be difficulty in establishing and maintaining a good mental model of all of the task requirements and their relative importance and urgency.

Finally, research reveals that under stress, crews seek out information less and communicate less effectively, presumably because of underlying impairment of the basic cognitive functions of attention and working memory. This is evidenced in most of the accidents that we studied, including a particularly acute example in which a crew continued an approach in adverse convective weather. As the weather situation became increasingly challenging, they made little attempt to clarify the maximum winds allowed for landing while hurriedly preparing for the approach, missing numerous callouts in the process.

3.1.3 Error Category 3: Inadvertent Omission of Required Actions (36 Errors; 17% of Total)

This category of error includes actions that are normally required or expected to be performed in the particular situation. These omissions appear to be inadvertent because the crew had no reason to deliberately omit the action, and—although the crews were in many cases busy—there appeared to be sufficient time to perform the action. However even in benign (normal) operations, crews frequently omit procedural steps, either because of the fallibility of human memory or because of sloppy habits or both (Dismukes and Berman, 2010; Dismukes, 2012). The probability of these inadvertent omissions very likely goes up substantially under the stressful challenges of non-normal situations, however little research has addressed this point directly.

Of the seven types of error within this category the most common one involved monitoring: failure to notice a pertinent event or the status of a relevant item (nine instances). Monitoring is a crucial defense against equipment malfunctions, changing conditions, and human error, yet this crucial defense often fails. In fact, an industry working group has conducted a major study of how to improve monitoring, and the results are expected to be published in late 2014 in the trade journal, *AeroSafety World*.

In one of the accidents we studied, the captain, who was flying, left the autopilot connected as he focused attention on the crew's response to a 'hung' #4 engine at FL 410. Unfortunately, the captain did not monitor control wheel deflection or airspeed, and so was not aware that the autopilot adjusted aileron, rudder, and elevator trim to their limits to maintain straight and level flight. Noticing that airspeed was bleeding off, the captain disconnected the autopilot, resulting in a steep roll to the right and loss of control.

Several cognitive factors tend to undermine monitoring. First, the human brain is simply not well designed to monitor for low frequency events, even if those events signal danger. The great reliability of modern aircraft makes unexpected events rare indeed. Pilots who have checked an engine instrument or control setting thousands of times over the years without ever seeing an anomaly are vulnerable *to expectation bias*—in this case, expectation of normality. All individuals are vulnerable to *inattention bias* in which they focus heavily on one aspect of a visual scene and fail to see salient events in another aspect of the scene. Individuals are also vulnerable to *change blindness*—when they divert attention from a scene momentarily they may fail to notice a substantial change when they return attention to the scene. These problems are compounded because pilots are not provided explicit training in *how* to monitor effectively. Specific monitoring techniques are rarely taught, and monitoring is rarely evaluated during recurrent evaluation of pilots' skills and performance[23].

Four of these error types involved checklists. In nine instances a pilot omitted a checklist item, in five instances the pilot responsible for initiating a checklist failed to do so, and in four instances the pilot flying or the captain failed to call for a checklist. As an example of failing to call for a checklist, a captain failed to call for the emergency evacuation checklist after a burning aircraft landed. A previous checklist error by the flight engineer (failure to open the outflow valve on landing) delayed opening the exit door and windows.

Multiple cognitive factors contribute to pilots' vulnerability to these types of omission. Experienced pilots have performed a particular checklist or a procedure such as a flow thousands of times, and over time execution of the checklist or procedure becomes largely automatic, requiring little conscious attention; performance of one step of the task automatically triggers performance of the next step. This automaticity is normally reliable and frees up the mind for other tasks, but it has an Achilles heel: If the checklist or procedural flow is interrupted, the delayed step may not be triggered by the last step before the interruption. Multitasking and interruptions are common, even in normal cockpit operations, and can be incessant in non-normal situations. In highly threatening and fast moving situations, such as an aircraft fire, stress greatly exacerbates these vulnerabilities.

Truncated training is one factor that may contribute to insufficient flightcrew response to a non-normal event such as an emergency evacuation. In training for such events, crews rarely complete

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[23] While the direction to "utilize all available resources" is common in air carrier training, the emphasis on information management (acquisition of valid and reliable data to be used in the planning and performance of a task or flight) and how to apply that information to the situation is not explicitly taught, but should be. It would also be helpful for training to emphasize integration of information and projection of consequences of the current situation (the highest level of situation awareness). Finally, training could inform pilots about cognitive biases, such as expectation bias.

every item and action on an emergency evacuation checklist. Therefore, the training typically consists of a rote list of words and the actions, and the consequences of inaction only emerge in a true emergency evacuation from the aircraft. This emergency, though extremely rare, requires recurring role-play and practice to its conclusion in real-time in order to (a) identify the difficulties with the event and (b) establish a mental model of the process needed to land and evacuate the airplane.

As Table B8 illustrates, crew errors in our sample were more common with non-normal checklists than with normal checklists.

Table B8 Checklist Errors Frequencies for Normal and Non-Normal Checklists

Error Label	*Total Frequency*	*Normal Checklist*	*Non-Normal Checklist*
Fail to call for checklist	4	0	4
Fail to call for checklist item	1	1	0
Fail to initiate checklist	5	0	5
Omit checklist item	9	1	8

In five instances a crew failed to initiate a required procedure, such as executing a go-around from a grossly unstabilized approach. We note that attempting to land from unstabilized approaches is a continuing problem even in normal flight operations. In an emergency situation the pressure to land is even greater than normal, and crews' limited cognitive resources of attention and working memory may be too overloaded to analyze the pros and cons of executing a missed approach.

In three instances pilots failed to make required callouts[24]. For example, a captain who was flying an approach in severe weather failed to make several callouts. He did *not* call:

- for flaps 28 or final flaps
- "Track—Track" when he had the initial movement of the localizer needle on his horizontal situation indicator
- "Outer Marker" and the crossing altitude as the airplane crossed the outer marker beacon on the ILS approach course
- "Landing" before descending below the decision altitude, which would have confirmed that he had adequate visual reference with the runway

Callouts are omitted for many of the same reasons as other omissions: non-normal situations often impose interruptions and additional task demands that disrupt the normal flow of actions, disrupt control of attention, and pre-empt working memory; this removes triggers that would normally prompt memory retrieval of the callout. In this case, though, there was not a non-normal situation

[24] Omitted callouts could, of course, also be considered as inadequate or improper communication, the next category. Somewhat arbitrarily, we listed omitted callouts under Category 3 to emphasize the inadvertent nature of the omission and the fact that these callouts are required and specified in flight manuals, in contradistinction to more general communication.

with the aircraft. Rather, the additional task demands had been created by the crew interaction with a harsh environment, illustrating the insidious way poor choices can escalate into an increasingly difficult situation.

3.1.4 Error Category 4: Inadequate or Improper Communication (30 Errors; 14% of Total)

This category, which had thirty instances, refers to providing or understanding verbal communication and whether pilots chose to communicate relevant information to other crewmembers. The most common error type within this category was failure to provide relevant information (12 instances). For example, a first officer who was the pilot flying failed to point out that a checklist was not complete. No doubt this was in part due to the time pressures of an immediate return to the airport after takeoff and multiple interruptions while trying to complete the checklist. However, the first officer's failure to inform the captain about the status of a checklist may have also been influenced by a previously established casual atmosphere regarding checklist procedures (e. g., not using the proper checklist name and adding non-pertinent words to the checklist items). When proper communication patterns and styles are not established and practiced during normal and routine operations, the stress of a non-normal situation will only further degrade the crew's ability to properly transfer relevant information.

A related category was failing to discuss a situation (3 instances); for example, one crew did not discuss speed increases required for icing and a flap anomaly. In addition, there was no direct communication regarding multiple stall warnings on approach. (The warning probably resulted from the reduced flap settings, incorrectly set airspeed bugs, and ice accretions.) The attempted stall recoveries were never verbalized either; had they been verbalized, recovery might have been more effective. Furthermore, the need for a go-around was only hinted at by the first officer in the form of a question: "Should I go around?".

In another eleven instances pilots did communicate, but the communication was incomplete or not sufficiently explicit. For example, a captain of an aircraft with both engines flamed out twice stated "300 knots" but never told the first officer, who was flying, that he had to increase speed to 300 knots to attempt a restart. The need to communicate explicitly in this scenario was critical. Since both engines (on a 2-engine airplane) were inoperative, the crew needed to try to get at least one engine restarted. This required a minimum of 300 knots. But, the flying pilot's mental model of the situation may have focused on the best glide (L/D) speed in order to reach a suitable airport. Without being specifically told *why* he needed to increase the speed, it could be that stress and his competing mental model kept him from adequately processing the information.

In three instances one or both pilots failed to understand a verbal communication. For instance, a first officer, who was the monitoring pilot, misunderstood a critical wind report, repeating it back to ATC incorrectly and failing to recognize that the wind was now exceeding the company's limits for landing this type of aircraft. The crew continued the approach as the weather deteriorated, making further errors. Thus, degraded communication contributed to other errors, especially in decision-making.

One instance of using non-standard terminology occurred: A first officer, who was the monitoring pilot, used non-standard, less explicit wording to alert the captain, who was flying, that the aircraft was out of lateral alignment on the approach. As the approach continued, the first officer made the required 500-foot altitude call and quietly stated “go around” because at this time he saw that the aircraft was well off course to the right and drifting further right (the strong winds were from the left). It is unlikely that the captain heard the “go around” call. And, although the localizer deviation was approximately 1 dot to the right and the aircraft was 1–1.5 dots high on the glideslope neither pilot called out the deviations. The first officer said “we’re way off,” but this was not a standard callout and he did not indicate the nature of the deviation.

Empirical research has shown that these types of communication errors are common among crews operating in stressful conditions. Crews under stress tend both to provide less information and to seek less information. Verbalization tends to be truncated and less specific under stress. Speech, especially verbalization about complex, unfamiliar situations encountered in emergencies, draws heavily upon limited cognitive resources that can be pre-empted by stress and high workload.

3.1.5 Error Category 5: Inadequate/improper Execution of Tasks (23 Errors; 11% of Total)

The twenty-three instances in this category predominantly involved either problematic use of checklists or incorrect execution of other written procedures. In eight instances a pilot used the correct checklist but executed it incorrectly. For example, when evacuating the cockpit of a burning airplane, a captain turned off the emergency lighting system during engine shut-down and before passengers had exited the airplane. It is not known whether he was viewing the appropriate checklist or attempting to execute it from memory. In two instances a pilot used the wrong checklist; for example, a flight engineer followed the checklist procedure (although he was not referring to any checklist) for a flamed-out engine, when in fact the engine was hung[25]. And in one instance, a captain failed to call for a checklist altogether.

In another eight instances, crews executed written procedures incorrectly or incompletely. For example, during an approach in an emergency situation, a crew failed to tune and identify a beacon required for the approach and did not brief the requirement to use Distance Measuring Equipment (DME) for identification. In two instances an accident crew failed to use automation appropriately; for example, the captain, who was the flying pilot failed to disconnect an autopilot before it reached its control limit, apparently not noticing the gradually increasing tilt of the control wheel.

In two other instances pilots failed to manage aircraft systems effectively or appropriately. For example, a crew failed to cancel a distracting C-chord warning while trying to determine why the aircraft was performing in an unexpected manner. In this instance the crew may have instead pressed the Master Caution button in error.

Errors using checklists occur with surprising frequency even in routine, non-stressful flight operations, for various reasons (Dismukes and Berman, 2010). It is not surprising that these errors also occur during emergencies. Although pilots practice using non-normal checklists during recurrent simulator training, the amount of practice is miniscule compared with extensive use of normal checklists during routine flight operations; thus execution of non-normal checklists is much

[25] A turbine engine ‘flameout’ occurs when combustion has ceased in the combustion chamber and the engine is not producing thrust. A ‘hung’ engine is one that fails to accelerate due to any number of reasons. In this accident the main fuel control unit failed to meter enough fuel to the engine, which affected its ability to accelerate again after it had been brought to idle.

more demanding of the limited cognitive resources of attention and working memory. At the same time, the anxiety likely to occur in threatening situations disrupts individuals' control of attention. Attention control theory (Allsop and Gray, 2014; Eysenck, Derakshan, Santos, and Calvo, 2007) poses that anxiety disrupts attention management in three ways: (a) By reducing normal inhibitory control, anxiety allows attention to be drawn to stimuli that are salient but less relevant to the task at hand, (b) anxiety reduces operators' ability to shift attention efficiently between separate tasks, and (c) anxiety reduces the ability to update and monitor information in working memory.

Execution of normal procedures in an emergency may also be impaired by these factors affecting execution of non-normal procedures. Non-normal procedures must be integrated with all of the normal procedures used to operate an aircraft. The sequence and character of this integration varies with the specific circumstances of the overall situation; thus the crew has had little opportunity to practice the particular combination of normal and non-normal procedures that is demanded by the situation. Since the demands on limited cognitive resources is quite high, pilots need the structure of well-designed, informative displays and checklist formats to help keep track of what they must do from moment to moment, what has been accomplished at any moment, and whether they have accomplished the required procedures correctly.

3.1.6 Error Category 6: Poor Decision-Making or Choice of Actions (16 Errors; 8% of Total)

It is generally accepted that poor pilot decision-making is a contributing factor to many aviation accidents, being frequently cited in accident investigation reports. However, in our data set, errors in the category of 'poor decision-making or choice of actions' occurred less frequently than errors in most of the other categories, accounting for only 8% of the error statements. Decision-making and its close associate, judgment, is a broad psychological construct and as such is variously defined. Definitions may include such cognitive processes as evaluating and selecting actions, reasoning, diagnosing, inferencing, prioritizing, integrating, and predicting. The relatively lower frequency of this category in our data set may have occurred in part because we defined the category more narrowly and more specifically than is sometimes done in the accident literature. Again, we were not constrained by any preexisting category scheme, but rather let the error data drive the categories. Our more focused approach is illustrated in the following discussion of ways stress may have affected decision-making by the pilots in our sample.

Under acute stress humans have been shown to replace thoughtful, strategic, deliberation with quick, reactive judgments. Often these quick judgments are more prone to error and so lead to degraded performance. Five of the decision-making errors in our taxonomy seem to fit this specific description. For example, in the Luxair accident (Table B1) the Captain/Pilot Flying (CA/PF) accepted a vector to the localizer and an approach clearance even though the weather was below minimums and the crew was mentally unprepared to fly the approach and land. The crew did not request a holding pattern or delaying vectors.

Choice of action or selection of response is a central aspect of decision-making. Expert performers often need to weigh and combine multiple sources of information in order to evaluate alternative actions and select the most appropriate response for the current context. Stress has been shown to reduce the number of alternatives considered by decision makers, thus reducing the quality of the choice. We classified five errors as decision-making errors because of a failure to choose an appropriate response to the situation. As one example: When an aircraft on approach broke out of the overcast at 500 feet (above ground) and 300 feet right of centerline, the CA/PF did not go-around.

The cognitive processes of decision-making are closely related to planning and problem solving, and it is often difficult to discriminate one from the other. There were three decision-making errors involving failure to resolve an issue confronting the crew, and one error involving lack of planning. These errors appeared to reflect a failure of the crew to adequately plan and/or think through solutions to problems confronting them. Two examples are: 'Crew communicated poorly and failed to resolve question of cross-wind limitation on a wet runway' and 'Crew did not conduct an approach briefing and had not previously made a plan of action to deal with the weather conditions.'

Two other errors in this category included directing a crewmember to make an inappropriate response and failing to sufficiently respond to a situation. Although these errors could conceivably be placed in other categories they as also are indicative of poor judgment. These two errors were: 'Captain/Pilot Monitoring (CA/PM) commanded First Officer/Pilot Flying (FO/PF) to continue approach after autopilot disconnect and stick shaker' and 'Although FO/PF did respond to the initial sudden roll after A/P disconnect by reducing AOA and rolling left, it is not clear that he reduced AOA enough.'

3.1.7 Error Category 7: Inadequate Physical Execution of Action (11 Errors; 5.2% of Total)

Although this category appears similar to category 4 (inadequate or improper execution of tasks), it is fundamentally different in that in these 11 instances pilots were attempting to perform the correct action but their *physical* execution of the action was problematic. In contrast, the category 4 errors apparently involved *cognitive* failures such as those in which pilots chose to make an incorrect action. In one type of error (seven instances) in category 7, pilots made incorrect physical responses, mis-controlling the aircraft. For example a reserve pilot who was the flying pilot made abrupt and excessive pitch inputs for several minutes during which cockpit displays were giving conflicting information. This may seem puzzling, since airline pilots' manual control skills are so highly practiced that they are largely automatic and thus much more resilient to stress than are cognitive skills. However, we suspect that the flying pilot's erratic and incorrect inputs were not due to poor control skills but rather were due to the result of confusion. The aircraft was not performing as expected, first because of conflicting displays, and because the pilot did not realize that the automation had switched control laws and that the pilot's control inputs were holding the aircraft in a full stall. Thus, improper manual control very probably resulted from mental confusion, and could equally well have been listed under category 4. In another example, a pilot, apparently spatially disoriented, misinterpreted aircraft attitude and energy state and made untimely and incorrect control inputs.

Confusion is a common consequence of emergency situations, especially those which are complex and for which no simple, highly practiced response exists. Interpreting complex unfamiliar situations makes heavy demands on attention and working memory at the very time anxiety is disrupting normal cognitive processing. With increased workload in the mix, the situation for the pilot can be extremely challenging to address.

Another error type involved action slips (three instances), in which the pilot understood the emergency situation and attempted to make the correct response, but unwittingly slipped into a habitual response that was inappropriate to the situation. In one example, a pilot unwittingly pressed the radio transmit button, broadcasting the flightcrew's conversation. Performance of highly practiced procedures is normally quite resilient to stress, but action slips like this one can still occur. These skills require some amount of executive oversight (another aspect of limited cognitive resources) to ensure that the selected action is the correct one for the particular moment. If executive oversight is disrupted, the pilot may make an unintended response—a response that would be appropriate in many situations, but not in the particular case.

In one instance, a captain, who was the flying pilot, allowed the airspeed to decrease until the stick shaker activated. This appears to be a failure to monitor the airspeed. It appears from our observations that monitoring is a crucial defense against various threats and errors, but can be vulnerable to lapses, especially when attention is distracted by other cognitive demands.

3.1.8 Error Category 8: Fail to Acquire Information (10 Errors; 4.7% of Total)

This category includes ten instances. The two most common error types within the category were failure to seek information (four instances) and failure to consider alternatives (four instances). An example of the former error type occurred after an emergency landing when the pilots did not seek information from the flight attendants about the situation in the cabin. An example of the latter type occurred when a crew, having lost both engines, failed to discuss diverting to an in-reach airport.

Two other subcategories had only one instance each. In one of the instances the captain discouraged the first officer (the monitoring pilot) from seeking relevant information. The captain sent a non-verbal message, by signaling the first officer to put away a reference manual in which he was looking up the tail-wind landing limitation, because the captain knew it was 20 knots. The other instance involved failing to retrieve knowledge from long-term memory; specifically, the need to turn on the auxiliary hydraulic pump with an engine failure, what other alerts are to be expected with an inflight engine shutdown, and how the fire shutoff handle works.

Of course, these types of errors can and do occur even on the most routine flights. Still, we believe that the stressful conditions of emergency situations substantially increase the probability of such errors. Stress undermines normal deliberative thought because it disrupts individuals' control of their attention and pre-empts working memory. It is likely that if these crews had been sitting in a room on the ground reading a description of the accident situation they would have had no difficulty determining what they should do to seek out pertinent information, and they would have systematically considered and discussed alternatives. However, normal deliberative processes are impaired in a stressful emergency situation because attention is diverted to salient but less crucial aspects of the environment, making it difficult to think in a logical, sequential manner.

Also, individuals often discover that under stress they momentarily cannot retrieve from long-term memory items of information that they know quite well. Presumably this impairment occurs because searching memory for information that is not frequently used requires individuals to focus attention long enough on what they are searching for and on how that information is characterized to be able to retrieve it from long-term memory.

3.1.9 Summary of Error Categories

The relative frequency of errors in these eight categories is surprising in some respects. Poor decision-making occurred far less frequently than one would expect from the accident literature, suggesting that accident investigations may lump a wide range of crew errors under this rubric. In our analysis of the accident data, inadequate comprehension, interpretation, or assessment of very challenging situations was by far the largest category, suggesting that flight deck displays should be designed to help experienced pilots fully grasp the nature and implications of an emergency, and that recognition and response to such situations should be emphasized and highly practiced in initial and recurrent flightcrew training for each make and model of aircraft flown.

The relative frequency of the error categories is, however, highly consistent with a cognitive appraisal model in which anxiety disrupts executive control of attention and pre-empts some of the limited capacity of working memory; attention and working memory being crucial resources for managing situations that involve some degree of novelty, difficulty, and/or danger. These stress-induced impairments of cognitive functioning go a long way toward explaining errors involving poor management of competing task demands, and errors involving inadequate communication, as well as several other categories of error.

The low frequency of errors in the category of 'inadequate physical execution of action' is also consistent with this model, because experienced pilots have highly practiced physical execution of tasks, making fewer demands on the limited resources of attention and working memory. Task execution errors are often related to selection of an incorrect response, as opposed to incorrect execution of the proper response. Thus, the separate and much larger category of 'inadequate/improper execution of tasks' very probably involves impairment of resource-demanding cognitive processes, rather than sensory-motor processes.

Around 17% of the 212 errors involved inadvertent omission of required actions; perhaps some of these omissions occurred because pilots simply lacked time to do everything they were trying to do, but we suspect that most of these errors occurred because of prospective memory failures. As a result of the stress experienced during the emergency, pilots simply forgot to do what they intended to do. Prospective memory has become a burgeoning field of research in recent years, however, so far, scientists have not examined how stress may affect remembering to perform intended actions.

3.2 Which Pilot Made the Error?

Forty-two percent of the errors (90 out of 212) involved both pilots; these were labeled as 'crew errors' (Table B2). When an error was attributed to just one pilot, that pilot was most often the captain rather than the first officer (66 vs. 34 errors). The reasons for this result, which mirror results found in previous studies of airline accidents (e.g., Dismukes, Berman and Loukopoulos, 2007), are not entirely clear. In part, it may reflect the fact that the captain has more tasks overall than the first officer, and also bears ultimate responsibility for the flight. The greater frequency of captain errors in our data set holds both in accidents in which the captain was the flying pilot and those in which the captain was the monitoring pilot. Errors were more frequent for both pilots in the flying role, but this may only reflect the fact that flying role responsibilities are more extensively enumerated in formal procedures.

3.3 Other Aspects

The phases of flight in which errors were most frequent (Table B3) were approach (77 errors), cruise (56 errors), and descent (45 errors). It is not clear which of many factors most shape the relative frequency of errors. Certainly, approach and descent are among the most challenging phases of flight, especially with a damaged aircraft or difficult weather. Many of the tasks required for flying an airliner are spelled out in formal procedures, even for emergency situations. In those cases in which we determined that pilots did not follow procedures correctly, it appeared that most of these deviations, by far, were inadvertent (Table B4). And, by far, most errors were omissions rather than commissions (Table B5), a fact that emphasizes the cognitive challenges of keeping track of all that must be done in an emergency situation, and the crucial importance of effective monitoring.

4. Conclusions

Experienced airline pilots routinely make small errors even in the most benign of situations (Dismukes and Berman, 2010), however these errors usually are not consequential, partially because of the many safeguards built into the air transportation system.[26] In contrast, many of the errors in our data set contributed to causing an accident or to the severity of its outcome. However, one must be careful of hindsight bias; no systematic comparison of pilot errors in routine flights and accident flights has been made, at least not to our knowledge. Also, we cannot be confident that the errors the accident pilots made in our data set were caused by the demanding circumstances the pilots encountered (in some cases, circumstances the pilots themselves engendered). Nevertheless, the compendium of errors produced by our analysis is useful because it demonstrates the specific ways crew performance most often falls short in accident flights. This compendium could provide the airline industry a foundation for developing countermeasures to reduce vulnerability to the kinds of error observed. In the other two reports produced by this study (Dismukes, Goldsmith, and Martinez-Papponi, 2013; Dismukes, Kochan, and Goldsmith, 2014) we suggest that specific ways that pilot training, operating procedures, and flight deck systems could be modified to provide such countermeasures. Findings in the current report and in our literature review suggest diverse issues that call out for research, which would provide an empirical foundation for improving training, procedures, and cockpit interfaces. The final report in our series examines operational implications of our findings and suggests specific directions for this research.

NextGen operations, which require increased navigational precision and reduced aircraft spacing, will reduce the time flightcrews have to interpret emergency situations and to select appropriate courses of action. The complexity of choosing an appropriate course of action may increase even beyond that now existing for crews encountering emergencies. Thus, as the airspace system evolves and grows more complex and crowded, the need for ways to help flightcrews deal with the heavy cognitive demands of emergencies becomes even more important.

[26] Line Operational Safety Audits (LOSA) provide detailed data on pilot errors made during normal flight operations and how pilots address those errors. Unfortunately, for our purposes, those data are not general published, although they are of course availaable to the participating airlines.

References

Allsop, J., and Gray, R. (2014). Flying under pressure: Effects of anxiety on attention and gaze behavior in aviation. *Journal of Applied Research in Memory and Cognition*, 63-71.

Berman, B. A., Dismukes, R. K., and Jobe, K. K. (2012) Performance Data Errors in Air Carrier Operations: Causes and Countermeasures, NASA Technical Memorandum *(NASA TM-2012-216007)* Moffett Field, CA: NASA Ames Research Center.

Bureau d'Enquêtes et d'Analyses. (2012). Final Report On the accident on 1st June 2009 to the Airbus A330-203, registered F-GZCP, operated by Air France flight AF 447 Rio de Janeiro. Paris. Retrieved from http://www.bea.aero/en/enquetes/flight.af.447/rapport.final.en.php

Dismukes, R. K., (2012). Prospective memory in workplace and everyday situations. *Current Directions in Psychological Science,* August 2012, 21(4), 215-220. doi: 10.1177/0963721412447621

Dismukes, R. K. and, Berman, B. A. (2010). Checklists and monitoring in the cockpit: Why crucial defenses sometimes fail. NASA Technical Memorandum *(NASA TM-2010-216396)* Moffett Field, CA: NASA Ames Research Center.

Dismukes, R. K., Berman, B. A., and Loukopoulos, L. D. (2007). *The limits of expertise: Rethinking pilot error and the causes of airline accidents*. Aldershot, UK: Ashgate Publishing Limited.

Dismukes, R. K., Goldsmith, T. E., and Martinez-Papponi, B. (2013). Selective review of stress literature: Implications for pilot performance. Report submitted to the FAA under FAA Grant 12-G-009.

Endsley, M. R., and Jones, W. M. (2013). Situation awareness. *The Oxford Handbook of Cognitive Engineering,* 88-108.

Eysenck, M. W., Derakshan, N., Santos, R., and Calvo, M. G. (2007). Anxiety and cognitive performance: attentional control theory. *Emotion,* 7(2), 336-353.

International Civil Aviation Organization. (2012). *Manual of evidence-based training*. Doc 9995, First Edition, Montreal, Canada: International Civil Aviation Organization.

Lazarus, R.S., and Folkman, S. (1984). *Stress, appraisal, and coping*. New York: Springer.

Le Gouvernement Du Grand0Duche' de Luxembourg. (2002). *Accident on 6 November 2002 in Luxembourg to the Luxair Fokker 27 Mk050 registered LX-LGB Initial issue: December 2003, Revised Issue: July 2009*. Revised Final Report No AET-2009/AC-01. Luxembourg: Ministere des Transports. Retrieved from http://www.mt.public.lu/ministere/services/coordination_generale/AET/aviation/pdf_EN_fokker.pdf

National Transportation Safety Board. (1985). *China Airlines Boeing 747-SP, N4522V, 300 NM Northwest of San Francisco, California, February 19, 1985. Aircraft Accident Report NTSB/AAR-86/03*. Washington, DC: National Transportation Safety Board. Retrieved from http://library.erau.edu/find/online-full-text/ntsb/aircraft-accident-reports.html

National Transportation Safety Board. (1992). *Aborted Takeoff Shortly After Liftoff Trans World Airlines Flight 843 Lockheed L-1011, N11002 John F. Kennedy International Airport Jamaica, New York July 30, 1992*. Aircraft Accident Report NTSB/AAR-93/04. Washington, DC: National Transportation Safety Board. Retrieved from http://libraryonline.erau.edu/online-full-text/ntsb/aircraft-accident-reports/AAR93-04.pdf

National Transportation Safety Board. (1994). *Runway Overrun Following Rejected Takeoff Continental Airlines Flight 795 McDonnell Douglas MD-82, N18835 LaGuardia Airport Flushing, New York March 2, 1994*. Aircraft Accident Report NTSB/AAR-95/01. Washington, DC: National Transportation Safety Board. Retrieved from http://www.airdisaster.com/reports/ntsb/AAR95-01.pdf

National Transportation Safety Board.. (1994). *On-Flight Icing Encounter and Loss of Control Simmons Airlines, d.b.a. American Eagle Flight 4184 Avions de Transport Regional (ATR) Model 72-212, N401AM Roselawn, Indiana October 31, 1994 Volume 1: Safety Board Report*. Aircraft Accident Report NTSB/AAR-96/01. Washington, DC: National Transportation Safety Board. Retrieved from https://www.ntsb.gov/doclib/reports/1996/AAR9601.pdf

National Transportation Safety Board. (1996). *In-Flight Fire/Emergency Landing Federal Express Flight 1406 Douglas DC-10-10, N68055 Newburgh, New York September 5, 1996*. Aircraft Accident Report NTSB/AAR-98/03. Washington, DC: National Transportation Safety Board. Retrieved from http://www.ntsb.gov/doclib/reports/1998/AAR9803.pdf

National Transportation Safety Board. (1999). *Runway Overrun During Landing American Airlines Flight 1420 McDonnell Douglas MD-82, N215AA, Little Rock, Arkansas, June 1, 1999*. Aircraft Accident Report NTSB/AAR-01/02. Washington, DC: National Transportation Safety Board. Retrieved from http://www.ntsb.gov/doclib/reports/2001/AAR0102.pdf

National Transportation Safety Board. (2004).*Crash of Pinnacle Airlines Flight 3701 Bombardier CL-600-2B19, N8396A Jefferson City, Missouri October 14, 2004*. Aircraft Accident Report NTSB/AAR-07/01. Washington, DC: National Transportation Safety Board. Retrieved from http://www.ntsb.gov/doclib/reports/2007/aar0701.pdf

National Transportation Safety Board. (2004). *In-Flight Left Engine Fire American Airlines Flight 1400 McDonnell Douglas DC-9-82, N454AA St. Louis, Missouri September 28, 2007*. Aircraft Accident Report NTSB/AAR-09/03. Washington, DC: National Transportation Safety Board. Retrieved from http://www.ntsb.gov/doclib/reports/2009/AAR0903.pdf

National Transportation Safety Board. (2009). *Crash During Approach to Landing Empire Airlines Flight 8284 Avions de Transport Regional Aerospatiale Alenia ATR 42-320, N902FX Lubbock, Texas January 27, 2009*. Aircraft Accident Report NTSB/AAR-11/02. Washington, DC: National Transportation Safety Board. Retrieved from http://www.ntsb.gov/doclib/reports/2011/AAR1102.pdf

Transportation Safety Board of Canada. (1998). *In-Flight Fire Leading to Collision with Water Swissair Transport Limited McDonnell Douglas Md-11 HB-IWF Peggy's Cove, Nova Scotia 5nm SW 2 September 1998*. Aviation Investigation Report, Report Number A98H0003. Retrieved from http://www.tsb.gc.ca/eng/rapports-reports/aviation/1998/a98h0003/a98h0003.pdf.

Table B9. The Set of 212 Error Statements Generated from the 12 Accidents	
Error #	*Error Statement*
1	1) Crew did not utilized PBE's even though the flight engineer had been to ground training including fire fighting with the PBE only 5 months previously; flight engineer stated he forgot the PBE was available in the cockpit.
2	2a) FE opened cockpit door several times. KD: not sure this is an error, depends on why he opened door. Might be an error in timing rather than in action.
3	2b) FE opened cockpit door several times. KD: not sure this is an error, depends on why he opened door. Might be an error in timing rather than in action.
4	3) CA/PM was a bit slow initiating the emergency descent.
5	4) FE self-initiated checklists instead of asking CA if he was ready for them.
6	5) FE failed to accomplish step 6 of checklist: Pull T handle.
7	6) FE failed to accomplish step 7 of checklist adequately: Fully open outflow valve control.
8	7) FE failed to confirm that checklist items were complete.
9	8) CA/PM failed to address and prioritize FE workload.
10	9) CA/PM failed to adequately monitor FE execution of checklists.
11	10) CA/PM repeatedly interrupted the FE during "Fire and Smoke" checklist - thereby further distracting FE from his duties.
12	11) CA/PM twice transmitted over radio communications intended for intercom, which may have prevented FE from hearing crucial info.
13	12) CA/PM failed to monitor and coordinate activities of crew.
14	13) CA/PM failed to call for emergency descent checklist.
15	14) CA/PM did not execute and accomplish emergency descent checklist completely.
16	15) CA/PM had poor communications with other crewmembers regarding emergency descent
17	16) Crew did not utilize all available resources, FE could have asked ATC for identifier for Stewart.
18	17) CA/PM did not call for an emergency evacuation
19	18) FO/PF and FE did not suggest running the emergency evacuation checklist
20	19) Poor communications from CA with crew regarding evacuation
21	1a) Crew failed to discontinue the approach when severe thunderstorms were realized; failure to evaluate other options; CA/PF comments: "This is a can of worms"
22	1b) Crew failed to discontinue the approach when severe thunderstorms were realized; failure to evaluate other options; CA/PF comments: "This is a can of worms"
23	2a) Crew made poor decision to accept a short approach (increased the crew's already high workload by compressing the amount of time that was available to accomplish required tasks.
24	2b) Crew made poor decision to accept a short approach (increased the crew's already high workload by compressing the amount of time that was available to accomplish required tasks.)
25	3a) Crew discussed decision issues at tactical level but not at strategic level (several instances can be listed).
26	3b) Crew discussed decision issues at tactical level but not at strategic level (several instances can be listed
27	4) Crew failed to infer from sequence of controller weather reports and their outside view that storm was already making landing questionable.
28	5a) Despite several cues that indicated that the weather at the airport had deteriorated, neither crewmember discussed a need to initiate a go-around, enter a holding pattern, or divert to an alternate airport.
29	5b) Despite several cues that indicated that the weather at the airport had deteriorated, neither crewmember discussed a need to initiate a go-around, enter a holding pattern, or divert to an alternate airport.
30	5c) Despite several cues that indicated that the weather at the airport had deteriorated, neither crewmember discussed a need to initiate a go-around, enter a holding pattern, or divert to an alternate airport.
31	6) CA/PF sent non-verbal message to FO/PM to not look up limitation because he thought he knew it was 20 kts.
32	7a) Crew communicated poorly and failed to resolve question of crosswind limitation on a wet runway.
33	7b) Crew communicated poorly and failed to resolve question of crosswind limitation on a wet runway.
34	8a) Crew failed to check actual crosswind limitation in company flight manual.
35	8b) Crew failed to check actual crosswind limitation in company flight manual.
36	9a) Crew continued approach, not realizing that landing was no longer legal under wind conditions.
37	9b) Crew continued approach, not realizing that landing was no longer legal under wind conditions.
38	10) FO/PM misunderstood critical wind report.
39	11) FO/PM failed to use standard terminology when trying to alert CA/PF to deviation from lateral alignment.
40	12) FO/MP failed to complete Before Landing checklist, including arming the spoilers.
41	13) CA/PF failed to notice spoilers not armed.
42	14) CA/PF forgot to call for final landing flaps and had thought he already had called for them when PM asked if he wanted them.
43	15) CA/PF failed to make several required callouts during final approach.
44	16) Crew did not notice spoilers did not deploy.

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Table B9. The Set of 212 Error Statements Generated from the 12 Accidents (cont.)	
Error #	*Error Statement*
45	17) CA/PF used excessive reverse thrust (greater than 1.3 engine pressure ratio) for conditions after landing.
46	18) CA/PF was slow to apply maximum braking.
47	1) Poor communication between FO/PF and CA/PM about aircraft state and what FO/PF thought was going on.
48	2) FO/PF interpreted cessation of climb as evidence of stall rather than being due to relaxed back pressure. Given the limited information the FO/PF had at the moment this was the most likely seeming interpretation, and deliberate, effortful analysis would have been required to reach a more accurate interpretation.
49	3) The CA/PM was even more likely to make incorrect interpretation of aircraft state, since his hand was not on the yoke and he had no way to know trim state or yoke control pressures.
50	4) FO/PF misinterpreted a false stick-shaker for a high angle of attack or approaching stall aircraft state and relaxed back pressure
51	5a) The stick shaker seems to have surprised the FO/PF to the point that he relinquished control to the CA/PM at an untimely moment in almost in a startle reaction.
52	5g) The stick shaker seems to have surprised the FO/PF to the point that he relinquished control to the CA/PM at an untimely moment in almost in a startle reaction.
53	6) FO/PF failed to communicate that he wanted the CA/PM to take control. (The sound of the stick shaker could not be heard on accident CVR.)
54	7) CA/PF landed hard. However, landing from this situation is extremely difficult and never practiced. It may be that many or perhaps most pilots, even if immune to stress effects, would not have managed a good landing in this situation.
55	8) CA/PF asked “what was the matter?” while applying brakes on the landing roll when he needed to be focused on getting the aircraft stopped.
56	1a) CA/PM failed to call immediately for the rejected takeoff checklist. When he did refer to it he called it incorrectly the abort checklist, and--most important--did not command it be executed, but rather said: “Where’s the checklist...the abort checklist?”
57	1b) CA/PM failed to call immediately for the rejected takeoff checklist. When he did refer to it he called it incorrectly the abort checklist, and--most important--did not command it be executed, but rather said: “Where’s the checklist...the abort checklist?”
58	2) The FO/PF did not ask the CA/PM if he wanted to run the checklist.
59	3) Crew did not execute some or all of the rejected takeoff checklist items (which might have been done from memory).
60	4a) CA did not call for the evacuation checklist and did not shut down the engines when required.
61	4b) CA did not call for the evacuation checklist and did not shut down the engines when required.
62	5) The CA called for emergency evacuation over the intercom without first running the evacuation checklist.
63	6) The FO did not prompt the CA to run the evacuation checklist.
64	7) CA turned off emergency lighting system during engine shut-down and before passengers had exited the airplane.
65	1a) Crew did not communicate the true nature of the emergency to ATC; implying that they had lost only one engine, probably to cover up their malfeasance.
66	1b) Crew did not communicate the true nature of the emergency to ATC; implying that they had lost only one engine, probably to cover up their malfeasance.
67	2) Crew responded to series of stickshaker and stickpusher activations by pulling rather than pushing nose down
68	3) Crew did not announce or discuss what was happening during upset and recovery
69	4a) CA/PM (not clear at times which pilot was PF and which was PM) was slow to start double engine failure checklist even after unknown crewmember stated “don’t have any engines.”
70	4b) CA/PM (not clear at times which pilot was PF and which was PM) was slow to start double engine failure checklist even after unknown crewmember stated “don’t have any engines.”
71	5) Crew did not don oxygen masks initially.
72	6) Dual engine failure checklist was run silently. (This also makes it hard for us to know what items were performed).
73	7a) Crew failed to achieve or discuss 240 knot descent required by checklist.
74	7b) Crew failed to achieve or discuss 240 knot descent required by checklist.
75	8) FO/PF did not achieve 300 knots required for restart.
76	9a) CA/PM mentioned 300 knots twice but did not make it an assertive command.
77	9b) CA/PM mentioned 300 knots twice but did not make it an assertive command.
78	10) CA/PM was probably not monitoring airspeed adequately as he attempted restarts.
79	11) Crew did not correctly follow procedures for APU bleed air start (which would not have worked anyway because of core lock).
80	12) Crew did not discuss the gravity of the situation between themselves.
81	13) Crew did not accept that engine re-starts were unachievable until very late.
82	14a) Crew did not discuss diversion to an in-reach airport.
83	14b) Crew did not discuss diversion to an in-reach airport.
84	15) Crew did not ask ATC for landing alternatives.
85	16) Crew could not assess whether they would be able to glide last few miles to airport until it was obvious they could not.

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Table B9. The Set of 212 Error Statements Generated from the 12 Accidents (cont.)	
Error #	*Error Statement*
86	17a) FO/PF did not turn away from houses soon enough and ended up stalling and spinning rather than executing a controlled crash in flat attitude.
87	17b) FO/PF did not turn away from houses soon enough and ended up stalling and spinning rather than executing a controlled crash in flat attitude.
88	1) FE did not follow "Unscheduled thrust loss or abnormal response to thrust lever advancement" or "Hung/slow engine acceleration" or "Inflight engine failure/shutdown" checklists as specified.
89	2a) FE missed steps (did not close bleed air valve, attempted restart procedure at too high altitude) and followed incorrect procedures (engine was hung, not flamed-out).
90	2b) FE missed steps (did not close bleed air valve, attempted restart procedure at too high altitude) and followed incorrect procedures (engine was hung, not flamed-out).
91	3) No mention of the previous discrepancy write-ups for Engine 4 in the maintenance logbook was made or considered.
92	4a) CA/PF failed to take control of the situation and call for the appropriate checklist.
93	4b) CA/PF failed to take control of the situation and call for the appropriate checklist.
94	5a) CA/PF failed to transfer control to the FO/PM or delegate duties to him while he was the flying pilot.
95	5b) CA/PF failed to transfer control to the FO/PM or delegate duties to him while he was the flying pilot.
96	6a) CA/PF failed to disconnect the autopilot with lack of thrust on the #4 engine (as recommended, but not required) and relied on autopilot to fly without monitoring or correcting with rudder.
97	6b) CA/PF failed to disconnect the autopilot with lack of thrust on the #4 engine (as recommended, but not required) and relied on autopilot to fly without monitoring or correcting with rudder.
98	7) CA/PF failed to observe the anomalous control deflections with the autopilot engaged.
99	8) CA/PF failed to disconnect autopilot before it reached its control limit.
100	9a) CA/PF did not interpret aircraft attitude and energy state properly and made untimely and incorrect control inputs (appeared spatially disoriented).
101	9b) CA/PF did not interpret aircraft attitude and energy state properly and made untimely and incorrect control inputs (appeared spatially disoriented).
102	10a) No one on the flight deck could interpret the flight instruments properly and contribute to the recovery.
103	10b) No one on the flight deck could interpret the flight instruments properly and contribute to the recovery.
104	11) The overall lack of crew coordination escalated throughout the event.
105	1) Crew did not investigate the cause of the autopilot disconnect.
106	2) Crew did not detect the initial airspeed anomaly.
107	3) Crew failed to recognize AP disconnect put them in alternate law and the implications thereof
108	4) Crew was unable to interpret loss of airspeed indications
109	5) RFO/PF made abrupt/excessive pitch-up input (perhaps initially unaware of doing so?) and continued pitch-up input through much of flight
110	6a) FO/PM Although he told RFO/PF to correct pitch attitude, he did not continue to monitor pitch indications adequately; made no further input to RFO/PF
111	6a) FO/PM Although he told RFO/PF to correct pitch attitude, he did not continue to monitor pitch indications adequately; made no further input to RFO/PF
112	7) Crew did not recognize, interpret, nor acknowledge the first stall warning.
113	8a) Crew did not accomplish any checklist or memory items on the QRH checklist (perhaps due to inability to identify condition?) resulting in disorganized and ineffective trouble shooting
114	8b) Crew did not accomplish any checklist or memory items on the QRH checklist (perhaps due to inability to identify condition?) resulting in disorganized and ineffective trouble shooting
115	9) Crew failed to cancel distracting C-Chord warning, perhaps pressing Master Caution in error.
116	10) RFO/PM took control without discussion with FO/PF.
117	11a) FO/PM changed AIR DATA selector and IRU to ATT/HDG without command or discussion.
118	11b) FO/PM changed AIR DATA selector and IRU to ATT/HDG without command or discussion.
119	12) Crew failed to interpret and respond to 2nd stall warning; possibly misinterpreted situation as overspeed
120	13) FO/PF Took control back without discussion
121	14) Captain on Relief (CAR) could not sort of situation when he returned to cockpit
122	15a) FO/PM After calling for Captain in Relief (CAR), seemed to stop trying to interpret and deal with situation
123	15b) FO/PM After calling for Captain in Relief (CAR), seemed to stop trying to interpret and deal with situation
124	16) No pilot identified the stalled condition of the aircraft.
125	17a) No pilot (RFO/PF, FO/PM, CAR) verbalized or discussed the possible situation or solutions.
126	17b) No pilot (RFO/PF, FO/PM, CAR) verbalized or discussed the possible situation or solutions.
127	1a) Crew quickly jumped to conclusion that odor and later smoke was an air conditioning system issue without discussing other possibilities or how to confirm diagnosis (but airline training and procedures provide little help in this regard).
128	1b) Crew quickly jumped to conclusion that odor and later smoke was an air conditioning system issue without discussing other possibilities or how to confirm diagnosis (but airline training and procedures provide little help in this regard).

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Table B9. The Set of 212 Error Statements Generated from the 12 Accidents (cont.)	
Error #	*Error Statement*
129	2) FO/PM was assigned flying duties and told to "descend immediately" versus initiating the emergency descent memory items and using checklist
130	3) Crew's initial reaction was to return to convenient landing spot, Boston. No discussion of whether to seek closer airport. (However, they readily chose Halifax when offered by ATC, so they recognized this was better--my point is they were reactive rather than actively discussing the nature of the threat and options.)
131	4a) CA/PM attention was diverted trying to have flight attendant help find approach charts
132	4b) CA/PM attention was diverted trying to have flight attendant help find approach charts
133	5) CA/PM did not monitor FO/PF's descent management resulting in perception that they were too high to go directly to Halifax airport
134	6) Crew did not descend at VMO/MMO
135	7) FO/PM gave gross weight of aircraft instead of fuel on board to ATC
136	8) Crew was speaking German in cockpit and accidently transmitted to ATC while talking about the emergency checklist they were running
137	9) Even after donning masks, crew did not declare an emergency (until 15 minutes after first indication of smoke)
138	10) Crew did not discuss or implement an emergency descent (they expedited descent but did not execute max performance descent)
139	11) Crew decided to level off to allow time to prepare cabin for landing. Clearly at this point the pilots still did not recognize the potential severity of the threat.
140	12a) Crew decided to turn away from airport to dump fuel and accepted routing that kept them some distance from the airport
141	12b) Crew decided to turn away from airport to dump fuel and accepted routing that kept them some distance from the airport
142	13a) Crew relied on ATC to tell them when it would be ok to dump fuel.
143	13b) Crew relied on ATC to tell them when it would be ok to dump fuel.
144	14a) CA/PM turned off cabin bus without alerting cabin crew.
145	14b) CA/PM turned off cabin bus without alerting cabin crew.
146	1) FO/PF did not initiate and call out go-around, instead asked "should I go-around?" when CA/PM called no flaps.
147	2) FO/PF did not state the problem with the aircraft (flying faster than expected) in a clear and concise manner; instead said "what the heck is going on?"
148	3a) Crew did not discuss speed increases for icing and flap abnormal.
149	3b) Crew did not discuss speed increases for icing and flap abnormal.
150	4a) No checklists were called for or accomplished.
151	4b) No checklists were called for or accomplished.
152	5) Neither pilot called for a go-around at anytime while flying an unstabilzed approach.
153	6a) CA/PM turned to circuit breakers (specifically discouraged per FOM) instead of monitoring the A/C and the FO and going to QRH.
154	6b) CA/PM turned to circuit breakers (specifically discouraged per FOM) instead of monitoring the A/C and the FO and going to QRH.
155	7) FO/PF failed to monitor A/S, G/S, and localizer after the autopilot disconnect (possibly distracted by CA/PM) and allowed speed to bleed off to stick shaker.
156	8a) CA/PM commanded FO/FP to continue approach after autopilot disconnect and stick shaker.
157	8b) CA/PM commanded FO/FP to continue approach after autopilot disconnect and stick shaker.
158	9) CA/PF took control (maybe ok decision) but continued approach.
159	10a) CA/PF did not explicitly assign FO/PM responsibilities as PM.
160	10b) CA/PF did not explicitly assign FO/PM responsibilities as PM.
161	11) FO/PM did not question CA/PF about continuing the approach.
162	12) When aircraft broke out at 500' 300' right of centerline CA/PF did not go-around.
163	13) When aircraft broke out at 500', 300' right of centerline, FO/PM did not call for go-around.
164	14) Runway callout by FO/PM was not helpful to CA/PF as stated, "There's the runway."
165	15a) CA/PF allowed speed to bleed to stick shaker.
166	15b) CA/PF allowed speed to bleed to stick shaker.
167	16) When stickshaker and TAWS went off CA/PF was slow to call for max power.
168	17) CA/PF continued to allow speed to bleed down into full stall without executing full recovery response.
169	1) Although FO/PF did respond to the initial sudden roll after A/P disconnect by reducing AOA and rolling left, it is not clear that he reduced AOA enough. However, apparently, AOA was reduced enough to stop the uncommanded aileron deflection momentarily.
170	2a) As the aircraft began to roll level, apparently the FO/PF began to pull back, increasing AOA and re-inducing uncommanded aileron deflection. I gather from the narrative that the pilots then held back pressure throughout the resulting 1 1/4-turn roll, which was the wrong thing to do. They should have been pushing once the aircraft went inverted.

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Table B9. The Set of 212 Error Statements Generated from the 12 Accidents (cont.)	
Error #	*Error Statement*
171	2b) As the aircraft began to roll level, apparently the FO/PF began to pull back, increasing AOA and re-inducing uncommanded aileron deflection. I gather from the narrative that the pilots then held back pressure throughout the resulting 1 1/4 turn roll, which was the wrong thing to do. They should have been pushing once the aircraft went inverted.
172	1) CA/PF did not communicate clearly the Start Valve Open light illuminated instead said “ah that # uh start valve light thing is * on.”
173	2a) Crew seemed unaware of the significance of the Start Valve Open light. CA/PF asked “does that mean the start valve is open?”
174	2b) Crew seemed unaware of the significance of the Start Valve Open light. CA/PF asked “does that mean the start valve is open?”
175	3) Crew did not confirm which throttle being brought to idle after fire warning
176	4a) CA/PF did not assign ATC communication duties. Would have been better for him as PF rather than allowing FO/PM to be distracted while running checklists. FO/PM did not suggest CA/PF handle comm. (FO was senior enough to have spoken up.)
177	4b) CA/PF did not assign ATC communication duties. Would have been better for him as PF rather than allowing FO/PM to be distracted while running checklists. FO/PM did not suggest CA/PF handle comm. (FO was senior enough to have spoken up.)
178	5) FO/PM (running the checklist) offers to fly while only completing 2 of the Engine Fire/Damage/Separation checklist.
179	6a) No positive transfer of control from CA/PF to FO/PF. CA transferred aircraft control to FO to make a flight attendant announcement without asking status of emergency checklist being run. (In a way two errors in one: wrong priority and causing checklist to be interrupted.)
180	6b) No positive transfer of control from CA/PF to FO/PF. CA transferred aircraft control to FO to make a flight attendant announcement without asking status of emergency checklist being run. (In a way two errors in one: wrong priority and causing checklist to be interrupted.)
181	7) FO/PF did not point out that checklist was not complete.
182	8) FO/PF did not tell ATC to standby until he could complete checklist.
183	9) FO/PF did not brief CA/PM on status of checklist when CA/PF re-took control, and CA/PF did not ask.
184	10a) Alternate landing gear extension “leave lever out” FO/PM asks if he should leave it out.
185	10b) Alternate landing gear extension “leave lever out” FO/PM asks if he should leave it out.
186	11) Crew unable to retrieve relevant systems knowledge from long-term memory, e.g., need to turn on the Aux Hydraulic Pump with an engine failure; what other alerts to be expected with an inflight engine shutdown; how the fire shutoff handle works)
187	12a) Miscommunications between ground and cockpit. Non-stop chatter instead of attending to the ongoing situation.
188	12b) Miscommunications between ground and cockpit. Non-stop chatter instead of attending to the ongoing situation.
189	13a) Crew did not call for or accomplish completely any of the appropriate checklists.
190	13b) Crew did not call for or accomplish completely any of the appropriate checklists.
191	14) Communications did not use standardized phraseology and alerts and components were not properly referred to by name (e.g., “Ah that # uh start valve light thing is * on” instead of “Left Start Valve Open light illuminated.”
192	15) Crew never referred to additional checklists and/or manuals to resolve the situation.
193	16) After aircraft stopped, pilots did not seek info from flight attendants about situation in cabin.
194	17) While Aircraft Rescue and Fire Fighting (ARFF) was putting out the fire, the crew engaged in non-pertinent conversation.
195	1a) CA/PF accepts a vector to the localizer and an approach clearance even though the weather is still below minimums and crew is mentally unprepared to fly the approach and land. Crew does not request the hold or delaying vectors.
196	1b) CA/PF accepts a vector to the localizer and an approach clearance even though the weather is still below minimums and crew is mentally unprepared to fly the approach and land. Crew does not request the hold or delaying vectors.
197	1c) CA/PF accepts a vector to the localizer and an approach clearance even though the weather is still below minimums and crew is mentally unprepared to fly the approach and land. Crew does not request the hold or delaying vectors.
198	2a) Crew fails to report established on the Localizer.
199	2b) Crew fails to report established on the Localizer.
200	3a) Crew is still uncertain whether they have the weather minimums for the approach. (FO/PM comments on needing Cargolux to go around to dissipate the fog.)
201	3b) Crew is still uncertain whether they have the weather minimums for the approach. (FO/PM comments on needing Cargolux to go around to dissipate the fog.)
202	4a) Crew does not conduct an approach briefing and had not previously made a plan of action to deal with the weather conditions.
203	4b) Crew does not conduct an approach briefing and had not previously made a plan of action to deal with the weather conditions.
204	5) Crew fails to follow SOP’s for monitored CAT II approach.
205	6) Crew fails to initiate go-around when below minimum weather report was issued (again) before commencing final segment of the approach.

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Table B9. The Set of 212 Error Statements Generated from the 12 Accidents (cont.)	
Error #	*Error Statement*
206	7) Crew failed to tune and identify ELU beacon and had not briefed to use DME for identification.
207	8) Crew fails to report ELU.
208	9) CA/PF attempts to continue the approach (after initially planning to go-around) outside of SOP parameters (300 feet high, not configured, not briefed, not a monitored approach for CAT II).
209	10a) CA/PF intentionally removes the Primary lock (ground range selectors) and reduces throttles below flight idle to increase descent rate as he was 300 ft. high
210	10b) CA/PF intentionally removes the Primary lock (ground range selectors) and reduces throttles below flight idle to increase descent rate as he was 300 ft. high
211	11a) CA/PF decreases throttles into beta range.
212	11b) CA/PF decreases throttles into beta range.

Synopses of Accidents

(The link to the online referenced report is included at the end of each synopsis.)

ID #1 – Fed Ex 1406

About 0554 Eastern Daylight Time on September 5, 1996, a Douglas DC-10-10CF, N68055, operated by the Federal Express Corporation (FedEx) as flight 1406, made an emergency landing at Stewart International Airport (Stewart), Newburgh, New York, after the flightcrew determined that there was smoke in the cabin cargo compartment. The flight was operating under the provisions of Title 14 Code of Federal Regulations (CFR) Part 121 as a cargo flight from Memphis, Tennessee, to Boston, Massachusetts. Three crewmembers and two nonrevenue passengers were aboard the airplane.

For our analysis, we assumed stress began at the first indication of cargo smoke and grew as conditions worsened. The captain allowed the first officer to continue flying the aircraft so that he could coordinate the emergency. The flight engineer, who had only been with the company 6 months and only had 188 on the DC-10, was repeatedly interrupted while trying to complete the emergency checklists. During the course of the escalating fire in the main cargo compartment (due to hazardous materials), the captain did not adequately manage the crew or resources. The interruptions and distractions during checklists, the failure to call for appropriate checklists, and the failure to follow procedures resulted in additional errors. A potentially catastrophic consequence of these errors was that the aircraft was still pressurized after landing, causing egress to be delayed. Fortunately, the crew and passengers were able to escape with minor injuries. The aircraft was destroyed.

http://www.ntsb.gov/doclib/reports/1998/AAR9803.pdf

ID #2 – American 1420

On June 1, 1999, at about 2350:44 Central Daylight Time, American Airlines flight 1420, a McDonnell Douglas DC-9-82, crashed after it overran the end of runway 4R during landing at Little Rock National Airport in Little Rock, Arkansas. This flight was approaching Little Rock Airport where thunderstorms were moving in. In an effort to beat the storm, the flightcrew accepted a short approach which, combined with the weather, did not allow for checklist completion and a stabilized approach. We assume stress started slowly as flight approached Little Rock and built to substantial levels during the short approach and landing. We assume the flight became increasingly stressful as the crew encountered the storm while attempting a short approach.

A number of human factors items were present in this accident including a large power-distance gradient between the captain (a chief pilot) and the first officer (new employee on probation). Although there were numerous indications of the growing intensity and proximity of the storm, the flightcrew continued the approach, deviating from several formal procedures in the process. The crosswinds were beyond the limitations for the aircraft and wind readouts indicated windshear in the area. Although the first officer at one point said, “go around,” the captain did not acknowledge and continued to land the aircraft. Due to the high workload, severe weather, and the crew’s failure to follow procedures, the aircraft was not configured properly for landing. The spoilers were not armed and the aircraft touched down at 160 knots, 2000 feet down a 7,200 runway. After touchdown the aircraft departed the departure end of the runway impacting the approach lights.

Decision making was flawed at several points in the flight and plan continuation bias was evident throughout much of the flight: the crew never discussed the alternatives of holding or diverting to a more suitable landing site.

http://www.ntsb.gov/doclib/reports/2001/AAR0102.pdf

ID #3 – TWA 843

On July 30, 1992, at 1741 Eastern Daylight Time, Trans World Airlines flight 843 experienced an aborted takeoff shortly after liftoff from John F. Kennedy International Airport. This accident occurred when L-1011 stickshaker activated just after takeoff rotation, and the First Officer, as pilot flying, perceived the aircraft as stalling. He immediately transferred control—without being command--to the Captain, who landed the aircraft without enough runway remaining. The captain maintained control of the aircraft throughout the event, managing to turn off of the runway onto a grassy area before hitting the barrier at the end of the runway. The airplane caught fire and was destroyed; however, all occupants escaped.

In this accident, the triggering event occurs (perceived lack of flightworthiness by the first officer), the crew reacts (first officer transfers control and the captain lands), and the accident is over (at least as far as critical flight performance) in less than a minute. We assume the flight became stressful as soon as the stickshaker activated.

http://libraryonline.erau.edu/online-full-text/ntsb/aircraft-accident-reports/AAR93-04.pdf

ID #4 – Continental 795

On March 2, 1994, about 1759 Eastern Standard Time, Continental Airlines flight 795, a McDonnell Douglas MD-82 sustained substantial damage. The captain, taking off from LaGuardia’s runway 13, performed a rejected takeoff at 5 knots above V1 resulting in the airplane overrunning the runway and hitting a dike. The captain rejected the takeoff because he saw that the airspeed indicators were giving anomalous readings, which happened because the crew had failed to turn on the pitot/static heat system as required by a checklist. When the aircraft came to a halt, the crew made several errors involving emergency evacuation procedures. We assume the flight became stressful from the moment the captain decided to reject the takeoff.

http://www.airdisaster.com/reports/ntsb/AAR95-01.pdf

ID #5 – Pinnacle 3701

On October 14, 2004, about 2215:06 central daylight time, Pinnacle Airlines flight 3701 (doing business as Northwest Airlink), a Bombardier CL-600-2B19, crashed into a residential area about 2.5 miles south of Jefferson City Memorial Airport, Jefferson City, Missouri. The airplane was on a repositioning flight from Little Rock International Airport to Minneapolis-St. Paul International Airport. During the flight, both engines flamed out after a pilot-induced aerodynamic stall and the pilots were unable to restart them. The crew did not fully inform ATC of the nature of their emergency and did not request guidance to the nearest suitable airfield. We assume the flight became stressful when the crew recognized that the engines had flamed out.

http://www.ntsb.gov/doclib/reports/2007/aar0701.pdf

ID #6 – China 006

About 1016 Pacific Standard Time, February 19, 1985, China Airlines Flight 006, A Boeing 747 SP-09, enroute to Los Angeles from Taipei, suffered an inflight upset. The #4 engine lost thrust at cruise, with the autopilot and autothrottle engaged. The captain (flying pilot) focused attention on decreasing speed and did not adequately monitor the flight instruments (ADIs) or the increasing deflection of the yoke. Furthermore, he did not disconnect the autopilot until the aircraft was well right wing down. The flight engineer and first officer were not particularly helpful during the event, perhaps even adding to the confusion regarding the #4 engine with was hung, but not flamed out.

When the autopilot finally disconnected, the upset roll and pitch excursion continued until both the captain and first officer became spatially disoriented. They misinterpreted the ADIs as having tumbled rather than indicating steep bank and pitch. An upset whose cause and nature is not recognized presents a very fast acting and highly stressful situation as evidenced by the amount of time and effort it took for the flightcrew to recover the aircraft to safe flight.

http://libraryonline.erau.edu/online-full-text/ntsb/aircraft-accident-reports/AAR86-03.pdf

ID #7 – Air France 447

On May 31, 2009, Air France 447, an Airbus A330 was on a flight from Rio de Janeiro, Brazil to Paris, France. Three and one-half hours into the flight, the reserve captain and first officer experienced unreliable airspeed indications at FL 380 likely due to obstruction of the pitot probes by ice crystals. The aircraft was inadvertently stalled and descended into the ocean in three and one-half minutes. For the purposes of this study, it is assumed that stress began when the autopilot disconnected as a consequence of the unreliable airspeed. Although the captain of the flight was called back to the flight deck from a rest period, he was unable to assist in the recovery. None of the pilots ever recognized that the aircraft was deeply stalled.
The confusion regarding the flight instrument displays and the aircraft state were evident during the entire event. The flight controls were never moved to reduce the angle of attack and recover aerodynamic stall.

http://www.bea.aero/en/enquetes/flight.af.447/rapport.final.en.php

ID #8 – Swiss 111

On 2 September 1998, Swissair Flight 111 departed New York, United States of America, at 2018 Eastern Daylight Savings time on a scheduled flight to Geneva, Switzerland. About 53 minutes after departure, while cruising at flight level 330, the flightcrew smelled an abnormal odor in the cockpit. Their attention was then drawn to an unspecified area behind and above them and they began to investigate the source. Whatever they saw initially was shortly thereafter no longer perceived to be visible. They agreed that the origin of the anomaly was the air conditioning system. When they assessed that what they had seen or were now seeing was definitely smoke, they decided to divert. They initially began a turn toward Boston; however, when air traffic services mentioned Halifax, Nova Scotia, as an alternative airport, they changed the destination to the Halifax International Airport. While the flightcrew was preparing for the landing in Halifax, they were unaware that a fire was spreading above the ceiling in the front area of the aircraft. About 13 minutes after the abnormal odor was detected, the aircraft's flight data recorder began to record a rapid succession of aircraft systems-related failures. The flightcrew declared an emergency and indicated a need to land immediately.

For the purposes of our analysis, we assume that stress started to occur, but only slightly when the pilots initially detected smoke, and gradually rose as the scenario unfolded. It does not appear that the situation was initially handled as an emergency requiring every effort to land the aircraft immediately. As the situation changed for the worse, there was little time left to correct the time-wasting errors made previously.

http://www.tsb.gc.ca/eng/rapports-reports/aviation/1998/a98h0003/a98h0003.pdf

ID #9 – Empire 8284

On January 27, 2009, about 0437 Central Standard Time, an Avions de Transport Régional Aerospatiale Alenia ATR 42-320, N902FX, operating as Empire Airlines flight 8284, was on an instrument approach when it crashed short of the runway at Lubbock Preston Smith International Airport, Lubbock, Texas. The flight was conducted under14 Code of Federal Regulations Part 121 as a supplemental cargo flight. The flight departed from Fort Worth Alliance Airport, Fort Worth, Texas at about 0313. Instrument meteorological conditions prevailed at the time of the approach to Lubbock Airport. The flightcrew experienced a flap asymmetry on approach, continued an unstabilized approach, and failed to monitor and maintain a minimum safe airspeed while flying in icing conditions. The aircraft crashed on the right side of the runway, 200 feet from the centerline.

For this accident, we assume that stress started when first officer/pilot flying noticed the aircraft was not responding normally to first flap position and that stress rose for both pilots steadily thereafter. Both pilots seemed slow to recognize the indications of flap asymmetry (e.g., control wheel deflected to left).

http://www.ntsb.gov/doclib/reports/2011/AAR1102.pdf

ID #10 – American Eagle 4184

On October 31, 1994, at 1559 Central Standard Time, an Avions de Transport Regional, model 72-212 (ATR 72) leased to and operated by Simmons Airlines, Incorporated, and doing business as American Eagle flight 4184, crashed during a rapid descent after an uncommanded roll excursion. The airplane was in a holding pattern and was descending to a newly assigned altitude of 8,000 feet when the initial roll excursion occurred. The loss of control was attributed to a sudden and unexpected aileron hinge moment reversal that occurred after a ridge of ice accreted beyond the deice boots.

At the time of this accident there was less emphasis on hazardous icing conditions and procedures for flight in known icing. However, the flightcrew failed to carefully monitor the situation while in the holding pattern. For this analysis, we assume that stress began when the autopilot disconnected. There were many precursor failures to follow procedural items that led to unexpected event of autopilot disconnect and subsequent stall and uncommanded roll. The flightcrew was so far removed from mentally flying the aircraft that they forgot to retract the flaps prior to starting the descent. They were both extremely startled with the uncommanded roll after flap retraction, which may have induced more stress and prevented any possible attempt at recovery.

https://www.ntsb.gov/doclib/reports/1996/AAR9601.pdf

ID #11 – American 1400

On September 28, 2007, about 1313 central daylight time, American Airlines flight 1400, a McDonnell Douglas DC-9-82, N454AA, experienced an in-flight engine fire during departure climb-out from Lambert-St. Louis International Airport (STL), St. Louis, Missouri. The takeoff was uneventful until the airplane reached an altitude of about 1,000 to 1,500 feet mean sea level. At about that altitude, the first officer stated that the Left Engine "ATSV Open" light had illuminated. A few minutes later, the CVR recorded a sound similar to the Engine Fire warning bell and then, the first officer stating that the Left Engine Fire warning light had illuminated. The Captain stated that they would return to STL. During the return to STL, the nose landing gear failed to extend, and the flightcrew executed a go-around, during which the crew extended the nose gear using the emergency procedure.

The stress in this accident is assumed to have started with the fire bell. Even before the fire bell sounded, there was confusion regarding the 'Start Valve Open' light and what the procedure was. Then, with the fire warning, the captain (pilot flying) did not allow the first officer to complete the Engine fire/Damage/Separation checklist. The errors that ensued were evident of a failure of long-term memory of aircraft systems that would not appear to be typical of a well-trained pilot. The effects of stress (due to their appraisal of potential harm) were evident in the communications, decisions, and actions of the crewmembers.

http://www.ntsb.gov/doclib/reports/2009/AAR0903.pdf

ID #12 – Luxair LG 9642/LH 2420

On November 6, 2002, Luxair flight AG 9642/LH 2420, a Fokker 27, departed Berlin enroute to Luxembourg. Due to weather at Luxembourg (clear sky with a low fog layer) the flightcrew was expecting to enter holding when they were unexpectedly issued a clearance for an ILS 24 approach. Although not prepared and not configured, the flightcrew accepted the clearance. On the approach, the weather deteriorated below company minimums, and although the captain (pilot flying) had said they would go-around, he continued the approach without any comment from the first officer (pilot monitoring). In an effort to descend and slow the aircraft, the flightcrew failed to follow procedures in many respects, including positioning the power levers below flight idle, and, upon landing gear extension, cancelling a secondary safety device for the propellers (allowing them to go into beta range) and increasing drag to the point that the engines were shut down by the crew.

For this report, we consider stress to start building when the flightcrew were unexpectedly cleared for approach ahead of other aircraft and before they had made normal preparations. In addition, to now being under time pressure, they were still debating whether to continue the approach with less than landing RVR, and they had not established SOP-required pilot duty assignments. The flightcrew was now under time pressure, disorganized, and confused.

http://www.mt.public.lu/ministere/services/coordination_generale/AET/aviation/pdf_EN_fokker.pdf

Appendix C

Stress and Pilot Performance: Operational Considerations

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1. Introduction and Overview of Stress Effects

This report is the third of a three-part study of the effects of stress on pilot performance. The first report critically reviewed the existing research literature on the effects of stress on human performance (Dismukes, Goldsmith, and Martinez-Papponni, 2013). The second report analyzed the kinds of errors made by airline pilots during accidents involving high levels of stress, workload, time pressure, uncertainty, and complexity (Dismukes, Kochan, and Goldsmith, 2014). In the present report, we first briefly summarize principal findings from the literature review and then examine the operational significance and practical implications of the two previous reports. Next, we suggest ways to reduce the harmful effects of stress on flightcrew performance, and, finally, we identify research topics that would benefit this effort and broader efforts to support flightcrew performance in NextGen operations.

We intend the format of this report to be accessible and useful to pilots, instructors, aviation managers, and designers of training, procedures, and equipment. In particular, the report attempts to show how the research findings on stress and human performance of flightcrews can assist FAA decisions in approving operational procedures, checklists, and flightcrew training. We suggest that a proper understanding of how stress and associated cognitive challenges (e.g., high workload, time pressure, uncertainty, and unfamiliarity) associated with flight deck emergencies affect skilled performance of the flightcrew. This knowledge can provide a foundation for methods to improve training, procedures, and equipment interfaces to help pilots manage these challenges. Beyond emergencies, these methods could also protect and enhance flightcrew performance in everyday flight operations.

The literature review was motivated by concern that in emergencies and other severely threatening situations, pilot performance is sometimes compromised by stress[30]. A substantial research literature on the effects of stress on human performance has been generated since World War II. Our literature review attempted to pull together the implications of this diverse literature to aid in understanding how stress affects pilot performance.

Our analysis is made more difficult by the loose and varied ways in which the term 'stress' is used in everyday parlance. Stress is often used to refer to almost any difficult situation humans encounter. Mirroring that everyday variability, numerous research studies have used diverse manipulations (e.g., workload, noise, temperature, electric shock, social threat) to induce 'stress,' and have also used diverse measures of stress effects on performance, for the most part involving simple laboratory tasks. Only a few studies have examined stress effects on the skilled performance of experts, such as pilots. Consequently, our findings were based on cautious extrapolation from these diverse studies.

1.1 Stress Defined

For the purposes of this report we used a focused and explicit concept of stress based on what is known as the *cognitive appraisal model,* for which there is considerable research support. This model proposes that when individuals encounter challenging situations they orient both their cognitive and physiological resources to deal with the situation. Physiological responses, such as

[30] This report considers only the *acute stress* arising in reaction to immediately threatening situations and does not address the effects of more prolonged life stressors, such as divorce and job loss.

increased heart rate and force, faster breathing, and restriction of peripheral blood flow, prepare the body for 'fight or flight.' Cognitively, the individual focuses attention to the challenging situation, mentally preparing for whatever tasks may be required. Up to this point, the individual's resources are mobilized to deal with the challenge, but stress is not necessarily involved. However, if the situation becomes threatening—physically or socially—and the individual is uncertain of his or her ability to handle the threat, anxiety may arise. This anxiety is maladaptive, because it disrupts the individual's ability to manage attention and pre-empts working memory, and both attention and working memory are crucial to managing challenging situations effectively.

1.2 Attention and Working Memory

The human brain has enormous—almost unlimited—capabilities for learning, pattern recognition, and long-term memory. However, two of its most critical functions—attention and working memory, known in the research community as limited cognitive resources—form a kind of bottleneck for information processing that drastically affects human performance. We all have an intuitive understanding of what attention is: the focus of one's mind on one task or thought or stream of sensory input from a myriad of other possibilities. Basically, we can only fully attend to one stream of information at a given moment. If we must deal with multiple tasks, we are forced to switch attention back and forth among them, somewhat like a spotlight.

Working memory is a very small subset of the vast store of an individual's long-term memory, momentarily activated so that it can be quickly accessed and manipulated. A classic example is looking up a telephone number and holding it in mind long enough to dial the number. Working memory consists of two components: the information stored and the control processes used to manipulate the information. For example, adding several numbers in one's head requires both storing information temporarily and manipulating that information. These control processes, known as *executive processes,* are also involved in directing attention.

To understand how stress affects the skilled performance of pilots, especially in emergencies (which by their nature involve novelty, uncertainty, and threat), one must understand the distinction between automated performance of highly practiced tasks and effortful performance of less familiar tasks that draws heavily on attention and working memory. If the threat produces anxiety (understandably), pilots' performance is likely to be undermined in specific ways. Attention and working memory are essential for tasks involving novelty, complexity, or danger. Performing tasks requiring these two limited cognitive resources is typically slow and effortful. If all tasks depended primarily on these limited resources we could hardly function in the world. Fortunately, with highly practiced tasks, our dependence on these two limited resources diminishes considerably, performance becomes largely automatic, and we can perform these practiced tasks with minimum attention and effort, as, for example, when driving a car.

Research shows that individuals under stress are less able to manage their attention effectively. They are less likely to notice more peripheral information in the visual field, and they may fixate on aspects more central, more salient, or more threatening. They are more likely to be distracted from a crucial task by highly salient stimuli, such as an alarm. They may process information less fully and may have difficulty switching attention among multiple tasks in a controlled fashion, and consequently their management of the overall situation may become disjointed and chaotic.

Because anxious thoughts tend to pre-empt working memory's limited storage capacity, the individual may have difficulty performing computations that would not normally be difficult and may have difficulty making sense of the overall situation and updating the mental model of the situation (i.e., situation awareness). In our study of accidents, by far the most common category of errors involved inadequate comprehension, interpretation, or assessment of the ongoing situation.

Highly practiced skills, such as manual operation of flight controls, are less vulnerable to stress because they are largely automated and are less dependent on attention and working memory. Inadequate execution of a physical action occurred only ten times among the 212 errors identified in our accident study (details noted in a prior report). However, emergencies almost always require interweaving of highly practiced tasks and less familiar tasks, novel situational aspects, and uncertainty. Thus, in an emergency situation, overall demands on attention and working memory are very high at a time when these limited cognitive resources may be disrupted by anxiety; consequently, the more cognitive aspects of pilots' performance are often disrupted, including the ability to make appropriate and timely decisions.

1.3 Decision-Making

Research has shown decision-making under stress to become less systematic and more hurried, and that fewer alternative choices are considered when making decisions. Decision-making may be impaired largely because of the disruption in attention and working memory due to stress as described above. To some extent, experts such as pilots may be protected from impairment from stress if they are facing very familiar situations. In these situations experts make decisions largely by automatic recognition of the situation and retrieval of the appropriate response from long-term memory. This is why pilots are required to practice responding to some emergency situations. For example, airline pilots are often given an engine failure during recurrent simulator training, and so pilots are typically fairly reliable in executing the appropriate response when experiencing an actual engine failure emergency in flight, even though the situation is somewhat stressful.

Unfortunately, most emergency situations are not rehearsed. Even in cases where the emergency procedures are practiced, the decisions that the pilot needs to make to respond appropriately in a particular emergency situation may be unique, and thus the required decision making is not rehearsed. For example, the immediate responses to an engine fire in flight are practiced in recurrent training and are likely to be fairly reliable. But, the decisions about the next steps to take depend on where the aircraft is, fuel remaining, weather, and many other variables. Consequently, deliberate thought is required about these aspects, and such necessary deliberation may be impaired by the stress that is induced during the emergency.

The decision-making of accident pilots is often criticized. Indeed it is easy to identify, after the fact, what the pilots could have done to avert the accidents. But, as we have previously argued (Dismukes, Berman, and Loukopoulos, 2007), that kind of assessment suffers from hindsight bias. In our previously reported study of accident errors, we found relatively few examples of poor decision-making or poor choice of action (16 of 212 errors). We suspect that—at least in the case of experienced airline pilots—'poor decision-making' may be used as a catch-all category, and we suggest investigations would be better served by deeper analysis of underlying cognitive factors.

1.4 Team Performance and Communication

In many studies, researchers have found that under acute stress team members search for and share less information, tend to neglect social and interpersonal cues, and often confuse their roles and responsibilities. Stress hinders team performance, including decision-making, primarily by disrupting communication and coordination. Coordination, of course, lies at the heart of effective team performance. Stress significantly reduces both the number of communication channels used and the likelihood that teammates will be provided needed information. Poor communication and coordination can lead to downstream errors by team members. In our previously completed accident study, 30 of the 212 errors involved inadequate or improper communication.

1.5 Accident Errors

Several findings from our analysis of accident errors have already been mentioned. Table C1, taken from our earlier report, summarizes the categories of error and their frequency. In addition to previously mentioned categories, poor management of competing task demands and inadvertent omission of required actions were also frequently occurring errors. Many, perhaps most, of the 212 errors in all categories identified in our earlier study are indicative of disruption of pilots' executive control of attention and pre-emption of portions of their working memory. These are the primary avenues by which stress is thought to undercut performance. Thus, although much of the research literature is based on laboratory studies not involving skilled experts such as pilots, our accident error analysis suggests that experienced pilots confronted by emergencies and other severely challenging situations are vulnerable to the cognitive effects of stress. We do not suggest that stress necessarily directly caused the errors of the accident pilot—indeed pilots sometimes make similar errors on routine flights, and most of the time pilots appropriately respond to emergencies—but rather we argue that stressful conditions made those errors much more likely to occur.

Table C1. The Eight Error Categories and their Corresponding Error Types

Category (# of Errors)	*Error Type (# of Errors)*
Inadequate Comprehension, Interpretation, and/or Assessment of the Ssituation (50)	Fail to adequately assess situation (5) Fail to comprehend checklist (2) Fail to comprehend/interpret situation (11) Fail to consider relevant aspects of situation (5) Fail to integrate information (1) Fail to recognize gravity of situation and respond appropriately (11) Fail to recognize threat and alter plan (7) Fail to timely interpret situation (1) Misinterpret aircraft state (3) Slow to assess and respond to situation (4) Fail to coordinate actions among crew (3)
Poor Management of Competing Task Demands (36)	Fail to coordinate actions among crew (3) Fail to direct/guide crewmember (6) Fail to distribute duties effectively (2) Fail to initiate checklist in timely manner (3) Fail to monitor and supervise (3) Fail to monitor flying pilot (1) Fail to take charge of situation (1) Fail to use available resources (6) Poor task prioritization (10) Poor timing (1)
Inadequate or Improper Communication (30)	Fail to communicate completely or explicitly (11) Fail to discuss situation (3) Fail to provide input to another crewmember (12) Fail to understand communication (3) Fail to use standard terminology (1)
Inadequate/improper Execution of Tasks (23)	Fail to appropriately manage systems (2) Fail to appropriately use automation (2) Fail to call for correct checklist (1) Fail to properly execute checklist (8) Fail to initiate correct checklist (2) Fail to properly execute procedure (8)
Poor Decision-making or Choice of Actions (16)	Decide in reactive/non-strategic manner (5) Direct crewmember to make inappropriate response to situation (1) Fail to choose appropriate response to situation (5) Fail to resolve issue (3) Fail to sufficiently respond to situation (1) Lack of planning (1)
Inadequate Physical Execution of Action (11) (Assumption here is pilot was trying to execute appropriate physical action but could not make it happen properly.)	Action slip (3) Fail to control airspeed (1) Fail to make correct physical response (7)
Failure to Acquire Information (10)	Fail to retrieve knowledge from long-term memory (1) Fail to consider alternatives (4) Fail to seek information (4) Discourage seeking information (1)

Readers should note that in our previously reported accident error study we could not differentiate effects of stress from high workload, time pressures, uncertainty, and unpracticed aspects of the accident situation. But to a large extent that does not matter for our purposes here. Aircraft crews experience some combination of all these factors in emergencies, and our objective is to find ways to reduce vulnerability to errors in these highly difficult situations.

2. Ways to Reduce Error Vulnerability

Taken together, our previous reports indicate that emergency situations undercut skilled performance by and large by reducing pilots' ability to: (a) manage and distribute their attention as a function of task requirements; (b) prioritize and direct attention among competing task demands; (c) manage multiple tasks concurrently; and (d) effectively monitor cockpit indicators, other crew members, and environmental cues. This is not to say that one should expect experienced pilots to fall apart when experiencing a life-threatening emergency; on the contrary, pilots have often shown remarkable skill in managing such situations, although not always successfully. But even pilots who have successfully managed difficult emergency situations often acknowledge that they were severely challenged and would have welcomed any help they could get.

> *Our experience over the years suggests that implicit in the design of operating procedures, training, and cockpit interfaces is an assumption that experienced pilots in an emergency situation will be able to perform 'normally.' That is to say, pilots are assumed to process information, communicate, analyze situations, and make decisions as well as if they were sitting safely on the ground. That assumption is patently wrong.* ***Operating procedures, training, and interfaces should be designed with the understanding that in emergency situations crew's cognitive capabilities will be impaired in varying degrees, sometimes substantially.***

With this understanding, it would be useful to re-visit the design of non-normal procedure documents, cockpit interfaces, and crew training. Applied research, coupled with analysis by the operational community, is needed to develop tools to help flightcrews with the following seven cognitive aspects impacting flightcrew performance under stress. These tools could help flightcrews:

1. Recognize, interpret, assess and comprehend the full implications of a challenging situation that may change dynamically.
2. Keep track of where they are in a procedure or checklist.
3. Shift attention among competing tasks without becoming locked into just one task.
4. Identify and analyze decision options.
5. Step back mentally from the moment-to-moment demands of the flight situation to establish a high-level (meta-cognitive) mental model that guides action.
6. Continuously update that mental model as the situation unfolds.
7. Maintain the cognitive flexibility to abandon a previously selected procedure or course of action that has become inappropriate for the situation.

2.1 Checklist Design and Content

Non-normal procedure manuals and checklists have generally improved over the years, but there is great variability across airlines. It is sometimes hard for pilots, even in non-stressful situations, to find the procedure that corresponds to the cockpit indications of a non-normal situation, even more so when the condition is un-alerted. Furthermore, guidance for multiple system failures can be problematic and pilots can get lost moving among normal and non-normal checklist procedures (or even within a single non-normal procedure) if a lot of jumping past non-pertinent actions is required. These problems are of course greatly exacerbated under stress. Thus, we need to re-write manuals and checklists with the expectation that in a non-normal situation pilots are likely to be cognitively impaired to some degree. And, they may have difficulty attending to all relevant cockpit cues when formulating a diagnosis and remembering and processing new information, especially when it comes from disparate sources over time. Non-normal checklists and procedures should be written to facilitate diagnosis and decision-making and to clearly guide accomplishment of only those actions that are appropriate. Indexes, the titles chosen for checklists, and other checklist features and content can help ensure that the correct checklist has been accessed for the situation in the first place.

2.2 Training to Mitigate Stress Effects

Training could also be modified to align with the seven aspects of supporting crew performance under stress, described above, which could be done in conjunction with Crew Resource Management (CRM) and Line Oriented Flight Training (LOFT). A Threat and Error Management (TEM) framework (ICAO Doc 9995) could be used to focus on the hazards inherent in stressful situations. This could be accomplished during routine initial and recurrent training after an introductory stress-training program has been completed. A stress-training program might start with an academic module, followed by LOFT scenarios in which stressful situations are encountered and managed (Table C2).

First, an awareness exercise (classroom, virtual, or computer-based) would provide background information about stress and stress effects on human performance. This would inform pilots about the physiological effects they may experience under stress (e.g., elevated heart rate, rapid breathing, anxiety), cognitive effects (e.g., narrowed attention, confusion), and team effects (e.g., impaired communication). This information would help pilots be prepared for these effects, to reduce distraction from the effects, and to monitor for alterations in their own performance[31]. In addition to stress effects on individual performance, this training should also emphasize how stress affects team performance, and could provide countermeasures such as making communication more deliberate and explicit and periodically reviewing together how team members understand the current state of the situation.

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[31] It might also be useful to explore whether exposing pilots to various stress relaxation exercises (Thomas, 1989; Driskell and Johnston, 1998) would help them deal with both routine challenges of normal flights and the highly stressful demands of emergencies. Portable physiological monitoring devices might also provide feedback that would help pilots learn to better control reactions to stress; however, more research is required to demonstrate effectiveness and practicality of these approaches.

Next, a scenario such as the one encountered in the FedEx 1406 accident can be presented for discussion in the classroom (or virtual classroom) to help pilots identify specific ways stress can affect the real-world performance of even the most experienced pilots. Then, during simulator training (LOFT), the pilots would encounter a similar realistic stress event which they would manage. Either by pausing the simulation at critical points and/or by debriefing after the flight, the facilitator/instructor could have crewmembers discuss (a) their mental model of the situation at critical points, (b) how stress might be affecting their perceptions and actions, and (c) how they might manage stress to allow them to deal with the situation effectively. In addition to helping pilots recognize and manage the effects of stress, this sort of training could improve crew coordination and decision-making more generally.

Anticipated results of the research described in the next section could provide a solid empirical base that would assist FAA personnel in their safety, regulation, and oversight roles to guide the industry in developing ways to reduce vulnerability to stress-related errors. Specifically, this research would help FAA aviation safety inspectors who evaluate and approve operating procedures and flightcrew training programs. Research results could also help aircraft certification personnel identify relevant policy, regulations and guidance for minimum characteristics of aircraft systems during the certification process.

3. Directions for Future Research

The previous section presented general ways that existing training, non-normal procedures and checklists, and cockpit interfaces could be improved to support flightcrew performance in emergencies and other stressful situations. However, devising specific improvements will require close collaboration between researchers and the operational community. For example, there is good reason to think explicit training in stress management could substantially improve pilots' performance under stress (Driskell and Johnston, 1998); yet, to our knowledge, no stress-management training module specifically for airline pilots has been developed and validated. To be adopted by the airline industry, any such module must be practical to implement and must not greatly increase training costs and time. Hence, collaboration between the airline operational community and applied researchers would be essential. Beyond stress management per se, research could provide specific techniques to train the seven cognitive aspects described in the previous section.

Over the years, manufacturers have greatly improved the usability and functionality of cockpit interfaces; however, research is still needed to develop new features to help pilots deal with the heavy cognitive demands of emergencies and other stressful situations. Especially needed are features that would help pilots keep track of where they are in a procedure or checklist, shift their attention among competing tasks, and establish and continuously update a high-level mental model of the operational situation. Working with industry, FAA research could establish minimum requirements for such features.

As previously mentioned, non-normal operating procedures and checklists seem to have been designed with the implicit but unexamined assumption that crews in emergencies will be able to operate at normal cognitive levels. Research is therefore needed to characterize the degree and impact of cognitive impairment on flightcrews under stress during in-flight emergencies. Furthermore, many existing non-normal procedures and checklists are written in such a way that even a pilot completely unaffected by stress, workload, or time pressure, might have difficulty finding, navigating through, and executing the procedure without error. Thus, the design of non-normal procedures and checklists could be substantially improved through human factors analysis, however, so far only a very few research studies have addressed this important question (Burian, in press).

This research could extend existing laboratory studies of stress to evaluate the effects of stress on the skilled performance of experienced pilots. As discussed in the introduction to this report, most laboratory studies have used inexperienced laboratory participants performing very simple tasks. Although research on stress and performance abounds, few studies directly address issues of flightcrews' performance under acute stress. Pilots are highly trained experts who work as a team to perform complex, dynamic tasks in a high-risk environment. It is difficult and expensive to replicate these variables in empirical studies, and further to create a stressor that mimics an in-flight emergency. Hence, studies have been inadequate and questions remain about the scope and nature of stress effects on pilots' cognition and performance, and also about the effectiveness of training methods that aim to teach pilots techniques for preventing and mitigating such stress effects.

Future studies will require experienced pilots to fly realistic scenarios in a full flight simulator, and will necessarily include a non-normal event sufficiently complicated to tax or exceed their abilities. Cockpit video along with flight parameters would be recorded and ideally multiple measures of pilot stress would be taken including cortisol samples and subjective ratings of stress. Well-designed studies of this caliber would likely be informative and the resulting data would like prove essential for characterizing stress effects on pilot performance, but undoubtedly such studies would also require considerable resources.

The following are specific areas in which research is needed to understand and reduce the effects of stress on pilot performance.

3.1 Design of Cockpit Interfaces

Cockpit interfaces have evolved enormously through generations of improvement, yet many studies have shown vulnerability to flightcrew error, especially involving understanding of automation status.

- What are the requirements for flight deck interfaces that are designed to better support aircrews whose cognition has been undercut by stress?

3.2 Design of Procedures and Checklists

A few studies have revealed that current written procedures and checklists do not adequately protect flightcrew from making errors, especially under stress.

- What principles would help designers devise written documents to reduce the types of errors flightcrews are most vulnerable to under stress?

3.3 Pilot Training and Stress Management

Several studies suggest that it is possible to train individuals to manage acute stress more effectively, but research is needed to develop practical and effective training for experienced pilots.

- What type of training would best help experienced pilots manage stressful situations and to what extent would the effects of that training generalize across diverse situations?

- What are the characteristics of an effective flightcrew training program for stress management and mitigation?
- How might pilots' ability to manage stressful situations be addressed in Practical Test Standards (which are being revised to Airman Certification Standards)?

3.4 Individual Differences and Stress

It is important to know what role individual differences play in pilots' perceptions and responses to stress. For example:

- Does experience/expertise (e.g., total hours flying, hours in current equipment) guard against the effects of stress?

Although experience undoubtedly helps pilots avoid stress, once stress does occur (as defined by the cognitive appraisal model):

- Is there any evidence that more experience reduces stress effects?

In our analysis of NTSB accidents there was not a clear relationship between experience (e.g., seat position) and stress-related errors, although the data were confounded by differences in the number and type of assigned duties.

It would be helpful to know whether and to what degree basic cognitive processes of working memory, long term recall, reasoning, and visual processing speed are affected by stress. A reduction in working memory capacity seems to be one of the most common ways stress degrades cognition. Additional research questions should include:

- Are pilots with larger working memory capacities more immune to stress effects?
- Does quicker visual processing offset stress effects?
- Which is more important for pilots to be able to handle stress; higher-level cognitive activities such as reasoning and comprehension or lower-level processes such as working memory and attention?

Finally, individual differences in social or personality variables may be relevant in pilots' perception of stress and their ability to handle stressful events:

- How do differences in trait anxiety affect pilots' ability to handle stress?
- What about other personality variables such as extraversion and openness?

3.5 Role of Context (Setting and Circumstances)

Much of human behavior takes into account the context of the situation. For the pilot, context is the setting, environment, and interrelated conditions and circumstances surrounding the activity. We respond in certain ways in certain contexts. Pilots perform well-learned procedures in a familiar setting and environment during normal flights. With experience, execution of these procedures becomes highly automated and normally quite reliable, making only small demands on the limited cognitive resources of attention and working memory. However, during an emergency the environment, setting, or any aspect of the context can change, and the execution of these automated procedures may be disrupted. Now, some amount of controlled processing is needed to ensure proper execution in the new setting.

- How much of performance disruption is due to the changing contextual aspects, per se, versus other negative stress effects?

This question could be addressed by a research study that manipulated both context variables and other aspects of stress (e.g., type and severity of stressor) and obtained some overall measure of pilot performance. A regression analysis on pilot performance as the criterion variable and the various manipulated variables as predictor variables could be carried out. The unique effects of context variables on the degradation of pilot performance could be assessed.

- If context-driven disruption is indeed significant, perhaps having pilots practice procedures in varied contexts could help guard against such disruption.

3.6 Role of Uncertainty and/or Novelty

Emergency events often involve some degree of uncertainty. For example, it is difficult to know how long an airplane with a cabin or cargo fire can be controlled.

- What role does uncertainty play in making an event stressful?
- And how much does uncertainty per se degrade cognition and performance?

If in fact uncertainty itself is found to be a major contributor to the degradation of human cognition under acute stress, then we can ask further if one type of uncertainty (e.g., uncertainty about the current situation vs the most appropriate response) is more detrimental. As more understanding of the role of uncertainty and stress is gained, implications for training and current practices should emerge.

We know from recurrent training data that even experienced pilots perform consistently worse on unexpected maneuvers than briefed maneuvers. These results come from First Look[32] evaluations made under the Advanced Qualification Program. Hence, uncertainty can degrade even well practiced performance, which in turn suggests the importance of mental preparation. Although there have been preliminary investigations into the effects of surprise or unexpectedness on the outcome of a flight (Kochan, Breiter, and Jentsch, 2004), and recent research has defined differences in pilots' startle and surprise reactions (Rivera et al., 2014), additional research is needed to determine:

- How important is the element of surprise in a flight deck emergency event?
- Is there any type of training that can help protect pilots against the effects of surprise?

3.7 Mental Perspective

A negative consequence of stress is to lose sight of the larger picture. Under stress people may exhibit 'tunnel vision' on a particular aspect of the situation, fail to notice relevant information, or even become paralyzed into inaction. A similar phenomenon is seen in classic studies of problem solving in which participants become locked into a particular way of interpreting a problem. The solution occurs only if the participant is able to step back and reinterpret the problem itself. In emergency situations, pilots may also benefit from being able to step back and take a larger

[32] 'First Look' maneuvers are those maneuvers that are often sensitive to loss of proficiency. Unbriefed, and therefore unexpected, First Look situations are presented to the flightcrew at the beginning of continuing qualification (recurrent training) events to assess the retention of their proficiency (FAA, 2006).

perspective. Research exploring the role of mental perspective in handling emergencies is needed along with ways of effectively training pilots to shift their perspective if this turns out to be an important factor. Research is also needed to devise ways to help pilots develop and update an accurate high-level mental model of the operational situation and its implications.

3.8 Judgment Heuristics

A large body of research on human decision-making characterizes decision-making in terms of judgment heuristics, which are mental shortcuts that save time and reduce cognitive demands in assessing situations but sometimes lead to incorrect assessments[33]. These heuristics include representative bias, framing effects, availability, anchoring, etc. Heuristics may provide a useful framework for understanding the nature of decision errors made by pilots during stressful events. A large proportion of the pilot errors we found in airline accident reports involved comprehension or interpretation, the sort of situation in which judgment heuristics might come into play. For example, when pilots use the availability heuristic, they base (or bias) their decisions on the ease with which a particular idea or situation can be brought to mind. This is illustrated by a situation in which a flightcrew boards the aircraft and reads in the aircraft maintenance log that a previous crew had reported an acrid/sulfur smell and subsequently maintenance replaced the forward galley oven fans and returned the aircraft to service. After this new crew takes off, one of their flight attendants reports the same sort of smell, triggering the flightcrew to go down the ‘cabin equipment smoke’ path on the Smoke/Fumes checklist. However, if the smoke is coming from the avionics compartment below deck, valuable time could be wasted pursuing an incorrectly assumed problem when instead the flightcrew should be preparing to land at the nearest suitable airport if the smoke continues. Poorly written Smoke/Fume checklists can exacerbate this problem.

- To what extent do pilots use judgment heuristics under stress?

It seems likely that when stress reduces limited cognitive resources, dependency on heuristics would increase, but this is an empirical question requiring research. If true, however, then it might be useful to teach pilots about the major judgmental heuristics and their use in flightcrew decision tasks.

3.9 Individual vs Team (Crew) Effects

We know from the research literature that stress degrades team performance. We saw numerous instances of poor crew communication and coordination in our analysis of accident flights. But, we do not know the proportion of individual to team errors.

- How much of the variance in degraded performance is due to actual team errors versus individual errors?

Well-designed studies could tease apart this difference. And knowing which source of variance is greater has implications for how to train pilots to guard against stress effects. Also, research is needed to develop a training module to teach pilots practical methods to communicate effectively in stressful situations.

[33] Heuristics are simple procedures that help find adequate, though often imperfect, answers to difficult situations. The biases that can arise when using judgment heuristics in situations of uncertainty can lead to systematic and predictable errors (Tversky and Kahneman, 1974).

The benefits of such a program of research would go beyond helping pilots under stress avoid errors. This research would provide deep insight into the normal cognitive demands of piloting and the nature of piloting expertise, and this might suggest ways to help pilots acquire and maintain this expertise more readily.

3.10 Implications for NextGen

The NextGen environment will present flightcrews with operating procedures and demands that could increase stress and the consequences of stress, especially in non-normal situations. Complexity and traffic density will increase in this environment, and thus margins for error and time to respond may decrease. Therefore, it is crucial to identify human factors challenges that may arise during implementation and to develop appropriate countermeasures.

The increased navigational precision and reduced aircraft spacing required for NextGen may sometimes reduce the time flightcrews have to interpret emergency situations and to select appropriate courses of action, thus increasing flightcrew stress and the consequences of stress-induced errors. The complexity of choosing an appropriate course of action may also increase for crews encountering emergencies because options may be constrained while conducting NextGen operations, such as closely spaced parallel operations. For example, if a crew is conducting an approach to an airport with parallel runways that are separated by 2,500 feet or less, they will be required to be at least 1.5 miles diagonally from their paired aircraft on the approach (FAA NAS Enterprise Architecture, Operational Improvement 102141; see nasea.faa.gov). If RNAV procedures are in effect, and the aircraft loses the required navigation performance for the approach (due to an onboard equipment failure), the breakout procedure and the subsequent missed approach procedure may impose heavy workload, as the flightcrew must coordinate with air traffic and precisely maneuver the aircraft on the specified flight path with narrow margins for error.

In contrast, in the past, a simple failure of one source of navigation information often required only selecting a different source of navigation information and perhaps selecting a different approach. Furthermore, should some additional unexpected event occur during the NextGen breakout procedure, the flightcrew may already have few remaining cognitive resources to apply to the task, and may thus be less able to multitask and more vulnerable to stress effects.

Our findings of the effects of stress on communication processes could certainly become more apparent with new NextGen communication channels, both inter- and intra-cockpit. Data Communication (DataComm) procedures may put pilots more at risk for communication errors in non-normal situations. DataComm will be used with many of the NextGen operational improvements and each application should be evaluated in both normal and non-normal operations to determine how communication may be affected in stressful situations. For example, if pilots on a point-in-space metering assignment (Operational Improvement 104120) encounter a time-critical emergency such as smoke in the cockpit and need to start an emergency descent, will they be able to communicate adequately via text on DataComm? How will oxygen masks or smoke hoods hinder the ability to send, read, or reply to messages? Will traditional or back-up voice messaging be available, and even required by procedure in such cases? Furthermore, if the flight is on a time-metered route, what additional considerations (and stress) may the crew face during the emergency?

New technologies will generate new failure modes that may increase stress and cognitive demands on flightcrews, and these could have negative consequences. Research would allow these to be characterized and well anticipated, and thoroughly covered in training that is designed to mitigate stress effects on flightcrew performance in the NextGen context. Existing alerting features on flightdecks may not be adequate for NextGen procedures and failures (Berman, et al., in press). Suppose a flightcrew has accepted a contract for Interval Management (Operational Improvement 102118) and is following their designated aircraft when they have a failure of ADSB-in and no longer have information displayed about their target aircraft. They must respond to the alert (presumably well designed to capture their attention and inform them of the nature of the problem) and then initiate the appropriate procedure. How much time will the crew have before spacing is compromised? How will air traffic control handle the situation? Since ground-based air traffic controllers will play a larger part in the movement of aircraft, how will the air-based and ground-based distributed team work to resolve the situation safely? Any uncertainties the flightcrew may have about the situation will increase their vulnerability to stress effects on performance and increase the likelihood for errors; thus it is crucial that interfaces and procedures be designed to simplify cognitive demands and clearly guide flightcrew responses.

Stress and cognitive demands of ground operations under NextGen should also be analyzed. NextGen procedures such as low visibility surface operations (Operational Improvement 107202) will use GPS, WAAS, GBAS, ADS-B and Ground-Based Transceivers combined with in-vehicle Cockpit Display of Traffic Information (CDTI) and/or Enhanced Flight Vision Systems (EFVS), Synthetic Vision Guidance System (SVGS), or other type or combination of advanced vision systems technology to move aircraft and ground vehicles in very low visibility. Currently, flightcrew taxi aircraft primarily using out-the-window vision. Integrating various electronic sources of position information may prove cognitively demanding for flightcrew, though undoubtedly if the interfaces are well designed, pilots will become proficient in this over time. However, a failure of a critical source of position information or other non-normal event, such as loss of brakes, during low visibility would be stressful, so here too procedures and interfaces should be designed to help pilots with stress-reduced cognitive functioning to manage the situation effectively. An additional payoff for this approach to design is that it will reduce pilot error from all sources, not just stress. In addition, such research could help to identify practical limits and good operating procedures and practices for the joint use of the latest aircraft and ground technologies (such as aircraft advanced vision systems and the Surface Movement Guidance and Control System (SMGCS) airport lighting technologies).

As the airspace and ground-space system evolves and grows more complex and crowded, the need for ways to help flightcrews deal with the heavy cognitive demands of non-normal situations becomes even more important. Transition to complex new technologies poses human factors challenges, and those in NextGen are particularly critical to its successful implementation. Difficulties will be worked out as they appear, but the transition period, including learning new procedures to proficiency, is likely to be especially cognitively demanding on flightcrew; thus it will be good to conduct realistic simulation research to characterize the human factors challenges and develop mitigations before NextGen systems are fielded. After NextGen technologies are in operation, it will be important to carefully monitor operations for indicators of latent human factors problems, particularly related to the effects of stress in normal and non-normal operations.

References

Berman, B. A., Kochan, J. A., Burian, B. K., Pruchnicki, S., Silverman, E., and Christopher, B. (in press). *Flight deck alerting: functions, characteristics, and implications for NextGen*. Report submitted to the FAA Human Factors Research and Engineering Division ANG-C1.

Bureau d'Enquêtes et d'Analyses (2012). *Final Report on the accident on 1st June 2009 to the Airbus A330-203, registered F-GZCP, operated by Air France flight AF 447 Rio de Janeiro. Paris*. Retrieved from http://www.bea.aero/en/enquetes/flight.af.447/rapport.final.en.php

Burian, B. K. (2014). *Factors Affecting the Use of Emergency and Abnormal Checklists: Implications for Current and NextGen Operations*. NASA/TM—2014–218382. NASA Technical Memorandum. NASA Ames Research Center, Moffett Field, CA.

Dismukes, R. K., Goldsmith, T. E., and Martinez-Papponi, B. (2013). *Selective review of stress literature: Implications for pilot performance*. Report submitted to the FAA under FAA Grant 12-G-009.

Dismukes, R. K., Kochan, J. A., Goldsmith, T. E. (2014). *Stress and flightcrew performance: types of errors occurring in airline accidents*. Report submitted to the FAA under FAA Grant 12-G-009.

Driskell, J. E., and Johnston, J. (1998). Stress exposure training. In J.A. Cannon-Bowers, and E. Salas (Eds.), *Making decisions under stress*. Washington, D.C.: American Psychological Association.

Federal Aviation Administration (2006). *Advanced qualification program*. (Advisory Circular 120-54A). Washington DC.

International Civil Aviation Organization (2012). *Manual of evidence-based training*. Doc 9995, First Edition, Montreal, Canada: International Civil Aviation Organization.

Kochan, J. A., Breiter, E. G., and Jentsch, F. (2004). Surprise and unexpectedness in flying: Database reviews and analyses. *Proceedings of the 48th Annual Meeting of the Human Factors and Ergonomics Society*. (pp. 335-339).

Rivera, J., Talone, A. B., Boesser, C. T., Jentsch, F., and Yeh, M. (2014, September). Startle and Surprise on the Flight Deck Similarities, Differences, and Prevalence. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 58, No. 1, pp. 1047-1051). SAGE Publications.

Tversky, A. and Kahneman, D. (1974), Judgment under uncertainty: Heuristics and biases, *Science, 27,* Vol. 185, no. 4157, pp. 1124-1131.

Thomas, M. (1989). *Managing pilot stress*. Philadelphia, PA: Lippincott.

Table C2. Example Syllabus for Stress Mitigation Training

Stress Mitigation Training Topic	*Learning Activity/Learning Outcome*
Types of stressors and defining stress	Online learning module on stressors specific to flightcrews.
Attention, working memory, and stress	Online learning module with example scenario to point out specific cognitive skills that could be affected by stress.
Stress and decision-making	Online learning module with example scenario to point out specific cognitive skills that could be affected by stress.
The effects of stress on team performance and communication	Online learning module with example scenario demonstrating the effects of stress on team performance. Use live ATC tapes and discuss the changes in communication styles and effectiveness.
Cognitive appraisal model and stress mitigating exercises	Online or face-to-face discussions and exercises. Introduce the cognitive appraisal model and how humans react to and deal with stressful situations. Introduce methods found to be effective in reducing stress in unexpected situations.
Preparing for LOFT sessions to practice dealing with stress events	Introduce sample LOFT scenarios to review prior to simulator session. Have crewmembers discuss the factors in the scenario (other than just being in the simulator) that may induce performance-degrading stress.
Stress scenario LOFT session(s)	Complete stress scenario LOFT. (Instructor training for the stress events should be a separate training event).
Debrief on stress effects on human performance	Using crew-centered debrief, review the LOFT with a focus on the stress aspects.
New and recurrent topics on stress and pilot performance	Using ASAP and ASRS data, keep crewmembers informed of good examples of dealing with stressful events and review events where stress may have been a factor in the pilot responses and outcome of the event.