CRM Principles and Practices for SPO

Literature Review

Final Report

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Introduction

Crew Resource Management has been an integral part of flight crew training since the 1970s, when it became clear that commercial aviation required more from a pilot than excellent stick-and-rudder skills. CRM training and practice brought about a focus on non-technical skills such as leadership, communication, and decision making, and on the crew rather than the individual pilot as the unit of measurement. Flight crews were trained on principles and practices for managing resources, identifying threats and trapping errors in the cockpit, and two (or in earlier aircraft, three) pilots sat together in the cockpit and worked as a team to ensure flight safety and efficiency. This side-by-side CRM collaboration was facilitated by a common knowledge base, shared goals and priorities, clear roles and responsibilities, and the use of gestures and signals to supplement verbal communication.

As CRM training and evaluation evolved through several ‘generations,’ they became increasingly behaviorally-based and standardized. Our observations of current CRM training modules indicate that across airlines coursework is geared toward the identification and management of threats and errors (TEM; see discussion in Section 1) and that similar themes are addressed (see report on CRM Interviews and Observations).

CRM is likely to look different in Single Pilot Operations (SPO), as every facet of CRM will be significantly altered from what is present today. Team building and maintenance will involve not only the pilot on the aircraft but also remote crewmembers on the ground. Current team building techniques such as briefings will need to be revised or restructured in order to be effective in the new distributed team. Communication will be altered significantly in SPO, as the affordances of face-to-face verbal interaction will be missing and some air-ground communication will be managed via data link. More frequent and very precise exchanges will be needed to establish shared mental models among remote crewmembers and verbal signifiers must be incorporated into procedures to compensate for missing non-verbal cues. Moreover, the impact of status and position differences on communication are likely to be exacerbated in SPO, as crewmembers on the ground may be regarded – and may regard themselves - as having lower status than Captains onboard the aircraft.

Team problem solving and decision making depends heavily on common ground among team members. This will be difficult to establish when crews are geographically dispersed in SPO. Moreover, varying types or levels of relevant expertise, different priorities and goals are likely to impact the effectiveness of decision making processes and outcomes. Maintaining situation awareness (SA) will also be a challenge in SPO. Shared situation models will be difficult to develop as remote crewmembers will not have direct access to all information sources – for instance, ground personnel will not have out-the-aircraft-window views. Shared task models will be dependent on collaborative tools or explicit procedures (including checklists) to make clear ‘who is doing what.’ Displays and procedures must foster the development of shared situation models and clarify tasks for all crewmembers.

Perhaps the most significant challenge for CRM in SPO will be in the area of managing automation. Sophisticated technology will be a key driver of SPO, and automation may be treated more as a team member than is the case in current operations. CRM issues for
automation use in SPO include function allocation between humans and automated systems, ensuring appropriate decision support for pilots and other crewmembers, and avoiding automation pitfalls such as complacency and automation bias.

In this report, we review the literature on CRM training, practices and procedures, with an eye toward how these might apply (or not) in SPO. Section 1, Background and History of CRM, contains a historical overview of the development of CRM and its evolution from Cockpit Resource Management to Crew Resource Management to Threat and Error Management. We discuss difficulties and issues inherent in training and evaluating the effectiveness of CRM/TEM behaviors. Section 2, Components of CRM/TEM, includes theoretical background for each of the areas of CRM (Team Building and Maintenance, Communication, Problem Solving and Decision Making including SA and Shared Situation Models, and Managing Automation), and provides a review of relevant literature for each area. The final section, Recommendations for CRM/TEM in SPO, contains recommendations derived from the literature for training, procedures, and automation design and practices for SPO.

This report is supplemented by an annotated bibliography as well as a spreadsheet listing of references on CRM and CRM-related literature. A separate report (CRM Interviews and Observations) contains a synthesis of CRM interviews with pilots, CRM and DRM (Dispatch Resource Management) managers and training personnel and observations of CRM and DRM training courses.

**Background and History of CRM**

*In the early years, the image of a pilot was of a single, stalwart individual, white scarf trailing, braving the elements in an open cockpit. This stereotype embraces a number of personality traits such as independence, machismo, bravery, and calmness under stress that are more associated with individual activity than with team effort.* (Helmreich & Foushee, 2010, p. 5)

**Cockpit Resource Management**

The US concept of Cockpit Resource Management (CRM) emerged in the 1970s from the realization that many of the accidents attributed to ‘pilot error’ were not caused by deficiencies in stick-and-rudder skills, but rather were rooted in non-technical factors such as decision making, leadership of command, communication, or crew coordination (e.g., Helmreich, Merritt, & Wilhelm, 1999b). A NASA full-mission simulation study led by British researcher Hugh Patrick Ruffell Smith produced the startling finding that most of the unresolved performance problems in the simulation scenarios were not due to insufficient resources, but instead to a failure of the crew to use all of the resources available to them, including other crewmembers (Ruffell Smith, 1979). The identification of skills related to efficient resource use led to the creation of CRM training programs, and initial efforts were formally presented and discussed at a 1979 NASA workshop. Importantly for the advance of CRM theory and training, NASA and the FAA established the confidential and non-punitive incident reporting system ASRS (Aviation Safety Reporting System) in 1976, initiating an analyzable database of human behavior and errors in aviation operations.
At the same time, recognition was growing across the world that human factors, defined as the concern “…to optimize the relationship between people and their activities by the systematic application of the human sciences, integrated within the framework of systems engineering” (Edwards, 1985, in Hawkins, 2002, p. 19), was a critical element in flight safety. The 1975 International Air Transport Association (IATA) conference in Istanbul focused on human factors, and is seen by some as the point at which recognition of the importance of human factors in air transport operations became official (Hawkins, 2002). Cockpit Resource Management became the accepted face of human factors in the aviation industry and many operators used the terms interchangeably, although they are in reality different concepts (e.g., Jensen, 1997).

Crew Resource Management

By the time of the second NASA industry workshop in 1986 (Orlady & Foushee, 1986), many commercial airlines in the US and elsewhere had initiated some type of resource management training for cockpit crews. Unfortunately, emphases on psychological testing and general concepts without clear definition and training of appropriate behaviors limited the acceptance and success of these early training programs (Helmreich et al., 1999b). A second generation of training programs, called Crew Resource Management, focused on aviation- and operation-specific group dynamics concepts such as team building, situation awareness, stress management, briefings, and decision making. Subsequently, third generation CRM programs extended the scope to the entire flight operations crew, with many airlines extending training to flight attendants (some with joint cockpit-cabin modules), dispatchers, and maintenance personnel. Special CRM training for Captains focused on leadership roles (Helmreich et al., 1999b).

The FAA Advanced Qualification Program (AQP) initiated in 1990 was a factor in fourth generation CRM. According to this voluntary program, airlines are given flexibility in developing training programs as long as they provide CRM training for all flight crews and integrate it into technical training as well as LOFT (Line Oriented Flight Training). As part of these programs, many airlines began to extend the focus of training and evaluation from the individual to the group or crew, and to proceduralize specific CRM behaviors evaluating crews based on behavioral markers.

Threat and Error Management - TEM

The fifth and current generation of CRM training shifted its focus from error avoidance to Threat and Error Management (TEM). TEM is rooted in the knowledge that errors are inevitable in normal operations, and that when crews recognize and acknowledge threats in a timely fashion, they are in a better position to manage them successfully. A threat is any event or element in the operational environment with the potential to harm. Threats faced by flight crews are varied and include external factors such as high terrain as well as internal factors such as aircraft malfunctions, fatigue, tendencies toward complacency and automation bias, or miscommunication between crewmembers. Threat management typically refers to how crews anticipate and/or react to threats in the environment. Types of flight crew errors include aircraft handling, procedural and communication errors (Merritt & Klinect, 2006). Aircraft handling errors involve aircraft direction, speed and configuration. Procedural errors occur when the flight crew deviates from regulations,
requirements or airline standard operating procedures. Communication errors involve miscommunications or misunderstandings between crewmembers, or between pilots and flight attendants, ATC controllers, and ground personnel.

TEM emphasizes three concepts: anticipation of threats, recognition of threats and errors, and recovery from errors. Training focuses on identifying potential threats and dealing with them via overlapping lines of defense: avoiding errors (prevention), trapping errors before they are fully committed (intervention), and managing the consequences of any errors that occur (mitigation; Merritt & Klinect, 2006). Effective threat management effectively reduces the complexity of the operational environment, decreasing the potential for crew error. Interactive communications, vigilance, monitoring and cross-checking are CRM strategies that assist crews in identifying threats and trapping errors (Gunther, 2010).

In order for the TEM approach to gain acceptance, airlines had to counter pilot concerns of punitive responses to error by reinforcing the fundamental TEM assumptions that errors will occur and can be managed (Helmreich et al., 1999b), and that effective error management should be rewarded (Gunther, 2010). TEM is now accepted as both the process and the goal of CRM in flight training, and crews are typically held responsible not only for their technical skills but also for their skills at using CRM behaviors as effective error countermeasures (Gunther, 2010).

Although the practice of TEM is generally believed to enhance flight safety, research examining its antecedents and outcomes is relatively sparse. In one of the few empirical studies, Thomas (2004) analyzed the types of contextual factors and nontechnical skills that support TEM. He examined the outcome of crews’ TEM actions across 323 flight observations. Over half (57.4%) of the 451 observed threats were well managed by the crews and did not lead to errors. However, nearly half of the errors that did occur remained undetected by the flight crew. Most errors (85%) occurred during high-workload phases of flight (pre-departure, takeoff, and descent/approach or landing). If the flight was late to depart, crews were almost twice as likely to fail to respond to errors during all phases of flight – suggesting that disruptions early on may induce rushed or error-prone behavior that continues throughout the flight. This tendency may be exacerbated in SPO, as pilots will not only have to deal with disruptions that delay their flight, but will also have to handle all other aspects of flight by themselves.

Thomas' (2004) findings suggested that the contribution of contextual factors and nontechnical skills was different for effective threat management when compared to effective error management. SA and decision making were related to effective threat management across all phases of flight, and decision-making performance, experience of the first officer, and experience of the captain were significant predictors of errors being trapped (managed) by the flight crew. Team building and maintenance behaviors as well as communication were also related to TEM. For example, briefing and planning increased the likelihood of effective threat management, and cooperation and interactive functions impacted performance during the preflight phase. Thomas concluded that “...a close relation exists between interactive group processes and effective threat and error management on the flight deck” (p. 223), a conclusion that is likely to be important for SPO.
Effective TEM will be essential in SPO. Flight crews in current operations are jointly responsible for TEM, providing two sets of eyes and ears to identify threats, trap errors, and cross-check actions. With the absence of a second pilot, current procedures will need to be revised and new procedures and crew processes for detecting and managing threats and errors will be required.

**CRM/TEM Training**

Early CRM training had mixed success, due in part to a lack of standardization in both methodology and training techniques. Many pilots reported that CRM training was interesting and informative, but that it was difficult to utilize the skills in the cockpit. In response to these issues, researchers recommended a more theoretically-driven approach to training development, processes and procedures, and evaluation (e.g., Salas, Prince, Bowers, Stout, Oser, & Cannon-Bowers, 1999; Salas, Wilson, Burke, & Bowers, 2002; Salas, Wilson, Burke, Wightman, & Howse, 2006), with the use of data from 1) “...formal evaluations of performance in training and on the line; 2) incident reports; 3) surveys of flight crew perceptions of safety and human factors; 4) Flight Operations Quality Assurance (FOQA) programs using flight data recorders to provide info on parameters of flight; [and] 5) Line Operations Safety Audits (LOSA)” (Helmreich, 2000, p.4) to identify effective behaviors for recognition and management of threats and appropriate responses to (traps for) errors. These recommendations and data sources should be used to guide the iterative design and evaluation of Single Pilot Resource Management (SRM) training and evaluation as well.

**LOEs and LOSAs.**

Behavioral data for evaluation of CRM/TEM training and effectiveness are typically collected in the context of simulated or actual flight operations. Line Operational Evaluations (LOEs) provide one opportunity to evaluate pilot CRM behaviors and provide customized feedback in a full-mission simulation. Approaches such as the Event-Based Approach to Training (EBAT) enable training developers to identify events that elicit specific CRM-related behaviors and to build elaborate scenarios that target multiple skill sets and Targeted Acceptable Responses to Generated Events or Tasks (TARGET; Curtis & Jentsch, 2010) in scenarios involving different phases of flight.

One issue for LOEs, however, is that they do not guarantee that CRM/TEM behaviors in the simulator will transfer to line operations (Helmreich, Kline, & Wilhelm, 1999a). LOSA, or the Line Operations Safety Audit, addresses this issue. The LOSA concept was developed in parallel with TEM, and was designed to collect normative data on how crews perform during actual flights. LOSAs use several methodologies to assess the strengths and weaknesses in flight operations. It is systematic and ‘non-jeopardy,’ that is, crewmembers are not penalized for anything uncovered during an audit. It includes both objective and subjective data - observations of crews are complemented by structured interviews that include questions about safety issues and pilot attitudes concerning the current state of flight operations. Data collected using LOSAs have been used to help organizations develop customized safety procedures and operations as well as training, to provide them with a view of normal operations, and to allow them to calculate the risk associated with different crews or environments (Helmreich et al., 1999a; 2001).
Early iterations of LOSA assessed behaviors related to CRM, technical proficiency and overall performance. As CRM started focusing on TEM, so did the audits (Helmreich et al., 1999a; 2001). The first TEM-based LOSA was conducted in 1996. Shortly after, Klinect, Wilhelm, and Helmreich (1999) audited three airlines with a total sample of 184 flight crews spanning 314 flight segments. Observers documented threats, recorded flight crew errors based on type, management, response, and outcome, and evaluated the crews on several CRM behavioral markers. Klinect et al. identified 606 external threats, with at least 72% of segments having at least one external threat – most often during descent, approach, or landing. Over half of all the threats that led to errors were due to unusual Air Traffic Control (ATC) commands. Interestingly, 22% of threats occurred while on ground and were likely due to delays and irregular operations. Intentional noncompliance accounted for more than half of the errors observed, but these were also the least consequential. The factors that had the most impact on error management included strong leadership, flight crew vigilance, comprehensive briefings, contingency planning, stating important information, asking questions, and speaking up. Although the data from Klinect et al. (1999) is somewhat dated, it is likely that the same TEM patterns – in terms of phase of flight differences, ATC interactions, noncompliance, and ameliorating crew variables - will be present in SPO.

By 2000, an analysis of one airline’s LOSA data in comparison to 1996 data showed that error management principles had been accepted and incorporated into everyday operations. LOSA data indicated that effective crews were not only good error managers, but more importantly were good threat managers. At this point, the effective strategies that crews utilized for threat/error management were developed into Standard Operating Procedures (SOPs; see Kanki, Helmreich, & Anca, 2010a) and used as the basis for training and evaluation of CRM/TEM.

**Single pilot LOSA**

Earl, Bates, Murray, Glendon, and Creed (2012) devised and tested a LOSA specific to SPO to determine whether single-pilot performance could be adequately rated using four standard categories of threat and error countermeasures: crew climate, planning, execution, and review/modification. They observed a sample of single-pilot subjects during fourteen flights, and noted that the top five most common threats included air traffic control interactions, airport conditions, weather, and operational and other environmental conditions. Consistent with two-pilot LOSA data, the majority of identified errors occurred in the pre-departure/taxi-out phase, followed by the descent/approach/landing phases of flight. Earl et al. noted high rates of intentional noncompliance on checklists, suggesting that some procedures were not necessarily appropriate for SPO circumstances. Communication with an external party, such as ATC, was identified as a significant risk in SPO. Single pilots who verbalized their intentions made fewer procedural errors or errors that were incorrectly managed than those who did not. In general, the threats, errors, and undesired aircraft states that were identified in SPO were similar to standard crew operations, but the need for more SPO-specific research was emphasized.

One issue in SRM/TEM training will be whether it requires the high-fidelity simulator environment. Salas et al. (2002) argue that a high level of psychological fidelity rather than physical environment fidelity is key for learning non-technical skills. Psychological fidelity
induces trainees to simulate cognitive processes similar to those needed in flight situations. Brannick, Prince, and Salas (2005), for example, found that PC based training was effective for assertiveness training – that is, teaching low experience pilots to speak up and question more experienced controllers when they recognize an error or a clearance that puts them in a risky situation. Likewise, Kearns (2011) targeted SRM computer-based training through hands-on practice and guided mental practice and demonstrated that guided mental practice accompanying computer-based SRM training results in improvements in situational awareness equivalent to traditional hands-on practice.

**CRM/TEM Evaluation**

Evaluation of the success of CRM/TEM training is difficult, as the non-technical skills involved are less amenable to demonstration and measurement than technical skills. Additionally, an ongoing challenge to CRM/TEM evaluations in LOEs and LOSAs is ensuring consistency, comprehensiveness, and comparability across raters (Baker & Dismukes, 2002; Deaton, Bell, Fowlkes, Bowers, Jentsch, & Bell, 2007). The use of behavioral markers or checklists, standardized systems to rate non-technical skills such as NOTECHS (Flin et al., 2003), and automated tools such as EPIC (Enhancing Performance with Improved Coordination; Deaton et al., 2007) have helped to ensure consistency in performance evaluation.

The most commonly used evaluation in CRM trainings is Kirkpatrick's (1976) model. Kirkpatrick prescribes four levels of evaluation: reaction, learning, behavior, and results. A meta-analysis of studies reporting one or more of these levels of evaluation for CRM/TEM effectiveness suggested that training had a definite effect on participants' attitudes and behaviors, and a medium effect on knowledge (O'Connor, Campbell, Newon, Melton, Salas, & Wilson, 2008). It should be noted that fewer than 16 of the 74 identified evaluation studies included data that were amenable to meta-analysis – highlighting the difficulties of stringent assessment of CRM/TEM training effectiveness.

O'Connor et al. (2008) concluded that there is no unequivocal answer to the question of whether CRM training is fulfilling its ultimate purpose of increasing safety and efficiency. CRM training evaluation has almost exclusively been carried out under Kirkpatrick’s (1976) framework, with limited success and/or generalizability. For example, O’Connor, Hörmann, Flin, Lodge, Goeters, & the JARTEL Group (2002) and Salas, Burke, Bowers, & Wilson (2001) showed some evidence of changes in behavior; however, Salas, Wilson, Burke, Wightman, and Howse (2006) observed no conclusive behavioral transfer. The organizational impact of CRM training is hard to assess due to low accident rates in airlines or other industries that implement the training. Moreover, CRM training designed for specific airline organizations does not transfer well to other organizations (Suffler, Salas, & Xavier, 2010). This finding highlights the need to consider organizational climate in training design; an issue that will also be important in SRM training development.

Developing CRM/TEM training and procedures specific to SPO that are robust enough to apply across airline cultures will be a daunting challenge. The literature on CRM/TEM and related topics captures the recognized issues and challenges for current CRM principles and practices, and also offers insights as to how these issues and challenges may play out in SPO. The most critical issues and challenges are described below, along with
recommendations for addressing them in Single-Pilot Resource Management. According to the FAA AC 120-51E (CRM Training), CRM activities include team building and maintenance, information transfer, problem solving and decision making, maintaining SA (Situation Awareness), and managing automated systems. Summaries are organized in terms of these processes and activities.

**Components of CRM/TEM**

**Team Building and Maintenance**

CRM/TEM in aviation is essentially a team process. A team is typically defined as a group in which members have specialized expertise aligned with their roles and responsibilities, members’ behaviors are interdependent, and communication is essential for coordinated action toward a common valued goal (Dyer, 1984). In current operations, the primary ‘team’ is the flight crew of multi-crew aircraft; other aviation teams include the flight crew interacting with Air Traffic Control (ATC) and the flight crew interacting with their Airline Operations Center (AOC). To the extent that automation is becoming more ‘intelligent’ and ‘adaptive,’ we may also consider the crew and flight deck automation as a team (Christoffersen & Woods, 2002; Prevot & Onken, 2003).¹

Effective interactive group processes for TEM are dependent on team building and maintenance behaviors. Team performance in general involves taskwork and teamwork (Cannon-Bowers, Salas, & Converse, 1993). Taskwork concerns behaviors that support a team’s task performance. Team members need to be vigilant, communicate to ensure shared situation models, manage workload effectively, respond adaptively to changing conditions, anticipate future developments, and monitor their progress and performance. Teamwork behaviors address the functioning of a team as a team, in particular maintaining a positive and open crew climate, and using compensatory strategies to manage fatigue or stress.

On the current flight deck, crewmembers share expertise. Both are pilots and have undergone the same crew training courses at their airline. Consequently, they have a common stock of knowledge concerning the operational environment, aircraft systems, procedures, practices and strategies. This shared expertise allows pilots to alternate roles of pilot flying and pilot monitoring during flight segments, and to divide responsibility for monitoring the environment, processing information, communicating with the outside resources, managing systems, preventing and correcting errors, and making decisions. The presence of two pilots helps to overcome limitations associated with individual stress, fatigue, situation complexity and workload, and thus promotes safe operations.

In contrast, teams that involve pilots and ATC, AOCs or other ground-based resources such as maintenance are geographically distributed. Communication between air and ground is mediated, and data sharing is frequently computer based. Moreover, spatially

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¹ Another type of distributed team includes members of airline operations centers (AOC) interacting with air traffic management, primarily during flight planning and replanning, a topic that will not be addressed in this report.
separated team members lack shared access to environmental cues or operator state knowledge. Perhaps most importantly, remote or distributed team members may have differences in their underlying knowledge, information sources, organization goals, roles and responsibilities. These differences may be the basis for misunderstanding, conflicts, or alternative evaluations of risk, as demonstrated in flight crew-ATC disconnects identified by Bearman, Paletz, Orasanu and Thomas (2010). Communication disconnects in this study highlight potential problems for SPO regarding remote team maintenance and cohesion. The data suggest that while both aircrews and ATC are concerned with overall system safety, local tactical goals may differ: controllers focus on keeping aircraft separated, maintaining the system flow, and managing their workload; flight crews, in contrast, worry about on-time arrivals and providing passengers with a smooth ride.

An empirical question is whether and how team-building and maintenance processes from current operations should be carried into SPO. One of the most important challenges for CRM in SPO will be to build cohesive crews with distributed players – pilots and ground support – who have varied priorities and goals. This will be especially tricky if the ground person following the flight and interacting with the pilot is also tracking 10 other flights, or if ground support personnel change during off-nominal situations. The ability to create a cohesive crew will depend in part on the roles and responsibilities assigned to each remote crewmember.

**Team Member Roles and Responsibilities**

In distributed flight operations as in other remote team settings (see Ebrahim, Ahmed, & Taha, 2009 for a review of virtual/remote teams), it will be important that pilots and remote crewmembers have clear roles and responsibilities. The current roles of PF/PM (pilot flying/pilot monitoring) are defined by a specified set of tasks and responsibilities and each pilot in the crew knows exactly what to expect from the other. Responsibilities of other personnel in the conduct of flights - such as dispatch or maintenance - are not as clearly delineated, and the extent to which these operations personnel are currently involved in CRM/TEM with pilots varies by airline and flight context. Cahill, McDonald, and Losa (2013), for example, found differences in the role of dispatchers (e.g., level of interaction with crew) and with the use of computers in the briefing process (some used hardcopy to access briefing packages) across five airlines and across situations within airlines. In longer or complicated flight circumstances, the dispatcher was involved more directly with flight crew. For example, on a complicated non-routine flight, the crew was likely to review the briefing (flight decisions) with dispatch.

Roles and responsibilities will need to be re-specified for SPO and an empirical issue concerns the extent to which ground personnel should be involved in TEM for specific aircraft. For example, when (if ever) should ground personnel be expected to perform the PM function in the cockpit – especially with respect to monitoring tasks and cross-checking of automation and automation inputs? One-to-many models of ground support preclude the intensive monitor/crosscheck functions of the current PM – and even when pilots solicit dedicated support, the extent to which ground personnel should be involved in TEM and decision making is unclear. Should ground team members perform a push or pull function? That is, should crewmembers on the ground be expected to be proactive in
identifying information needs, issues or problems in all of their aircraft and pushing information to the pilots or volunteer to perform tasks - or is the pilot responsible for requesting (pulling) support? Responsibility for non-specific support tasks (e.g., getting the ATIS, checking the weather) will also need to be specified, as well as responsibility for psycho-social functions such as engaging in non-operational conversations to help keep the pilot alert, and most critically for pilots onboard the aircraft, when (if ever) should ground personnel take over the flying task?

In general, all of the questions above concern the role of ground crewmembers in managing overall flight workload. Without the second pilot onboard, there is an increased chance that the Captain’s workload will become overwhelming. Burian (2007) looked at workload and performance in incidents and accidents in single-pilot very light jets (VLJs) over a 12-month period. Significant risks were indicated in single pilot operations specific to planning, such as inadequate preparation for takeoff and landing, inadequate preparation for climbs at high rate or speed, inadequate checklist use, low fuel arrivals, and lack of compliance with preflight inspection and preparation procedures. There were also broad and pervasive problems with SRM that likely influenced problems with planning. It is clear that pilots in SPO will need to be more proactive concerning workload than in dual pilot operations, and both pilots and ground personnel will need training on roles and responsibilities for workload management. In particular, pilots will need to work with ground crewmembers to get as much information and complete as many activities as possible during pre-flight and low workload phases.

**Trust**

Trust among team members, is an important determinant of successful task performance (Ebrahim et al., 2009). A finding most relevant to SPO is that in remote teams trust can lower the adverse impact geographic distribution has on team members (Martins, Gilson, & Maynard, 2004). Moreover, high levels of trust among remote team members has been associated with predictable communication patterns, provision of feedback on performance, positive leadership, enthusiasm, and ability to cope with technical uncertainty (Moe & Smite, 2008).

Trust in SPO distributed crews will have two components: trust in *capability* and trust in *accountability*. Because virtual teamwork relies heavily on perception of trustworthiness, perceptions of ability may be a more important factor in trust prediction among virtual crews than in co-located crews (Yakovleva, Reilly, & Werko, 2010). Pilots must be able to trust that ground personnel have the *capability* to understand their situation, handle their needs, and share their priorities and concerns. This component of trust may become an issue if pilots feel that ground support personnel are not as expert as they are or are unfamiliar with flightdeck tasks and activities. It will also depend on the extent to which pilots consider dispatch, maintenance, or other ground personnel to be crewmembers rather than just ‘resources.’

Pilots must also trust that ground personnel will feel *accountable* to be responsive to their needs and requests. If ground personnel are supporting multiple aircraft at once, their sense of accountability to any one aircraft may decrease. Additionally, some research has shown that when team members are unable to see one another they may feel less
accountable for the results of the mission, or may exhibit ‘social loafing’ if they believe there is no way for anyone to know if they are underperforming (Gilson, Maynard, & Bergiel, 2013).

**Leadership and Briefings for Team Building**

The Captain of the aircraft as leader of the distributed team will set the tone for team processes. The Captain’s leadership creates the foundation for effective strategies to manage threats and trap errors (Helmreich & Foushee, 2010). Captain’s briefings comprise a critical leadership activity in current operations insofar as they give captains an opportunity to establish common goals, create a positive crew climate, and promote inquiry, advocacy and assertiveness – not just by talk, but also by modeling (Cahill et al., 2013; Ginnett, 2010).

The importance of briefings is likely to increase in SPO, especially if remote team members differ in terms of expertise and responsibilities. Research with distributed teams in other domains suggests that briefings with remote members serve several functions. During the initial phase of remote teamwork, it is important that the leader ensures that team members have a common understanding of their task, in particular what their objectives are, their plans, their individual roles and responsibilities, and how they as a team are to interact (Cannon-Bowers & Salas, 2001; Shuffler, Wiese, Salas, & Burke, 2010). Additionally, these face-to-face meetings of distributed members could provide the personal contact that is necessary for team building and cohesion; a point emphasized in the literature on virtual team management (e.g., Hertel, Geister, & Konradt, 2005).

**Joint Training for Team Building**

The challenge of building and maintaining a cohesive team in SPO will be daunting. Participation in joint training or cross-training would be one way for pilots and ground personnel to learn about the other’s perspective and develop trust in each other. Research in anesthesiology CRM (ACRM; Gaba, Howard, Smith, Smith, & Sowb, 2001), for instance, has demonstrated the positive impact of rotating team members through different roles in the operating room. This cross-training provides practice in rapid transfer of information and establishment of leadership. Having members simulate each role also enables a full understanding of what other roles entail and how those roles interact.

Joint training would also enable the proceduralization of team processes across air and ground team members and facilitate team building and maintenance. Holt, Boehm-Davis, and Hansberger (2000) examined the effectiveness of Advanced Crew Resource Management (ACRM) training, which included proceduralization of certain CRM behaviors and a broad sequential framework for communication and coordination among team members. They tested their procedural intervention within a commercial airline and found evidence of better performance in team communication, planning, and decision-making by the ACRM trained pilots compared to the control group. Their results suggest that proceduralization of certain essential teamwork components can be beneficial – a concept that could almost certainly extend to SPO.

Currently, many airlines have resource management programs for flight attendants, dispatchers and maintenance personnel (e.g., DRM - Dispatch Resource Management; MRM
- Maintenance CRM; Taylor & Patankar, 2001), but most airlines do not provide more than a brief segment of joint training for pilots, flight attendants, maintenance and dispatch (e.g., one training module or visit to an operations or maintenance center). If these distributed crewmembers are expected to function as a cohesive team in SPO, much more in-depth joint training will be required.

**Communication**

Team communication is an essential component of crew resource management. Typically CRM courses focus on Captain-First Officer communications, and may also address communication between pilots and flight attendants. Communication issues with other players, such as ATC, dispatch or maintenance are rarely included. Crew communication research, in contrast, has examined both issues specific to flight deck crews as well as the challenges of remote communication, in particular of pilot-ATC interactions. Because pilot communication in SPO will involve remote partners, our review will also include a discussion of research on pilot-ATC communication.

Crew communication became a central topic in CRM courses after aircraft accident and incident analyses indicated that breakdowns in pilots’ interactions played a significant role in these events. Pilots’ communication failures can be traced in part to challenges inherent in their operational environment. Crew communication occurs concurrently with other piloting tasks such as monitoring systems, interacting with air traffic control, or inputting information into the flight management system. Consequently, because pilots need to divide their attention between these tasks and crew communication, they may fail to share task-critical information, neglect to ensure a common understanding of their flight situation or not adequately monitor their colleagues’ actions. A second communication-related challenge pilots face concerns the social characteristics of their work environment. While crewmembers have a shared set of expertise, status differences between them and the fact that they often do not know each other prior to their first flight segment may hamper communication, especially in situation in which they need to challenge decisions and actions by their colleague (Brown & Moren, 2003; Fischer & Orasanu, 2000; Linde, 1988; Orasanu, Fischer, McDonnell, Davison, et al., 1998; Thomas, 2004).

**Intra-Crew Communication**

In the current cockpit, pilots can take advantage of characteristics of face-to-face communication (Clark, 1996). As they sit side by side, crewmembers may presume as mutually known information that is in their shared visual field and can rely on gestures and facial expressions to direct the other’s attention and provide feedback on understanding. For instance, pilots can point to instruments to establish shared references, and may come to a shared situation understanding by observing their colleague’s actions (Segal & Jobe, 1995). However, non-verbal communication is inherently ambiguous and open to multiple interpretations and thus may not be sufficient to support common ground. For instance, by observing the First Officer interact with the FMS, a Captain may infer that information in the flight computer has been changed but there is no certainty that this indeed has happened nor any understanding as to what changes took place. Additionally, research has
shown that pilots have interpreted flight situations differently even though they were presented with the same weather data and systems indications (Fischer, Orasanu, & Wich, 1995; Fischer, Orasanu & Davison, 2003).

Communication procedures and tools—such as specific callouts, prescribed communication sequences and checklists—have been developed to enable pilots to come to a shared understanding of their flight situation at relatively low cognitive costs. However, not all pilot communication is —nor can be—governed by standard operating procedures. Non-SOP talk goes beyond the exchange of routine information and may concern some flight safety-related event or problem and pilots’ problem solving efforts (Orasanu & Fischer, 1992). The need for communication efficiency and effectiveness is heightened in these situations as crewmembers face off-nominal events and need to make decisions under considerable time pressure and dynamic conditions. To identify communication behaviors that support flight deck crew performance and thus flight safety in these situations, researchers have employed a multitude of methodologies, ranging from the analysis of “black-box” recordings of crew communications during aircraft accidents and the analysis of crew discourse during flight simulations to scenario-based surveys.

A recurrent finding has been that successful crew performance is associated with explicit communication. Explicitness is used here to refer to both the amount of task-related communication and the cognitive transparency of crewmembers’ contributions. With respect to the former, research showed that high-performing crews shared more information about the problem they faced and talked more about their response to it than did poorly performing crews (Bourgeon, Valot, & Navarro, 2013; Helmsich & Foushee, 2010; Mjos, 2001; Sexton & Helmreich, 2000); in particular, successful teams were more likely to articulate new plans and changes in task allocation and expectations about future events (Gillan, 2003; Orasanu & Fischer, 1992). Members of successful crews were also more explicit about their reasoning. For instance, Bourgeon and colleagues (Bourgeon et al., 2013) found that crews who discussed critical aspects of their current flight situation and justified their opinions based on available information, were also less likely to commit continuation errors; i.e., to stick to a plan of action even in the face of information inconsistent with their decision. Likewise, research by Fischer and Orasanu (2000) and Fischer, Rinehart, and Orasanu (2001) indicates that pilot error is best mitigated when the other crewmember not only corrects the mistake but also mentions a reason for his or her intervention. It is important to note that pilots did not consider these complex utterances (i.e., correction plus reason) as more polite; rather they judged them as more informative and consequently as more effective in changing their behavior. In detailing their reasoning and providing a context for their assessments, crewmembers lay out their situation model, ensure that others share their understanding, and thus reduce the likelihood of misunderstandings as fewer inferences are required by their team mates. At the same time, they invite others to verify the accurateness of their judgments and associated decisions and, on a more subtle level, create a team climate characterized by open communications.

Communication efficiency is also enhanced if crewmembers engage in ‘closed-loop’ communication (Kanki, Lozito, & Foushee, 1989) by which team members immediately acknowledge or answer an initiating utterance. In so doing, crewmembers may reduce their cognitive load because conversations have a tight structure and thematically related
contributions follow one another in a coherent fashion. Read-backs or active listening that builds on the prior utterance (Fischer, McDonnell, & Orasanu, 2007) are strategies with which pilots can indicate understanding of what was said. Adherence to these practices is common in high-performing flight deck crews whereas violations are prevalent in crews involved in aircraft accidents and incidents (Dietrich, 2004; Kanki et al., 1989).

**Monitoring/challenging**

Monitoring/challenging is one of the most important components of intra-crew communication for TEM. In fact, a primary focus in CRM/TEM training is on enforcing ‘monitor/challenge’ procedures as part of each crewmember’s responsibilities. Crew monitoring allows pilots to double-check each other’s actions and to catch errors. Effective crew monitoring and cross-checking can enhance overall flight safety; poor monitoring/challenging performance has been identified as a factor contributing to aviation accidents and incidents. An examination of two-hundred ASRS incident reports, for example, revealed that monitoring errors resulted in a host of problems including altitude deviations, controlled flight towards terrain, loss of aircraft control, stall onset, and deviations in course, heading and track. Additionally, data from over 2000 LOSAs revealed that 64% of unintentional errors in that sample were undetected by the flight crew (Sumwalt, Thomas, & Dismukes, 2002).

Checklists are typically viewed as the best line of defense against errors and offer a standardized venue for monitoring and cross-checking. They provide a memory aid for dealing with normal and off-nominal situations, as well as a mechanism for team members to share critical information about the state of the aircraft (Hazlehurst, 2003). Current checklists, however, may be inappropriate or impractical for SPO. Earl and colleagues (Earl et al., 2012) created and tested a single-pilot LOSA and found that checklists comprised the largest category of errors, including incorrect or late checklists, missed items, or items performed from memory. Additionally, required cross-verifications were sometimes not carried out by the single pilot. Without the cross-check of a second pilot, ensuring that items have been performed on time and correctly will require some other method of verification in SPO.

**Status and position issues in team communication**

Cockpit crews have a hierarchical structure. Captains are of higher rank than first officers; they are usually the more experienced pilot in the crew and, as pilot in command, have final authority and responsibility for the operation and safety of the flight (CFR Title 14 Part 1 Section 1.1). Differences in status and experience between team members give rise to status generalization; that is, an individual’s status or seniority influences other team members’ perceptions of his or her competence, and how much he or she contributes to and shapes the team’s problem solving and decision making (Milanovich, Driskell, Stout, & Salas, 1998). For instance, Prince and colleagues (Prince, C., Salas, Brannick & Prince, A., 2010) examined communication and decision processes in military crews and observed that commanders predominantly issued commands rather than indirect requests to direct the actions of co-pilots and often ignored input from them, even if they were their equals in terms of flight experience. On the other hand, in crews comprised of equally inexperienced pilots, co-pilots tended to be more direct in their communications compared to co-pilots.
who were paired with senior commanders. Similar results are reported by Orasanu and Fischer (1992) who examined communication patterns in commercial air transport crews during simulated normal and abnormal flight segments. Their analyses suggest that first officers were reactive to the style of their captains. If the captain had everything in hand, first officers just did their job, which in the abnormal phase was to troubleshoot, monitor systems, and to assess progress. If the captain did not take charge of the situation, first officers were more likely to suggest plans and strategies, apparently in an attempt to compensate for the captain’s lack of leadership. Unfortunately, captains in these crews tended to dismiss or disregard suggestions made by first officers, behavior that likely contributed to the overall poor flight performance by these crews.

Status-based communication by captains and first officers has also been linked to poor threat and error management. Accident analyses as well as studies of crew communication in the flight simulator and the laboratory have consistently shown that junior crewmembers are reluctant to challenge captains’ actions or decisions (Bienefeld & Grote, 2012; NTSB, 1994; Orasanu, et al., 1998; Thomas, 2004), and that if they do, they prefer to rely on indirect communication strategies, such as merely hinting at a problem (Brown & Moren, 2003; Cushing, 1994; Fischer & Orasanu, 2000; Jentsch, Martin & Bowers, 1997). However, indirect speech is ambiguous and downplays the need for action as well as the speaker’s commitment to it (Brown & Levinson, 1987). That is, by being indirect junior crewmembers run the risk of not being heard or of being misunderstood as captains fail to make the correct inferences (Linde, 1988). Similar status issues have been identified in the communications between pilots and flight attendants (Chute & Wiener, 1995) and may also play a role in the interactions between flight deck crews and ground personnel, such as ATC, dispatch, or maintenance.

Effective error correction strategies were found to de-emphasize status differences between crewmembers and instead stress their shared responsibility for flight safety. As shown by Fischer and her collaborators (Fischer & Orasanu, 2000; Fischer, Rinehart, & Orasanu, 2001), the social risk that is present in TEM-related communications can be mitigated by using crew-centered strategies, such as crew obligation statements (e.g., “We need to deviate right about now”), preference statements (e.g., “I think it would be wise to turn left”), and problem statements (e.g., “That return at 25 miles looks mean”; Fischer & Orasanu, 2000). Common to these strategies is that they address threats and errors while fostering a positive team climate. Also, both captains and first officers rated action requests that were supported by problem or goal statements (e.g., “We need to bump the airspeed to Vref plus 15. There’s windshear ahead.”) as more effective than those without supporting statements, presumably because the supporting statements enabled crewmembers to verify the accuracy of their situation understanding and contributed to a shared situation model. In subsequent research, Fischer, McDonnell and Orasanu (2007) noted that open and inclusive interactions between team members helped their joint performance. Team communication was de-centralized and members contributed equally to the team discussion.

The aviation industry’s method for fostering equal participation among crewmembers has been to encourage consultative leadership in their Captains and assertiveness in their First Officers (Helmreich & Foushee, 1993). Research by Fischer and Orasanu (2000)
proposes detailed strategies on how this can be achieved. The monitor/challenge practice that is standard in dual-pilot cockpits must be extended to SPO team members, especially during dedicated support situations. This will require that ground personnel are trained to feel comfortable expressing concerns or challenging actions, and that pilots are trained to accept and respond to input from the ground. Although CRM/TEM training has made great strides in ameliorating negative status effects in crew communication, the issue may resurface in SPO where ground personnel are likely to be perceived as having lower status than first officers. SPO will require people from different levels of seniority and different specializations to collaborate effectively, and this will need to be addressed in crew training.

**Shared Mental Models**

The term ‘mental model’ was introduced by cognitive scientists initially to characterize knowledge structures underlying system knowledge (Gentner & Stevens, 1983) and deductive reasoning (Johnson-Laird, 1983). It was soon applied to explanations of expert performance in complex operational environments (Rouse & Morris, 1986), and specifically to flight crew performance (Orasanu, 1990). Experts are said to have multiple mental models (Cannon-Bowers & Salas, 2001; Rouse, Cannon-Bowers, & Salas, 1992; Salas, Cooke, & Rosen, 2008). For pilots these models comprise detailed knowledge of flight deck systems, of flight operations and of their current flight situation, and they include knowledge relevant to teamwork (Orasanu, 1994) given that flying aircraft involves the coordinated action currently by two co-located pilots, and in SPO by spatially distributed team members.

Teamwork requires that team members have knowledge in common. Shared mental models foster effective team processes, and enable team members to understand behaviors of other members and to anticipate others’ information needs resulting in implicit coordination—that is, team members volunteer task-relevant information before it is requested and thus reduce overall communication (Entin & Serfaty, 1999; Grote, Kolbe, Zala-Mező, Bienefeld-Seall, & Künzle, 2010; MacMillan, Entin, & Serfaty, 2004; Mathieu, Heffner, Goodwin, Salas, & Cannon-Bowers, 2000; Rouse, et al., 1992; Smith-Jentsch, Cannon-Bowers, Tannenbaum, & Salas, 2008; Stout, Cannon-Bowers, Salas, & Milanovich, 1999).

Since the concept of shared mental model was introduced into the teamwork literature, most researchers have equated its meaning with knowledge convergence (Cannon-Bowers et al., 1993; Orasanu, 1990, 1994; Orasanu & Salas, 1993). Team processes were interpreted in terms of common knowledge structures (e.g., Entin & Serfaty, 1999; Orasanu, 1994), and cognitive measures were developed to tap similarity in team members’ knowledge (e.g., Smith-Jentsch, Campbell, Milanovich, & Reynolds, 2001). This conceptualization seems best suited to characterize teams like current flight deck crews in which members have common expertise and training: both are pilots with comparable knowledge concerning aircraft systems, flight operations and teamwork. However, this view of shared knowledge may not generalize to task contexts in which individuals with different expertise need to collaborate. Surgical teams are a prime
example, and pilot-ground support teams in SPO seem to fall into this category as well, as pilot and ground personnel will likely have diverse expertise.

An alternative definition of shared knowledge that seems most appropriate for heterogeneous teams emphasizes the complementariness in team members’ knowledge; that is, shared knowledge is distributed knowledge (Cooke, Salas, Cannon-Bowers, & Stout, 2000; Mohammed & Dumville, 2001; Wright & Endsley, 2008). Task performance, according to this view, rests on the pooling of expertise insofar as team members bring in their share of unique knowledge. This idea was experimentally tested by Cooke et al. (2003). In a simulation study involving U.S. Navy helicopter pilots, they were able to show that high position-specific task knowledge coupled with low intra-team similarity was associated with superior task performance. However, in addition to unique knowledge, team members also need to have some overlapping knowledge, as illustrated in the Cooke et al. study. Exactly what information this common knowledge base needs to include is open to debate. Cannon-Bowers and Salas (2001) enumerate the aspects that have traditionally dominated the discussion of shared knowledge. Proposals by others (e.g., Mohammed & Dumville, 2001; Sperling & Pritchett, 2005) have emphasized interpositional knowledge (i.e., team members know what information others have) as well as certain domain knowledge (e.g., technical vocabulary, standard procedures). Additionally, team members have to have a common situation understanding. In contrast to system knowledge or task and team models that reflect knowledge team members bring to a task, shared situation models evolve as team members assess and respond to current task conditions. The communication between team members plays a pivotal role in this process (Orasanu & Fischer, 1992; Salas et al., 2008; Salas, Sims, & Burke, 2005), as discussed in the section on team communication.

Finding the optimal balance of overlapping and complementary knowledge in pilot-ground support teams will be of vital importance to flight safety in SPO. Answers to this question most likely will center on the expertise requirements for ground support.

Air-Ground Communication

Aerospace research addressing communication issues between remote participants has focused predominantly on interactions involving ATC and pilots, presumably because these interactions are more common than those involving other players, such as pilots and airline dispatchers.

Communication media

In the current air management system, controllers and pilots communicate by radio/telephone. This medium is susceptible to a number of data-driven communication problems, such as poor transmission quality (Casto & Casali, 2012; Morrow, Rodvold, & Lee, 1994) that may lead to misunderstandings, at times with disastrous consequences—a particularly tragic example is the 1977 Tenerife disaster in which two Boeing 747s collided. Communication via radio/telephone also places considerable demands on participants’ working memory because workload from concurrent tasks may exacerbate the inherent limitations of audio communications (Morrow & Rodvold, 1998). A technological solution to these problems is offered by data link insofar as communication between remote partners is computer-mediated. ATC messages delivered by visual data link rather than
voice were found to be better remembered by pilots, presumably because the visual modality taxed working memory to a lesser degree than the transient auditory modality (Morrow & Rodvold, 1998).

While data link has been used in the oceanic environment for some time, its elevation to the primary communication mode in SPO will come with a price. The cockpit in SPO will likely include more automation than is the case today. Data link messages will be another piece of visual information. Given the array of visual information a pilot needs to attend to, text messages may be easily overlooked, especially if system indications are more salient. Such a lapse could have disastrous consequences if ground communications included time-critical information. There is also some evidence that data link, like other forms of computer-mediated communication, is slower than voice, with more cognitive cost involved in producing messages and turn taking. This, combined with lack of participant audibility may lead to miscommunication (McGann, Morrow, Rodvold, & Mackintosh 1998). For example, visual data link eliminates voice-based cues that can reflect the speaker’s emotional state in addition to conveying message content—for instance, when a controller says, “Turn left twenty degrees NOW,” the stress on the final word emphasizes the urgency of complying with the command. A visual data link message would either strip away this critical signal or convey it less directly (e.g., by using more words). Data link communication may also threaten mutual understanding between pilots and ground support because certain error checking procedures, such as pilots reading back ATC instructions, will not be available. Furthermore, as information is directly uploaded into the FMS, pilots may be pushed out of the loop, passively receiving information rather than interacting with ground support to come to a shared situation understanding.

Two flight simulation studies examined pilot performance in relation to three different ATC environments: pilot-ATC communication involving single medium (auditory or data-link) vs. mixed-media (auditory and data-link). Using experienced general aviation (GA) pilots (flight instructors) as participants in a single-pilot experiment, Helleberg and Wickens (2003) observed that pilots were most accurate in their readbacks of ATC clearances when they received them via data-link. Data-link messages also interfered least with pilots’ traffic monitoring and flight path tracking performance. Pilot performance was overall worst in the auditory-only condition. The mixed-media condition resulted in intermediate performance or performance equal to the data-link condition. Research by Lozito and colleagues (Lozito, Verma, Martin, Dunbar, & McGann, 2003) found that the mixed media-environment was least supportive of pilot performance, both in terms of transaction time and errors (i.e., missed clearances or execution errors), compared to the single medium conditions. The authors speculate that especially under time pressure, the mixed-media condition did not enable crews to exploit the advantages of either media, increasing the number of clarification requests in voice as well as review log use in data link.

How ground communication is displayed in the cockpit may also impact its effectiveness. Research examining the effect of communication medium on pilot performance in unmanned aerial systems (UAS) operations found that pilots showed slower reaction times, took longer to complete tasks and had poorer situational awareness when they received information via a text chat medium than via three other display
formats: a text-based Multi-Function Display (MFD), a graphical MFD, and a graphical map overlay (Fern & Shively, 2011). This finding suggests that data link text messages in SPO may need to be supplemented by other display features.

Sophisticated communication tools, such as live video feeds, can facilitate distributed team performance and enable remote members to work as efficiently as co-located teams by providing them with the benefits of face-to-face interactions (e.g., Hertel, et al., 2005; van der Kleij, Lijkwan, Rasker, & De Dreu, 2009). These tools could also be implemented in SPO to support pilot-ground support collaboration. The use of video resources in particular has been found to enhance the quality of remote teams’ decision making (Martins et al., 2004).

**Communication breakdowns**

Several issues that have been identified in ATC-pilot communication have also relevance to SPO, most notably controllers’ insensitivity to pilots’ workload as well as communication failures resulting from goal conflicts.

Remote partners may misjudge the other’s workload and make requests that their teammates perceive as insensitive to their situation and overly demanding (Olson, J. & Olson, G., 2006; Weisband, 2002). The resulting tension between team members may well jeopardize their joint task performance. Pilots reported being irritated by air traffic controllers who talked too fast, or provided too much information increasing the likelihood of pilots misremembering or forgetting crucial items (Davison, Fischer & Orasanu, 2003; Morrow & Rodvold, 1998). Pilots were found to accommodate these cognitive demands by shortening acknowledgments, which could further undermine mutual understanding (Morrow, Lee, & Roldvold, 1993; Morrow, et al., 1994).

ATC communications, especially voice transmissions, may capture pilots’ attention and interfere with their ongoing tasks, such as control inputs. This issue may be of particular concern in SPO where a single pilot cannot shed tasks to his or her co-pilot. Single pilot operations therefore will require that ground personnel are cognizant of the pilot’s workload and facilitate comprehension, for instance by ensuring that messages are sufficiently spaced and their content clearly structured (Nevile, 2006). Specific procedures may target resource allocation and workload management. For example, during high workload flight segments ground support could announce the transmission of critical information to give the pilot time to shift attention to this incoming message and to indicate his/her availability.

Tensions between remote team members are also likely when they have different priorities and concerns. For instance, conflicts between pilots and ATC were reported in situations where pilots expressed a safety concern or discomfort about a clearance that reflected ATC priorities (e.g., reducing spacing to enable a faster traffic flow), and ATC was perceived as dismissive or uncooperative. If pilots felt that ATC did not adequately address their concerns, or that the affective tenor of an ATC response was not appropriate (e.g., social pressure, punishment, ridicule), conflict could be extended or exacerbated (Mosier, Rettenmaier, McDearmid, Wilson, et al., 2013). Team conflict and an associated decrease in trust may also arise when team members misattribute the delay in their partners’
responses and their coordination difficulties as expressions of choice and ill-will (Cramton, 2002).

**Problem Solving and Decision Making**

**Front-end and Back-end Processes of Aviation Decision Making**

Mosier and Fischer (2010) offered the terms *front end* and *back end* to delineate two phases of decision making. Crew decision making is triggered by some cue, pattern of cues or event that crew members perceive as inconsistent with their current situation understanding or their task goals. As shown in Figure 1, front-end cognitive processes not only concern problem identification but also include information search, problem diagnosis, risk assessment and the evaluation of time constraints (C.f., Orasanu, 2010; Orasanu & Fischer, 1997). Front-end processes make up what is most often referred to as the judgment phase of decision making. Related terms are diagnosis, situation awareness and assessment, situation model, and pattern recognition. Front-end processes result in a judgment, which may be a rather straightforward evaluation of the initial cue (as when flight crews judge their fuel remaining as insufficient to reach their destination airport), or it may involve a complex mental representation (as when a pilot integrates status indicators from various systems to diagnosis a problem). An individual’s judgment is not always based on deliberation; for instance, pattern recognition is an intuitive, rather than an analytical process. However, once operators make a judgment about a problem, their judgment will trigger decision processes.

Decision processes form the back end of decision making, concern the response to the problem, and culminate in a final decision. Back-end processes may involve retrieving an appropriate course of action from memory, locating a prescribed response in the appropriate manual, adapting a known response to the specific demands of the current situation, mentally simulating a possible response, planning a sequence of actions, or evaluating alternatives. A pilot may run a procedure through his or her mind, envisioning the outcome of a particular choice or action - for example testing the accuracy of his/her judgment of height and distance by imagining him/herself making the turn to final at a particular spot and completing the landing.

The distinction between front-end and back-end processes is not merely of theoretical significance; rather it is important for SPO because system design and training must be approached very differently depending on the target phase. For example, training and decision support geared toward front-end processes will facilitate diagnoses, situation awareness and situation assessment; training and systems geared toward back-end processes will focus on achieving correct option selection or choice of actions.
Figure 1. Components of decision making in human factors domains such as aviation. Ovals signify cognitive processes; rectangles refer to process outcomes. From Mosier and Fischer (2010).

Front-end Processes

Situation awareness

Situation Awareness (SA) is a concept that originated in aviation psychology to characterize critical components of pilots' understanding of their current flight situation and has since been widely adopted by human factors researchers (Durso & Gronlund, 1999). SA is generally assumed to depend on data-driven processes (e.g., pilot notices an engine warning light) as well as knowledge-driven processes (e.g., pilot searches for specific information or evaluates significance of cues).

Endsley (1995, 1999, 2000; 2004) characterizes SA as a three-stage process: perception of cues, comprehension of their meaning, and projection of future states. In contrast, Durso and collaborators (Durso, Rawson, & Giroto, 2007; Durso & Sethumadhavean, 2008) conceive of situation awareness as comprehension of dynamic situations, which, analogous to text comprehension, relies on several integrated cognitive processes each targeting different kinds of information. Surface level processes concern the perception and mental representation of elements in the environment, as well as their spatial or temporal relationships. Interpretive processes integrate individual elements in the environment into a coherent scene, creating an event-base representation. Representational processes operate on scenes and relate them to domain knowledge to produce an information-rich and highly structured situation model. The situation model enables operators to infer causes of events and to predict future developments.

Perceptual, attentional and memory requirements involved in SA pose formidable challenges to practitioners operating in complex, dynamic environments. For instance, attention and memory failures have been identified as underlying causes in many aviation
accidents and incidents involving inaccurate situation understanding by flight crews or air traffic controllers. Operators were found to have overlooked relevant cues (Jones & Endsley, 1996), failed to monitor the situation, misread or misheard information, as well as misremembered or forgotten information (Durso, Hackworth, Truitt, Crutchfield, et al., 1998).

In addition to perceptual and working memory failures SA errors may also reflect problems with the integration and interpretation of cues. An analysis of ATC incidents by Durso and colleagues identified instances in which controllers’ situation awareness was degraded as a result of poor judgment, faulty reasoning or planning, false beliefs, or erroneous assumptions (Durso, Truitt, Hackworth, Crutchfield, & Manning, 1998). Similar problems were identified in several studies investigating factors underlying pilots’ decisions to continue with a plan of action (e.g., to continue into hazardous airspace) despite evidence suggesting that their original plan should be modified—a phenomenon referred to as “plan continuation error” (Orasanu, Martin, & Davison, 2001). Pilots who opted to stay with their original flight plan expressed greater optimism about weather conditions or their overall situation than pilots who decided to divert (Fischer, et al., 2003; Goh & Wiegmann, 2001; Wiegmann, Goh, & O’Hare, 2002). That is, pilots who “pressed on” evaluated cues more positively than their more cautious colleagues and anticipated no or only minor negative outcomes if they continued. Jones and Endsley (2000) posit that these misjudgments “reflect problems with the assimilation of information into a person’s current mental model” (p. 368) and suggest that operators may explain away cues that are inconsistent with their situation model. The presence of team members may mitigate these problems as they are able to catch operator error and to challenge incorrect assumptions and a colleague’s inaccurate situation model. However, as discussed in the section on team communication, team members may fail to adequately monitor or challenge each other as a result of complacency due to status or position issues. Monitoring and challenging failures may also occur, as we will elaborate below, because team members do not realize critical differences in their situation models but instead presume a common situation understanding.

SA is certain to be an issue in SPO, in particular as it relates to system monitoring and the detection of system changes. A further challenge in SPO will be for distributed team members to develop shared situation models including a common understanding of the significance of threats and mutual awareness of each other’s activities and their impact on flight and system status.

Change blindness

An important perceptual phenomenon with implications for SPO is change blindness—an operator’s failure to detect significant changes in system status or the operational environment. This phenomenon has been demonstrated in research involving realistic tasks, such as naval combat (Divita, Obermayer, Nugent, & Linville, 2004) and flight simulations (Sarter & Woods, 1994). For instance, Muthard and Wickens (2002) presented pilots with a graphic display of a flight path and potential hazards (terrain, weather, other traffic). Pilots had to monitor the flight environment for changes that could pose a safety threat. Results indicate that pilots missed almost one third of the safety-critical changes presented to them.
A common misconception about change blindness is the belief that it only occurs because an individual’s attention is elsewhere (Simons, 2000). To the contrary, multiple studies have demonstrated that attending to where the change occurs is not sufficient for better than average detection of the change (Ballard, Hayhoe, & Pelz, 1995; Simons, 1996). Instead, what is necessary is that one attends to and encodes individual features in a display or in the environment in order to detect subsequent changes (Simons, 2000). Change blindness has been identified as an attentional threat in current operations, and it is exacerbated by cluttered displays (Treisman & Gelade, 1980). One problem for designing training to counteract change blindness is that people are generally poor at predicting their own ability to detect changes (Levin, Momen, Drivdahl, & Simons, 2000).

Several factors may impact change blindness within distributed SPO teams: 1) a single pilot (rather than two) will be monitoring cockpit displays, increasing the chances that no attention will be focused in the area of change; 2) the number of automation and information displays to be monitored is likely to increase; 3) ground support personnel may be responsible for many aircraft at once, decreasing the chances that they notice and process changes in a given aircraft’s displays. Improved displays as well as advanced technology will be required to mitigate change blindness. For example, displays that minimize clutter facilitate operator response, decrease the mental demands of the task, and increase operators’ awareness of significant threats (St. John, Smallman, Manes, Feher, & Morrison, 2005). Additionally, new technology may automate the search for system changes and alert the operator when they occur (see section on Managing Automated Systems).

**Shared situation models: Establishing common ground**

Successful teamwork requires that team members develop shared situation models (Mathieu, et al., 2000; Orasanu, 1994; Stout et al., 1999). These models reflect a common understanding of an emergent situation, and the team’s response to it as well as shared expectations about future events. In operational environments such as aviation, task conditions are not static but dynamically changing, and plans that were appropriate at some point in time may become inadequate. Thus, accurate situation assessment is critical. Team members must monitor their task environment for cues and information that are inconsistent with their original assumptions and if necessary, call for a change of action.

The development of shared situation models is anything but guaranteed, even when team members are co-located and have the same expertise (Orasanu, 1994). For instance, research by Fischer and colleagues showed that pilots interpreted the same information differently because it was ambiguous (Fischer, Orasanu, & Davison, 2003) or because crewmembers focused on different situational aspects consistent with their position-specific responsibilities (Fischer, Orasanu, & Wich, 1995). In SPO, pilot-ground support teams will include members with different expertise and operational priorities, and these differences may manifest themselves in divergent situation models, as suggested by research comparing pilots’ and air traffic controllers’ decisions in response to traffic conflicts. Pilots and air traffic controllers were found to frame flight situations differently (Barshi & Chute, 2001), to focus on different cues in traffic situations, and, as a result, to disagree in their risk assessments and action responses in identical flight scenarios (Davison & Orasanu, 2001). It is important to note that these studies did not include pilot-
ATC teams, rather they focused on each side individually, obtaining judgments and decisions by individual pilots and controllers.

The impact of expertise

Domain experts see and process information differently than non-experts. They quickly identify the subset of information and cues that is critical to situation assessment, and match these cues against patterns in their experience base (e.g., Klein, 1993). Their decision processes are intuitive and recognitional, and they are often unable to articulate precise explanations for their choices. Less experienced decision makers, in contrast, must use analytical techniques to work through the same situations or problems. These differences may surface as problems in SPO, as pilots and ground crewmembers will not possess the same levels of situation-specific expertise (e.g., concerning cockpit systems, weather patterns, maintenance issues, operational constraints), and may not understand decisions for which reasoning is not transparent.

One area where expertise differences between pilot and ground support could have serious implications is risk assessment. Risk assessment is inherently subjective and as such, it is influenced by individuals’ technical knowledge, administrative practices, prior professional background, and especially the subculture they belong to (Mearns, Flin, & O’Connor, 2001). Moreover, ‘risk’ in operational environments is not a singular concept but instead includes different classes. For instance, a survey of pilots from major and national US carriers revealed that they are concerned about five different types of risk: physical—threats to the safety of the flight and passengers; professional—threats to career goals or job security; economic—threats to company profits; productivity—threats to flight efficiency; and social—threats to professional image (Orasanu, Fischer, & Davison, 2004). Survey data further indicated that pilots are predominantly influenced by safety considerations, followed by concerns for job security and career. In SPO, it is conceivable that ground support personnel while agreeing on the importance of safety risk may weigh the remaining risks differently from pilots, and thus may come to a different situation understanding. Pilots’ and ground personnel’s joint risk assessment may be further complicated by disagreements concerning the basis on which to make these judgments. For instance, Fischer, Davison and Orasanu (2003) report that commercial pilots’ assessment of safety risk was driven by two factors: the timeline of a threat and its controllability. As a result of their different expertise, ground personnel could use different factors to assess safety risk, or rely on a more simplistic concept similar to the GA pilots in the Fischer et al. (2003) study. These differences may be difficult to detect and to resolve unless air and ground crewmembers not only articulate how they perceive a situation but also share the basis on which they make their assessment.

Pooling expertise

Research examining decision making by remote teams point to advantages but also to problems associated with diversity in teams. For instance, a study by Orasanu, Wich, Fischer, Jobe et al. (1993) showed that dispatcher-pilot teams developed more accurate models of problem situations resulting in better decisions than homogenous pilot or dispatcher teams. On the other hand, a pernicious issue in remote collaboration is that team members, especially when they possess diverse expertise, overestimate the extent to
which their task- and team awareness is shared by their partners, and thus fail to communicate relevant information, neglect to highlight the criticality of information, or misunderstand their partners’ intended meaning (Cramton, 2001). This problem may remain undetected for quite some time while team members seem to communicate successfully. Such errors have been noted in mission control–space crew interactions as well as in ATC-pilot communications (Bearman, et al., 2010; Davison, et al., 2003) and have contributed to commercial aviation accidents (e.g., Eastern Air Lines 401 near Miami in 1972; collision of KLM 4825 and PanAm 1736 on Tenerife in 1977; Avianca Air 52 at Cove Neck, NY in 1990; American Airlines 965 near Cali in 1995).

Ensuring SA across remote crewmembers

Displays and procedures in SPO must be designed to support shared situation models among crewmembers. Pilot interviewees (see CRM Interviews and Observations) have expressed a concern that the person on the ground won’t have the total picture because he/she has no out-the-window view, and no presence in the aircraft (i.e., is not ‘in the middle of things’). Pilots in the SPO studies (Lachter, Battiste, et al., 2014) noted problems that emerged because air and ground participants could not see what their remote crewmembers were doing with respect to aircraft systems and flight path. Ensuring that all crewmembers have shared SA with respect to internal and external elements will be a significant challenge.

Mimicking aircraft displays for ground support has been proposed as a way to share internal aircraft information, however these displays may not in themselves guarantee equivalent in-the-cockpit SA for pilots and ground. As mentioned above, even when crewmembers are side-by-side, they do not always absorb the same information or interpret it the same way. In SPO, not only will ground support personnel be distant from the pilot, but they also may be handling many aircraft at once and dividing attention among them. Additionally, stress or high workload may interfere with maintenance of SA on both sides of the air-ground partnership, and may increase the time it takes for ground support to come up-to-speed when off-nominal events occur.

Mutual awareness between pilots and ground personnel concerning individual actions may be addressed through a combination of displays and procedures. For example, collaborative tools such as those in SPO II (Lachter, Brandt, et al., 2014) can enhance SA by providing information concerning ‘who is doing what’ and by giving air and ground partners access to the same automated displays. Current standard CRM practices provide verbal cues for some control changes (e.g., You have the aircraft / I have the aircraft), and the requirement for verbal confirmation can be extended to many other actions. Current non-verbal acknowledgments of changes, such as pointing to a control or system that has been changed (e.g., an altitude, speed, or route), must be replaced in SPO by verbal signifiers. In particular, transition of any task or authority must be explicitly stated.

Certain training initiatives, such as joint training or cross-training, may facilitate the development of shared situation models as they will enable pilots and ground support personnel to view flight situations from the other’s perspective. Additionally, communication between distributed team members could be scripted to support shared situation models. For instance, Fischer and Mosier (2014) designed a communication
protocol to aid collaboration between space crewmembers and Mission Control. The protocol structures team communication by specifying critical message components and by prompting for specific content. This type of structured communication could be adapted to distributed flight operations to increase the efficiency of pilot-ground interactions and guard against misunderstanding.

**Back-End Processes**

**Types of aviation decisions**

Analyzing incident reports submitted to NASA's Aviation Safety Reporting System (ASRS), Orasanu and Fischer (1997) identified three classes of decisions pilots may face. Decision types reflect different constraints and affordances characterizing aviation situations—for instance, presence of time pressure or availability of procedures—and place different cognitive demands on pilots (see also Rasmussen, 1983).

Aviation is a highly procedure-driven work environment in which pilots’ responses to events—especially those that are time-critical and highly consequential—are prescribed in company operations manuals or by FAA guidelines. Typical examples of rule-based decisions concern responses to an engine stall during takeoff, or to windshear. Rule-based decisions are cognitively speaking straightforward (“no-brainers” in pilot parlance): once the problem has been identified, the appropriate response is clear. Front-end processes preceding rule-based decisions include cue identification or pattern recognition (Klein, 1989; 1993); the decision process itself involves retrieval of the procedure or regulation, either from memory or manuals, whose conditions match cues or patterns in the situation.

Some situations require pilots to choose among alternative courses of action. The prime example of a choice decision is the selection of an alternate airport, for instance due to poor weather at the planned destination or in response to some mechanical failure. In these situations, pilots need to consider which option accommodates best various constraints, such as suitable weather conditions, appropriate runways, or the availability of company mechanics. Choice decisions often include discussions with ground personnel, most commonly dispatch. Observations of crews in the flight simulator suggest that pilots may employ two strategies to make choice decisions (Fischer, Orasanu, & Montalvo, 1993; Klein, 1993; Mosier-O’Neill, 1989). They either create a situation that gives them time to consider several options simultaneously, or they evaluate options serially; that is, pilots settle on one likely option (for instance their designated alternative) but continue to evaluate its appropriateness and if necessary, generate an alternative solution.

On rare occasions pilots may need to create a solution either in response to an ill-defined problem or because there is no known response. In the former case, in particular if the situation is time-critical, pilots may adopt a procedure that as far as they understand prevailing conditions, seems most suitable to stabilize events (procedural management; Orasanu, Fischer & Tarrell, 1993). In the latter case, pilots need to engage in creative problem solving relying on their system and operational knowledge and input from ground personnel to invent a response. Possibly the most famous example of this type of decision is United Airlines flight 232 (NTSB, 1990). The DC10 lost all hydraulic systems due to an explosion in the number two engine; a problem situation that no one had anticipated would
ever occur and thus no procedures existed to cope with it. After considerable diagnostic effort, the Captain determined that the two outboard engines were still running, but no flight controls were operative. Knowing this, the crew reasoned they could use asymmetrical engine thrust to turn the plane and power level to control the altitude, which they used to bring the aircraft to a semi-controlled landing. This event is often touted as the epitome of creative problem solving and CRM.

Type of decision will have an impact in SPO in several ways. While rule-based and also some choice decisions may be manageable for a single pilot decision maker, his/her workload will be increased relative to a two-pilot cockpit. Decision situations requiring creative problem solving, in contrast, will require help from ground support. These are the types of decision situations that are currently managed by delegating the flying task to one pilot (usually the First Officer) while the other pilot (usually the Captain) concentrates on situation assessment and decision making. New procedures for handling complex decision situations – perhaps by delegating some tasks to automation or to ground personnel - will be needed for SPO.

**Who should make decisions in SPO?**

Although the Captain will be the person in command of the flight in SPO as in current operations, he or she is not infallible with respect to decision making. In the two-person cockpit, the second pilot serves as a cross-check for decisions made by the Captain, and is trained in CRM to challenge any decisions perceived to be unsafe.

One issue for CRM in SPO is the extent to which ground support personnel will be authorized and expected to make decisions for a given flight, or to challenge or override decisions made in the cockpit. On the one hand, ground personnel may be able to contribute an essential perspective, as they have a more ‘objective’ view of a given situation because they are not in the midst of it. They may have more situation-specific information or expertise than the pilot (e.g., for system problems or maintenance issues). They are less susceptible to stress-induced tunnel vision and may see elements that the pilot misses. For example, it is reasonable to posit that a dedicated ground person who was not engrossed in cockpit events and interactions may have been successful in alerting the crew to the descent and slowing of Asiana Flight 214 at SFO. Also, ground personnel will not be impacted by adverse conditions in the air such as turbulence, noise, or mild hypoxia.

On the other hand, not being in the midst of a situation may have drawbacks in terms of TEM and decision making, as ground personnel may not pay attention to or fully realize threats in the effects of physical and psychological stressors such as extreme stress, injury or hypoxia in the cockpit. Additionally, their access to raw data for decision input will be limited relative to what is available in the cockpit. Ground personnel, for example, will not have access to cues such as the smell and denseness of smoke or strategies such as manipulating the throttle to see its effect. The extent to which ground personnel will be prepared and able to contribute to decision making will depend on the information and capabilities afforded by automation, and by training not only on aircraft systems but also on situation and risk assessment as well as decision making processes.
Training for problem solving and decision making in SPO

In keeping with research on expertise, risk assessment, and distributed teams, decision strategies for SPO should be trained with domain-specific content, as is done in current AQP’s where CRM/TEM is integrated into technical training. In order to cultivate expertise, training should be scenario-based and focus on providing a store of experiences from which pilots and ground personnel can draw for situation assessment and decision making. Cross-training may be particularly suited to enhance crewmembers’ expertise development and to help partners understand each other’s perspective, what each partner knows, and what each can best contribute to the decision making process.

Additionally, training for decision making must include the components of metacognition, or the process of monitoring and controlling one’s cognitive processing to ensure the appropriateness of decision strategies, and metacognitive monitoring skills of critiquing and correcting to verify the correctness of diagnosis or situation assessment (Cohen, Freeman, & Thompson 1997; Cohen, Freeman, & Wolf, 1996). Experts have been shown to be more likely than novices to recheck and confirm or revise their initial situation assessments (e.g., Chi, Glaser, & Rees, 1982; Khoo & Mosier, 2008; Patel & Groen, 1991). For instance, Orasanu and Fischer (1997) observed that professional pilots frequently engaged in diagnostic actions to obtain additional information about a problem situation and re-allocated task assignments. Metacognition will be an important component of decision making in SPO, and automated support as well as procedures will need to promote awareness of how the distributed crew is making decisions and whether the decision strategies are appropriate.

Managing Automated Systems

It is certain that highly sophisticated automation will have a key role as the enabler of SPO and the proposed solution to many of the CRM issues identified in this review. For example, system alerts can assist single pilots in the identification of threats. Decision support systems can facilitate diagnosis and decision making. Control automation can assume the brunt of the flying task. Technology also provides advantages such as enhanced monitoring and data processing capabilities that can reduce workload and compensate for the absence of a second pilot. In fact, because the technology to manage aircraft without anyone in the cockpit exists, it may be tempting to engineer a SPO cockpit that does not require any input from the pilot in nominal (or even off-nominal) operations. So long as the pilot is there, however, automation design and procedures must take into account characteristics of human behavior and cognition.

Burian (2007a) noted that although there is an assumption that technologically advanced aircraft improve situational awareness, reduce workload, and benefit single pilot operations, these systems also create new cognitive demands relative to those of two-pilot cockpits. For example, advanced technologies are able only to make information available to the single pilot, requiring the pilot to notice, acquire, synthesize and interpret the information during judgment and decision making without the contribution or expertise of the second pilot (Burian & Dismukes, 2007a). Primary design goals for automated systems
in SPO will be to address the cognitive requirements and limitations of the solo pilot and to facilitate diagnosis and decision making.

**Decision Support**

A basic enabler of collaborative problem-solving and decision-making is information, and many new automated systems will involve information automation. Flight crews will have access to weather and traffic information via technologies such as the 4-D Weather Data Cube and CDTI (cockpit display of traffic information). Design decisions concerning the placement of information (e.g., electronic flight bags vs. primary displays), characteristics of its display (e.g., graphical, fostering intuitive cognition vs. text, fostering analytical cognition), and accessibility (e.g., surface vs. layered or hidden) will impact how and how well pilots can use this information. For instance, formats that elicit intuitive and holistic processing should not require analysis for interpretation. Timeliness, accessibility, and comprehensiveness of information will be critical – a challenge to designers will be to ensure that the right information is available at the right time, especially when decisions need to be made under time pressure. An additional challenge will be to convey to the pilot the limitations of even the most sophisticated automation. For example, automation cannot be wholly aware of the context or the pilot’s intent, and may inadvertently place the aircraft in a dangerous situation (e.g., a CAT III landing on top of another aircraft or vehicle) or countermand or limit pilot maneuvers inappropriately (as in the US Airways landing on the Hudson – pitch control entries were restricted by the aircraft systems) Harris, 2007; Mosier, 2002).

An on-going debate with respect to decision support systems is whether they should support the front-end (problem identification, information search, problem diagnosis, risk assessment and the evaluation of time constraints via information or status displays) or back-end (decision and the selection and implementation of a course of action via commands, recommendations, and/or executing a course of action) decision processes (Mosier & Fischer, 2010; Orasanu, 2010; Orasanu & Fischer, 1997). Research has suggested that supporting front-end processes through information acquisition/integration or status displays is critical for effective decision aids because it keeps the operator in the loop (e.g., Endsley & Kaber, 1999; Sarter & Schroeder, 2001). This recommendation is consistent with models of expert decision making, which describe the decision process as heavily rooted in situation assessment. Additionally, some research has shown that when the pilot is removed cognitively from the diagnosis phase by back-end decision aids that issue a command or action directive, the risk is that he or she may enter a “purely reactive mode” and follow system recommendations blindly (Sarter & Schroeder, 2001, p. 581). If the pilot is engaged in the process, he or she is better able to detect flaws in the aid’s recommendations and is more prepared to intervene as needed.

**Allocating Roles and Responsibilities to Humans and Automation**

Appropriate allocation of responsibilities to pilot, ground support, and automation will be essential for automation management in SPO. For example, advanced technologies can provide the pilot flying with information through multi-function displays, and reduce the need for second pilot or ground contributions. They enable automated performance of routine activities, and can sense and track inputs to flight systems. However, automated
systems cannot participate equally with humans in critical judgments and decision making, and those tasks should be the responsibility of a human (Burian & Dismukes, 2007b). In fact, when situations require complex decision making, the Captain of the aircraft should be able to focus solely on the decision problem at hand. This recommendation is in keeping with current policies that require the Captain to focus on off-nominal problems while the First Officer flies the aircraft (Boeing interview) and is also supported by research. In a simulator study of team performance in the face of challenging hydraulic failure problem, crews in which the Captain assigned the job of flying to the First Officer in order to deal with the problem himself were more successful in coping with the difficulties than those in which the Captain continued to fly (Orasanu & Fischer, 1992). One role of automation in SPO, then, will be to reduce the pilot’s workload by handling flying tasks and enabling the human to focus on problem solving and decision making.

The allocation of tasks between humans and automation may also depend on context features such as normal vs. off-nominal operations, phase of flight, workload, or time pressure. One possible role for automation would be to track contextual elements such as phase of flight and automatically assume some roles during high-workload phases of flight. Automation could also monitor workload by tracking pilot activity and provide suggestions for managing or off-loading tasks when workload is high. Research in UAV control, for example, has demonstrated that technology such as Playbook can provide scripts (pre-made automations) and plays (specific delegated controls) to reduce operator workload during nominal and some off-nominal conditions (e.g., Shaw et al., 2010; Shively, Flaherty, Miller, Fern, & Neiswander, 2012).

Training for automation management in SPO must include procedures for shedding tasks and shifting responsibilities for tasks from pilot to automation. However, it will be critical that displays in the cockpit and on the ground should indicate the transition of task performance so that shifts between pilot and automation are clearly signaled. The SPO I and II studies as well as some work with UAVs (e.g., Fern & Shively, 2011) have tested tools and displays to support the transition of tasks between operators. The same concept could be applied to the transition of tasks between humans and automation.

**Automation Bias**

One danger in the high-technology cockpits required for SPO is that they may promote automation bias - decision errors resulting from the use of automation as a heuristic replacement for vigilant situation assessment (Mosier & Skitka, 1996; Mosier, Skitka, Heers, & Burdick, 1998). Pilots who are used to relying on automation for information and instructions may stop checking other sources of information to verify automated displays, leaving them susceptible to omission errors (i.e., failing to notice problems because an automated aid fails to detect them) and commission errors (i.e., inappropriately following an automated decision aid’s directive or announcement). In the two-person cockpit, pilots are expected to monitor and crosscheck automated systems as well as each other as a guard against automation errors. Although the presence of the second pilot has never in itself guaranteed that automation and information will be appropriately monitored or crosschecked (Harris, 2007; Mosier, Skitka, Dunbar, & McDonnell, 2001), when a single pilot is monitoring and controlling the aircraft, the tendency to over-rely on automation
and the susceptibility to automation bias errors is likely to increase. This means that CRM/TEM solutions for SPO that rely on automation to compensate for the absence of a second pilot may produce the unintended consequence of fostering complacency and automation bias in the solo pilot.

**Designing for SPO – A New Cockpit?**

One issue for CRM in SPO is the extent to which changes in current cockpit layout and technology will be required. Harris (2007) suggests that commercial aircraft are already designed to be flown by a single pilot in either seat and that removing the second pilot will not inherently increase the workload of the single pilot. With current automation technologies monitoring more aircraft systems, the pilot has become a monitor of the aircraft monitoring systems (i.e., monitoring the monitoring automation), and his or her primary function is to ensure that the aircraft computer is following the correct rules in monitoring the aircraft systems. According to Harris, the single pilot’s role in SPO will be to provide context to the automated systems on the aircraft through flight planning, communicating with ATC, and functioning as surveillance operative – and these activities do not require new procedures or aircraft system redesign.

Deutsch and Pew (2005), in contrast, emphasize the need for a substantial redesign of the current two-pilot flight deck procedures to support SPO. Following a review of NTSB accident reports of currently identified aircrew vulnerabilities to error, Deutsch and Pew caution that SPO procedures will need to target common errors, such as checklist events, tunneling, decision-making biases, missing knowledge, errors of omission, missed situational alerts, and tracking the time-risk relationship. They note that voice technologies may be promising in allowing the single pilot to speak directly to the automation and accomplish tasks that currently rely on the communication between the PF and the PM; however, the reliability of such systems must be improved. The push-to-talk approach may be no less demanding on workload than directly interacting with the automation, and a replacement for the common informational and acknowledgement gestures between PF and PM will need to be closely considered for SPO procedures. Procedures for data link operations and multi-tasking in agent-based software will also need evaluation and revision for SPO.

**Naturalistic flight deck**

Schutte et al. (2007) created the Naturalistic Flight Deck (NFD), a comprehensive model for single pilot operations that uses a type of human-centered automation called complementation. In complementation, the human and automation are independent collaborative agents with different strengths (i.e. they complement one another). For example, the human has commonsense knowledge, general intelligence, and creative thinking, while the machine has specialized intelligence and control, extreme vigilance, resistance to fatigue, and encyclopedic memory. In general, tasks are divided to exploit the different strengths so that non-critical, redundant and deterministic tasks are completed by automation, while the human completes the tasks that are more mission critical and novel. NFD expands the effectiveness of a human-automation team by developing a greater level of awareness and intelligence between man and machine. NFD consists of three multiple components: the pilot, the Actual system and the Notational system. The Actual and Notational systems
perform all tasks not assigned to the pilot. The systems manager within the Actual system configures the aircraft systems to support both the trajectory and flight requirements. It monitors the performance of all systems and detects any aberrations, it communicates systems information to the pilot by maintaining a real-time description of aircraft systems, and in the case of an aberration, it indicates where intervention is necessary. The Notational system consists of components that are not flight critical but used to inform and direct flight operations - the planning and problem-solving tools. The major component of the Notational system is the Interactive Trip Planner (ITT). This is separate device from the Actual system, best conceptualized as a tablet and similar to an electronic flight bag. Using the ITT, a pilot can develop a flight plan, find alternate flight plans, plan tasks, play out ‘what-if’ scenarios and even simulate a flight.

Although advanced technologies and automation such as proposed in the NFD will be of benefit in single pilot operations, they are not without their potential costs. The time demands in setting up automation may be offset by reduced flying and navigation task demands. Potential increases in SA are met by increased needs for monitoring and other system management tasks. Off-loading tasks during high workload will still require set-up time, which itself increases workload. These benefits and costs are not offered as a deterrent, but rather to indicate that more research is needed to maximize the benefits of advanced technologies and automation – typical in technologically advanced aircraft – in single pilot operations. Additionally, the option of higher-level automation – for example, command decision support as opposed to status support – may be resisted if pilots are not able to override automation decisions (e.g., Verma, Kozon, Ballinger, & Farrahi, 2013) or gains may be reduced if operators are not able to recognize inaccuracies in information (e.g., Sarter & Schroeder, 2001).

In sum, automation management in SPO may not be simple - even in light of sophisticated flight deck technologies. Without the PM to monitor data link communications, there will be additional head-down time in SPO that must be evaluated. Additional use of head-up display, and less reliance on head-down electronic moving maps, may be required for SPO. While speech-recognition and text-to-speech software present some promising support for SPO, the questionable reliability of the software and competition with flight deck noise must be addressed. Existing agent-based software will need to be revised in order to transform the tasks that are commonly shared in two-pilot operations to individually-executed SPO procedures that are instead supported by automation. Additionally, automation must be designed to be more pro-active in TEM; that is, automated systems should not only aid in the identification of threats via alerts and alarms, but also help pilots manage them by suggesting actions, monitoring the results of inputs, and checking for errors.

**Recommendations for CRM/TEM in SPO**

Several themes emerge from this examination of literature related to CRM/TEM. One theme concerns the value of face-to-face interactions for CRM activities such as creating a cohesive team, communicating, establishing shared situation models, establishing trust, coordinating tasks, cross-checking automation or control input, or maintaining alertness.
Clearly, CRM procedures and training for SPO must be designed to compensate as much as possible for the loss of face-to-face contact.

*Joint training or cross training* for remote team members appears often in the literature as an important step in the creation of effective remote crews, establishing trust among members, and clarifying roles and responsibilities, and it will be important to implement this recommendation in SPO. Additionally, *specific procedures and scripts for communication* among remote team members can replace non-verbal cues with verbal signifiers, clarify situation and task models, and facilitate coordination of tasks and activities.

A second theme concerns *automation* – the use of automation as a ‘second crewmember,’ the role of automation in decision support, allocation of tasks and transition between the human operator and automation, and potential human pitfalls in automation use such as complacency or automation bias. Automation design and procedures for managing automation will need to take these considerations into account.

Other recommendations are listed below, organized with respect to CRM activities.

**Team Building and Maintenance**

An important challenge for CRM in SPO will be building cohesive crews with distributed players – pilots and ground support.

- Crewmembers must have clear roles and responsibilities – during normal as well as off-nominal situations.
- Pilots must trust that ground personnel are capable of fulfilling their responsibilities and accountable to their needs and requests.
- Crew briefings (at minimum, pre-flight and approach) should include ground support personnel.
- Ground personnel must be regarded as crewmembers rather than just ‘resources.’
- Pilots and ground personnel should participate in joint training to develop trust and learn each other’s perspective.
- The elimination of psycho-social roles that in-cockpit crewmembers serve (e.g., keeping each other alert) will need to be addressed in SPO.

**Communication**

- SPO will require more and explicit communication between air and ground to compensate for loss of non-verbal cues and to ensure shared situation models.
- Air-ground communications should always be acknowledged (providing feedback)
- Sophisticated technology such as video feeds may facilitate communication.
- Current monitoring/challenging practices should be extended to remote SPO crewmembers.
- Status and position issues (air/ground differences, professional cultures, etc.) will need to be addressed in SPO to ensure open and inclusive communication.
- Communication medium should be matched to the situation (e.g., phase of flight, workload).
- Goals and priorities between air and ground will need to be matched to avoid communication breakdowns.
- Communication procedures must take into account the pilot and ground workload.
Maintaining Situation Awareness

- Specific procedures in SPO will be required to achieve and maintain shared situation and task models.
- Displays and automation in SPO should facilitate shared situation and task models. This may entail automated information about the external flight environment (e.g., weather), flight path trajectory, and internal systems status. This may also entail mirrored displays, alerts for system status or flight control changes, or prioritization of tasks and goals. In particular, transition of authority must be clearly signaled via automated displays and/or verbal signifiers.
- Checklists have typically been used as a structured way to maintain a shared task model. Checklists in SPO may need to be restructured and automation and/or procedures for crosschecking will be required.
- Shared displays of electronic checklists may accomplish the dual function of verifying item completion and updating task models for ground personnel.

Decision Making

- SPO crews will require mutual knowledge and common ground for decision making.
- Training for decision making should focus on front-end processes, such as situation assessment.
- Decision training for SPO crews should recognize processing differences between experts and non-experts. Scenario-based training can be used to develop a repertoire of situations and foster expertise among remote crewmembers.
- SPO crews should be trained to choose the appropriate decision response for specific situations (e.g., rule-based, option selection, procedural management, creative problem solving).
- SPO crews should receive training in metacognitive processes.
- Clear rules and procedures that delineate who makes decisions should be part of SPO training.

Managing Automated Systems

- Automation will be a key enabler of SPO. Systems should be designed to aid SPO crewmembers by facilitating team maintenance, information transfer, problem solving and decision making, and SA.
- Alerting functions of automated systems will be important for TEM. Systems should be designed to be proactive in identifying threats and managing errors.
- Decision support systems should support the front-end processes of problem identification, information search, problem diagnosis, risk assessment and the evaluation of time constraints via information or status displays.
- Automation should keep pilots and ground support personnel in the loop for problem solving and decision making.
- Automation design and procedures must mitigate human tendencies toward overreliance, complacency, and automation bias.
- Automation design and procedures should target common errors in current cockpits, such as checklist errors, missed alerts, tunneling, and decision biases.
- Appropriate allocation of tasks between humans and automation will be critical for SPO, and may depend on contextual factors. One important function for automation will be to handle flying tasks so that the pilot (or ground) can focus on problem solving and decision making.
- Automation should support smooth transitions of task control between human and automation.
- Automation will function more as a team member in SPO than in current operations. This shift may require substantial redesign of systems and procedures to ensure an effective collaboration.
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