The Role of Cognitive Processes in Air Traffic Control: Theory and Practice

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Contents

Abbreviations

ADS-B: Automatic Dependent Surveillance–Broadcast
AI: Artificial Intelligence
ASIAS: Aviation Safety Information Analysis and Sharing
ATC: Air Traffic Control
ATCO: Air Traffic Controller
ATCT: Air Traffic Control Tower
ATM: Air Traffic Management
CRM: Crew Resource Management
DCA: Ronald Reagan Washington National Airport
EEG: Electroencephalography
EUROCONTROL: European Organisation for the Safety of Air Navigation
FAA: Federal Aviation Administration
FRAM: Functional Resonance Analysis Method
HFACS: Human Factors Analysis and Classification System
HRA: Human Reliability Analysis
ISA: Instantaneous Self-Assessment
NASA: National Aeronautics and Space Administration
NASA-TLX: NASA Task Load Index
NextGen: Next Generation Air Transportation System
NTSB: National Transportation Safety Board
SA: Situation Awareness
SAGAT: Situation Awareness Global Assessment Technique
SESAR: Single European Sky ATM Research
SPAM: Situation Present Assessment Method
STAMP: Systems-Theoretic Accident Model and Processes
TCAS: Traffic Alert and Collision Avoidance System

TBO: Trajectory-Based Operations

TEM: Threat and Error Management

TRACEr: Technique for the Retrospective and Predictive Analysis of Cognitive Errors

TRM: Team Resource Management

VFR: Visual Flight Rules

XAI: Explainable Artificial Intelligence

1. Introduction To Cognitive Processes in Air Traffic Control

The aviation industry has experienced unprecedented technological advancement over the past several decades. Innovations in surveillance technologies, communication systems, navigation capabilities, automation, and artificial intelligence have fundamentally transformed the operational landscape of air traffic management (ATM). Despite these technological developments, however, the safe and efficient management of air traffic continues to depend largely on the cognitive capabilities of human operators. Air traffic controllers remain responsible for continuously interpreting dynamic operational information, anticipating future traffic developments, resolving potential conflicts, coordinating multiple stakeholders, and making safety-critical decisions under conditions characterized by uncertainty, high workload, and severe time constraints. Consequently, contemporary air traffic control should no longer be regarded merely as a procedural occupation but rather as one of the most cognitively demanding professions within modern socio-technical systems (Hedayati et al., 2021; Malakis et al., 2023; Gerdes et al., 2025).

Historically, the primary responsibility of air traffic controllers centered on maintaining aircraft separation through standardized procedural control supported by radar surveillance and voice communication. However, the exponential growth of global air transportation, increasing airspace congestion, expanding traffic diversity, and the emergence of advanced automation technologies have substantially transformed the controller's role. Rather than reducing cognitive demands, technological developments have shifted the nature of controller work from direct operational control toward continuous monitoring, strategic planning, conflict prediction, adaptive coordination, and supervision of increasingly sophisticated automated systems. Contemporary controllers are therefore expected not only to manage aircraft movements but also to effectively collaborate with decision-support technologies and artificial intelligence applications while preserving overall system safety (Chen et al., 2024; Liu et al., 2024; Tyburzy et al., 2024; Yu et al., 2025).

This transformation reflects a broader paradigm shift within aviation human factors research. Earlier studies primarily conceptualized air traffic control as a problem of human information processing, emphasizing perception, memory, rule application, and decision-making under temporal constraints. Contemporary research, by contrast, increasingly views controller performance as an emergent property of complex interactions among human cognition, technological systems, operational procedures, organizational structures, and collaborative teamwork. Within this perspective, cognitive performance cannot be understood solely through the characteristics of individual operators but must instead be examined within the broader socio-technical environment in which cognition is continuously distributed across humans, interfaces, automation, and organizational processes (Lundberg & Johansson, 2020; Hancock et al., 2022; Muecklich et al., 2023).

The central role of cognition in air traffic management arises from the dynamic and continuously evolving nature of the operational environment. Air traffic controllers must simultaneously perceive information originating from multiple surveillance sources, selectively allocate attention across numerous aircraft, maintain and update working memory representations of traffic situations, anticipate future aircraft trajectories, communicate effectively with pilots and adjacent control sectors, and rapidly adapt to unexpected operational events. These interdependent cognitive activities collectively enable the development and maintenance of situational awareness, which remains one of the strongest determinants of safe operational performance in aviation (Endsley, 1995; Hancock et al., 2022). Consequently, failures in perception, attention allocation, memory, information integration, or decision-making may progressively compromise controllers' ability to detect conflicts and maintain adequate aircraft separation, particularly during periods of elevated workload or rapidly changing operational conditions.

Recent empirical evidence further demonstrates that cognitive workload should be considered a core safety variable rather than merely an indicator of operator discomfort. As traffic complexity increases, controllers experience substantial changes in attentional allocation, visual scanning behaviour, mental workload, and situational awareness. Contemporary studies employing eye-tracking technologies, electroencephalography (EEG), and multimodal physiological measurements indicate that cognitive workload fluctuates continuously throughout operational tasks rather than occurring in discrete levels, suggesting that future air traffic management systems should incorporate adaptive mechanisms capable of monitoring and supporting controller cognition in real time (Yu et al., 2025). Similarly, studies investigating controller performance have shown that perception-related errors constitute a significant proportion of operational mistakes, highlighting the fundamental importance of cognitive processes in maintaining aviation safety (Hedayati et al., 2021).

The increasing integration of automation and artificial intelligence introduces an additional dimension to controller cognition. Contrary to earlier assumptions that automation would substantially reduce human workload, recent research suggests that automation primarily redistributes cognitive demands rather than eliminating them. Controllers increasingly perform supervisory functions that require continuous monitoring of automated systems, evaluation of system recommendations, management of automation failures, and coordination between human expertise and algorithmic decision support. Consequently, future ATM systems are progressively evolving toward models of human–AI collaboration in which safety depends on effective interaction between human cognitive capabilities and intelligent technological systems rather than on either component independently (Malakis et al., 2023; Liu et al., 2024; Tyburzy et al., 2024).

Equally important is the recognition that air traffic control represents a collaborative rather than purely individual cognitive activity. Modern controller operations rely extensively on communication, coordination, shared mental models, and team situational awareness among multiple operational actors. Although individual cognitive processes such as perception, attention, and decision-making remain fundamental, safe system performance increasingly depends upon how effectively cognitive information is shared, updated, and coordinated across controller teams, adjacent sectors, pilots, and automated decision-support systems. Early work by Mica R. Endsley and later developments in team situation awareness and distributed cognition have demonstrated that shared awareness is not merely the sum of individual cognitive states but rather an emergent property of continuous interaction among team members operating within complex environments (Endsley, 1995; Endsley & Jones, 2001; Inoue et al., 2010). This perspective has become increasingly influential as air traffic management evolves toward highly interconnected and collaborative operational ecosystems.

Despite substantial advances in aviation technology, important knowledge gaps remain. Current research demonstrates considerable progress in fields such as workload estimation, eye-tracking, explainable artificial intelligence (XAI), adaptive automation, and traffic-flow optimization. However, these research domains frequently evolve independently, employing different theoretical perspectives, analytical frameworks, and evaluation criteria. Consequently, relatively limited research has integrated these diverse perspectives into a comprehensive understanding of controller cognition within contemporary ATM systems (Razali et al., 2021; Pinto Neto et al., 2023; Chen et al., 2024). Moreover, although human–AI teaming has become one of the most rapidly expanding research areas, empirical evidence regarding its long-term effects on operational safety, controller cognition, and real-world implementation remains limited (De Rooij et al., 2022; Malakis et al., 2023; Tyburzy et al., 2024).

Against this background, this book adopts an integrated cognitive perspective on air traffic control. Rather than examining perception, attention, working memory, situational awareness, decision-making, workload, communication, teamwork, automation, and organizational influences as independent phenomena, the book conceptualizes these cognitive processes as interconnected components of a complex socio-technical system. Drawing upon theories from cognitive psychology, human factors, cognitive systems engineering, resilience engineering, organizational safety, and contemporary air traffic management research, the subsequent chapters examine how controller performance emerges through the interaction of individual cognition, technological systems, operational procedures, organizational structures, and environmental constraints.

To bridge theoretical knowledge with operational practice, the second part of the book presents an in-depth case study of the 29 January 2025 mid-air collision between PSA Airlines Flight 5342 and the U.S. Army Priority Air Transport Flight 25 (PAT25) near Ronald Reagan Washington National Airport (DCA). Rather than treating the accident as the consequence of isolated human error, the case study analyzes the event as a manifestation of interacting cognitive, technological, organizational, and systemic factors within one of the world's most operationally demanding terminal airspace environments. Based extensively on the official investigation conducted by the National Transportation Safety Board (NTSB), the case examines the accident through multiple human factors perspectives, including attention allocation, mental workload, situational awareness, decision-making, communication processes, Threat and Error Management (TEM), the Swiss Cheese Model, the Systems-Theoretic Accident Model and Processes (STAMP), and organizational safety culture. By integrating empirical accident evidence with contemporary cognitive theory, the case study demonstrates how theoretical concepts discussed throughout the book can be applied to understand the mechanisms underlying complex aviation accidents and to identify opportunities for improving future air traffic management systems.

Accordingly, this book aims not only to provide a comprehensive synthesis of current knowledge regarding cognitive processes in air traffic control but also to establish an integrated conceptual framework linking cognitive psychology, human factors, socio-technical systems, and operational safety. By combining contemporary scientific evidence with an extensive real-world accident analysis, the book seeks to contribute to a deeper understanding of controller cognition and to support the development of safer, more resilient, and human-centered air traffic management systems capable of addressing the challenges of increasingly complex global airspace.

2. Cognitive Architecture of Air Traffic Control

Air traffic control represents one of the most cognitively demanding operational environments in modern transportation systems. Unlike routine monitoring tasks, controllers operate within a dynamic, time-constrained, and information-rich environment in which multiple aircraft continuously change position, speed, altitude, and future trajectories. Consequently, controller performance depends not on isolated cognitive functions but on the continuous interaction of perception, attention, memory, mental representation, prediction, and decision making. Rather than processing information sequentially, controllers integrate multiple visual, auditory, procedural, and contextual information sources into a coherent understanding of the evolving traffic situation while simultaneously anticipating future developments and coordinating appropriate control actions (Niessen et al., 1999; Gerdes et al., 2025).

The cognitive architecture underlying air traffic control is therefore best understood as a dynamic information-processing system. Contemporary human factors research describes controller cognition as an adaptive process in which environmental information is continuously sampled, interpreted through prior knowledge, incorporated into an internal representation of the traffic situation, and translated into operational decisions under severe temporal constraints (Hedayati et al., 2021; Xia et al., 2025). Rather than reacting to isolated aircraft movements, controllers actively construct a continuously evolving "traffic picture" that supports both current aircraft separation and anticipation of future conflicts.

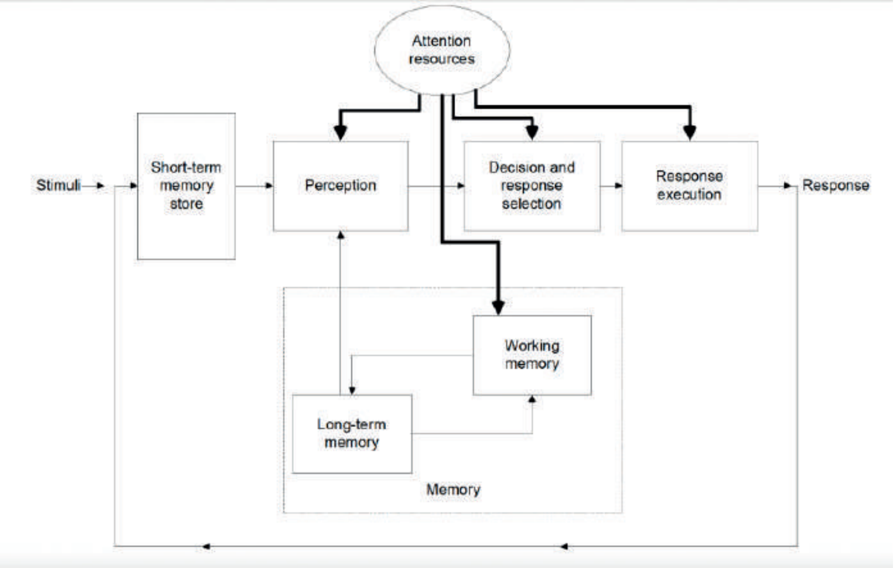

Figure 1. Information-processing architecture underlying human cognition in air traffic control (adapted from Wickens & Kessel, 1980; reproduced from EUROCONTROL, 2014).

Unlike static decision environments, ATC requires the continuous updating of cognitive representations. Every new aircraft entering the sector, every altitude change, heading modification, pilot request, weather deviation, or coordination message modifies the cognitive demands imposed on the controller. Consequently, cognitive processing is inherently cyclical rather than linear, consisting of repeated perception–interpretation–prediction–decision cycles that evolve throughout the control task (Lundberg et al., 2024). This perspective closely aligns with cognitive systems engineering, which conceptualizes controller activity as the continuous interaction between monitoring, evaluating, planning, and executing actions within a complex socio-technical system.

One of the earliest comprehensive theoretical explanations of this process was proposed by Niessen et al. (1999), who argued that ATC performance depends upon three essential cognitive requirements: maintaining an updated representation of continuously changing aircraft relationships, anticipating future traffic developments to identify emerging conflicts, and coordinating multiple cognitive activities according to strict temporal priorities. These requirements cannot be fulfilled through isolated perceptual or memory processes. Instead, they require an intermediate cognitive representation—

referred to as the controller's "picture"—that integrates information from radar displays, flight strips, radio communications, procedural knowledge, and environmental cues into a coherent mental representation of the operational environment. This mental representation forms the cognitive basis of situation awareness and supports prediction, prioritization, and adaptive decision making.

Consistent with broader theories of mental models (Craik, 1943; Johnson-Laird, 1983), the controller's picture is neither a complete nor permanent representation of reality. Instead, it constitutes a simplified, task-oriented representation that selectively preserves information relevant to ongoing operational goals. The representation is continuously updated as new information becomes available, reorganized whenever traffic relationships change, and manipulated to generate predictions regarding future aircraft trajectories and potential conflicts (Niessen et al., 1999). Contemporary situation awareness theory similarly argues that operators maintain only those environmental elements necessary to support current and anticipated task demands, while long-term domain knowledge provides the conceptual framework required to interpret incoming information (Endsley, 2000).

Recent empirical research further supports this view by demonstrating that controller performance depends less on the amount of available information than on the efficient selection, integration, and prioritization of diagnostically relevant cues. Perception in ATC is therefore inherently selective rather than exhaustive. Under increasing traffic density or task complexity, controllers must rapidly discriminate between operationally relevant and irrelevant information while avoiding attentional capture by less important events. Studies have shown that many operational errors under high traffic conditions arise not from insufficient information availability but from failures of information interpretation, including aircraft misidentification and incorrect assessment of developing traffic situations (Hedayati et al., 2021). Consequently, perception, attention, and working memory function as tightly integrated processes supporting dynamic situation assessment rather than isolated cognitive mechanisms.

The interaction between attention and memory represents another defining characteristic of the cognitive architecture of air traffic control. Controllers simultaneously process multiple visual displays, auditory communications, flight progress information, and procedural constraints while maintaining awareness of several ongoing control tasks. Such demands place considerable pressure on working memory capacity and attentional resources. Information-processing models specific to ATC propose that attentional mechanisms continuously select relevant information into working memory, while temporary memory buffers retain unattended but potentially useful information until it becomes operationally significant (Xing & Bailey, 2010). These processes operate within strict cognitive capacity limitations, making efficient attentional allocation essential for maintaining situation awareness during periods of elevated workload.

Long-term memory complements these temporary cognitive processes by providing controllers with extensive procedural knowledge, airspace structures, aircraft performance characteristics, standard phraseology, conflict-resolution strategies, and accumulated operational experience. Rather than increasing raw memory capacity, expertise reorganizes cognitive processing by enabling rapid pattern recognition, efficient retrieval of relevant procedures, and compression of complex traffic situations into meaningful operational structures. Consequently, expert controllers rely less on deliberate analytical reasoning and more on experience-based recognition of familiar traffic patterns, allowing cognitive resources to be allocated toward monitoring atypical situations and anticipating future developments (Mouratille et al., 2022; Hedayati et al., 2021).

Decision making within this architecture reflects a dynamic interaction between multiple cognitive control levels rather than a single reasoning process. Classical models of cognitive control proposed that operators shift between automatic skill-based behavior, rule-based processing, and knowledge-based reasoning depending on environmental demands (Rasmussen, 1986). However, subsequent studies suggest that these control levels often operate concurrently rather than sequentially. Morineau et al. (2003) demonstrated that controllers simultaneously execute procedural actions while continuously monitoring the validity of those procedures through higher-level cognitive evaluation. Similar observations have been reported in other complex safety-critical domains, where operators maintain parallel streams of procedural execution and strategic situation assessment. Such findings suggest that adaptive ATC performance depends on the coordination of multiple cognitive processes rather than switching exclusively between discrete control modes.

This layered cognitive organization has become increasingly important as air traffic management evolves toward human–AI collaboration. Contemporary ATM systems no longer rely solely on individual controller cognition but increasingly integrate automation, decision-support systems, digital assistants, and intelligent conflict-detection tools. Nevertheless, recent systematic reviews consistently conclude that automation should complement rather than replace the controller's cognitive architecture. Effective human–AI teaming requires artificial systems capable of supporting shared situation awareness, maintaining compatible mental models, assisting workload management, and enhancing adaptive decision making without disrupting existing cognitive strategies (Gerdes et al., 2025; Xia et al., 2025). Accordingly, modern cognitive architectures increasingly conceptualize ATC as a distributed cognitive system in which human operators and intelligent technologies jointly contribute to safe and efficient air traffic management.

Taken together, contemporary research supports viewing the cognitive architecture of air traffic control as an integrated adaptive system composed of selective perception, attentional resource allocation, working memory, long-term knowledge, dynamic mental representations, predictive reasoning, and flexible cognitive control. Rather than functioning as independent cognitive components, these processes continuously interact to construct, maintain, and revise the controller's traffic picture, enabling safe decision making within one of the most complex socio-technical environments currently operated by humans.

3. Situational Awareness in Air Traffic Control

Situational awareness (SA) has long been recognized as one of the most fundamental determinants of safe and effective air traffic control performance. Within highly dynamic and time-critical operational environments, controllers must continuously maintain an accurate understanding of the current traffic situation while simultaneously anticipating future developments that may compromise aircraft separation or operational efficiency. Unlike static decision-making environments, air traffic control requires controllers to integrate multiple streams of rapidly changing information, interpret their operational significance, and project future system states under considerable temporal and cognitive constraints. Consequently, situational awareness represents considerably more than the passive acquisition of information; rather, it constitutes an active cognitive process through which controllers transform fragmented environmental cues into a coherent and continuously evolving understanding of the operational environment (Endsley, 1995; Mogford, 1997; Chi et al., 2023).

The concept of situational awareness has been most comprehensively articulated through Endsley's three-level model, which continues to serve as the dominant theoretical framework within aviation human factors research. According to this model, situational awareness develops through three interrelated cognitive levels: perception of environmental elements, comprehension of their operational significance, and projection of their future status (Endsley, 1995). The first level involves the accurate detection and recognition of relevant environmental information, including aircraft position, altitude, speed, heading, weather conditions, system alerts, and communication inputs. At this stage, controllers continuously monitor multiple information sources while selectively attending to operationally relevant cues. However, successful perception alone is insufficient to support safe operational performance.

The second level of situational awareness requires controllers to integrate individual pieces of information into a meaningful understanding of the operational situation. Through pattern recognition, interpretation, and cognitive integration, isolated observations are transformed into an organized representation of current traffic dynamics. Controllers must evaluate relationships among aircraft, recognize emerging conflicts, understand operational priorities, and determine how the evolving traffic situation relates to both immediate and future control objectives. This level therefore depends heavily upon attention, working memory, long-term procedural knowledge, and well-developed mental models that enable rapid interpretation of complex traffic scenarios (Endsley, 1995; Yonggang, & Wenting, 2023).

The highest level of situational awareness involves projection—the ability to anticipate how the operational environment is likely to evolve over time. Rather than responding solely to current aircraft positions, experienced controllers continuously predict future aircraft trajectories, identify potential conflicts before they occur, estimate the consequences of control instructions, and proactively adjust traffic flows to preserve separation. This predictive capability distinguishes expert air traffic control from reactive monitoring and represents one of the defining characteristics of controller expertise. Projection depends upon accurate perception and comprehension while simultaneously drawing upon accumulated operational experience and domain-specific knowledge to anticipate future system behavior (Endsley, 1995; Mogford, 1997).

While the three-level framework provides a conceptual description of situation awareness, Endsley (1995) further integrated these levels into a broader dynamic decision-making model that illustrates how situational awareness interacts with environmental conditions, individual cognitive factors, decision making, and operational performance. As shown in Figure 2, situation awareness is not an isolated cognitive construct but rather an adaptive process continuously influenced by task characteristics, system design, operator goals, prior knowledge, experience, workload, and feedback from actions. The model also emphasizes that accurate perception (Level 1), comprehension (Level 2), and projection (Level 3) collectively provide the cognitive foundation for effective decision making and safe operational performance in dynamic environments.

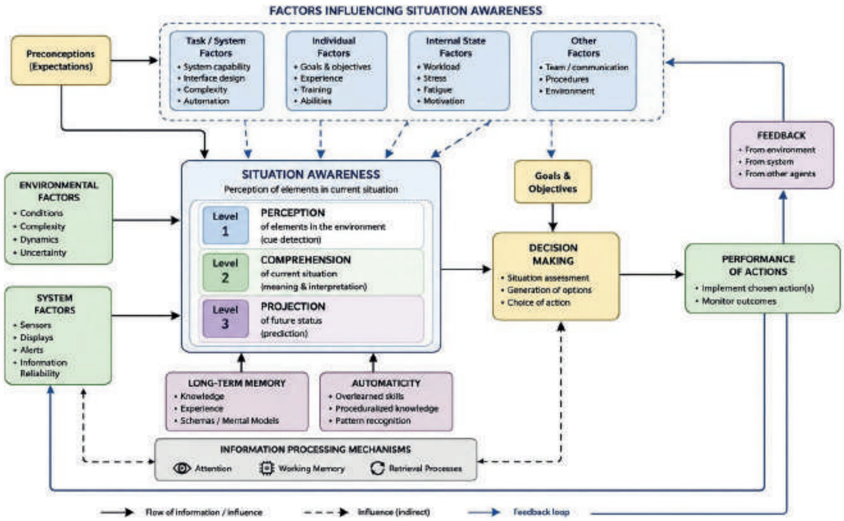

Figure 2. Integrated model of situation awareness in dynamic decision making (adapted from Endsley, 1995).

Although Endsley's framework remains the most influential conceptualization of situational awareness, subsequent research has expanded the concept beyond individual cognition. Mogford (1997) argued that situational awareness should be understood not merely as awareness itself but as the transient contents of awareness supported by an underlying mental representation of the operational environment. Within air traffic control, this representation is commonly referred to as the controller's *traffic picture*, a dynamic cognitive model that integrates aircraft positions, trajectories, sector characteristics, operational procedures, and anticipated future developments into a coherent representation supporting both present control and future planning. Rather than maintaining a complete representation of the operational environment, controllers continuously construct and update a simplified but functionally meaningful picture containing information most relevant to ongoing operational goals.

Recent research further conceptualizes situational awareness as a multidimensional cognitive process emerging from the interaction of perception, attention, working memory, mental models, and decision-making mechanisms. Controllers must continuously allocate attentional resources across multiple aircraft, prioritize competing information sources, maintain temporary representations within working memory, retrieve relevant procedural knowledge from long-term memory, and integrate these cognitive processes into coherent operational judgments. Consequently, situational awareness cannot be regarded as an isolated cognitive function but instead represents the emergent outcome of several interdependent cognitive mechanisms operating simultaneously under dynamic conditions (Hedayati et al., 2021; Chi et al., 2023).

The operational importance of situational awareness has been consistently demonstrated across both empirical and theoretical aviation research. Safe aircraft separation, conflict detection, traffic sequencing, weather avoidance, rerouting decisions, and emergency management all depend fundamentally upon controllers' ability to maintain an accurate and continuously updated understanding of the operational environment. Numerous studies have reported strong associations between degraded situational awareness and operational errors, including aircraft misidentification, delayed conflict recognition, incorrect prioritization, and inadequate decision-making under time pressure (Hedayati et al., 2021; Zhou et al., 2024). Similarly, large-scale investigations have shown that deficiencies in situational awareness frequently contribute to aviation incidents and accidents by disrupting the continuous information-processing cycle necessary for effective control. Yonggang and Wenting (2023), for example, reported that all three levels of situational awareness were positively associated with safe operational behaviour among professional controllers, with projection demonstrating the strongest predictive relationship with safety performance.

As air traffic management has evolved into an increasingly collaborative socio-technical system, the concept of situational awareness has likewise expanded beyond the individual controller. Modern operations require continuous coordination among controllers, pilots, supervisors, adjacent sectors, flow management units, and increasingly sophisticated automated systems. Consequently, contemporary research distinguishes individual situational awareness from team situational awareness and distributed situational awareness. Team situational awareness refers to the shared understanding developed among multiple operators who coordinate their activities toward common operational objectives, whereas distributed situational awareness conceptualizes awareness as a property emerging from interactions among people, technological systems, procedures, and organizational structures rather than residing exclusively within individual operators (Nguyen et al., 2018). This perspective has become increasingly important as digital decision-support systems and artificial intelligence assume more active roles within future air traffic management environments.

The rapid expansion of automation and artificial intelligence has introduced both opportunities and challenges for maintaining situational awareness. Advanced decision-support systems are increasingly capable of assisting conflict detection, uncertainty visualization, trajectory prediction, workload management, and adaptive information presentation. Such technologies have the potential to enhance controller awareness by improving information integration and reducing cognitive workload. At the same time, excessive dependence on automation may reduce active information processing, increase complacency, and contribute to out-of-the-loop performance problems when automated systems fail or produce unexpected recommendations (Kim et al., 2022; Xia et al., 2025). Consequently, contemporary research increasingly emphasizes that automation should be designed to support rather than replace human situational awareness, ensuring that controllers remain actively engaged in the cognitive processes necessary for effective supervisory control.

Recent technological developments have also transformed the assessment of situational awareness itself. Traditional measurement approaches, including subjective rating scales and simulation-based techniques such as the Situation Awareness Global Assessment Technique (SAGAT) and the Situation Present Assessment Method (SPAM), are increasingly complemented by objective physiological and behavioural measures. Eye-tracking, electroencephalography (EEG), machine learning, and multimodal human-performance monitoring now offer opportunities to estimate controller situational awareness continuously during operational tasks. Experimental studies have demonstrated that EEG combined with eye-tracking can reliably distinguish high and low situational awareness states under varying workload conditions, while deep-learning algorithms using eye-movement patterns have achieved promising levels of classification accuracy, suggesting that real-time monitoring of controller cognitive states may become feasible within future ATM systems (Li et al., 2022; Yu et al., 2024).

Despite considerable advances, important research challenges remain. Most contemporary studies continue to rely on simulation environments or laboratory experiments, leaving relatively limited empirical evidence regarding the long-term validity of situational awareness models within live operational settings. Similarly, while theoretical developments in team and distributed situational awareness have progressed substantially, empirical methods capable of reliably measuring shared awareness among multiple operators remain comparatively underdeveloped. Furthermore, the rapid integration of artificial intelligence into air traffic management introduces new questions regarding transparency, trust, explainability, and human–AI coordination, all of which may fundamentally influence how situational awareness is established, maintained, and shared within future operational environments (Nguyen et al., 2018; Xia et al., 2025).

Situational awareness should be understood as a dynamic, multi-level cognitive capability that integrates perception, comprehension, projection, attention, memory, mental models, and predictive reasoning to support safe and efficient air traffic control. Rather than representing an isolated psychological construct, situational awareness emerges from the continuous interaction between individual cognition, collaborative teamwork, technological systems, and organizational context. As automation and artificial intelligence become increasingly embedded within air traffic management, preserving and enhancing controller situational awareness will remain one of the central challenges for future aviation safety and human-centered system design.

4. Decision-Making And Cognitive Biases

Decision-making is a fundamental component of air traffic control because controllers are required to intervene continuously in an operational environment that evolves both independently of and in response to their own actions. Unlike conventional decision problems in which a decision maker selects among clearly defined alternatives at a discrete point in time, air traffic control involves a continuous sequence of interdependent judgments and actions. Controllers monitor changing traffic relationships, establish operational goals, formulate and modify plans, issue control instructions, and evaluate whether previous interventions are producing the anticipated system state. Decisions are therefore embedded within an ongoing stream of activity and are directed primarily toward establishing and maintaining control over a dynamic airspace system (Niessen et al., 1999; Gyles & Bearman, 2025). This perspective challenges simplified accounts of decision-making as a single choice between alternatives and instead conceptualizes it as a goal-directed, temporally extended, and adaptive cognitive process.

The cognitive foundations of controller decision-making are closely connected to situational awareness and the maintenance of an operational mental model. Controllers construct and continuously revise a representation of the traffic environment—the *traffic picture*—through the integration of surveillance information, communication, procedural knowledge, aircraft performance characteristics, and expectations regarding future traffic development (Niessen et al., 1999; Mogford, 1997). This representation allows controllers not only to interpret the present configuration of traffic but also to anticipate future system states and identify circumstances requiring intervention. Consequently, the quality of a decision cannot be separated from the quality of the cognitive representation upon which it is based. Inaccurate perception, incomplete integration of relevant information, or an inappropriate projection of future traffic may orient the controller toward a goal or plan that is poorly aligned with the actual operational situation. Decision errors may therefore originate before an explicit choice is made, within the perceptual, attentional, and interpretative processes that shape the decision context itself (Hedayati et al., 2021; Gyles & Bearman, 2025).

Decision strategies in air traffic control can broadly be located along a continuum between analytical and intuitive processing. Analytical decision-making involves the deliberate evaluation of information, explicit comparison of possible courses of action, and conscious assessment of potential consequences. Although such processing can support complex and unfamiliar decisions, it is relatively slow and places substantial demands on working memory and attentional resources. Heuristic and intuitive processes, in contrast, allow decisions to be made rapidly by reducing the amount of information that must be explicitly evaluated. Rather than considering every available variable, controllers may rely on diagnostically important cues, learned traffic patterns, and established operational strategies to identify an appropriate response (Gerdes et al., 2025).

The prominence of intuitive processing in air traffic control is consistent with the broader Naturalistic Decision-Making tradition and the Recognition-Primed Decision model. Naturalistic approaches emerged from the recognition that experts working in safety-critical domains rarely make decisions by systematically generating and comparing an exhaustive set of alternatives. Instead, experienced operators frequently recognize familiar patterns, activate a plausible course of action, and assess whether that action is likely to achieve the intended goal (Klein, 1998; Lipshitz et al., 2001). Recognition-primed decision-making is particularly relevant to ATC because controllers frequently operate under time pressure, uncertainty, and continuously changing conditions. Recent theoretical developments have sought to extend recognition-based models by incorporating probabilistic memory processes, selective feature reduction, and continuous information streams, thereby providing a more detailed account of how relevant environmental cues are selected and matched with previous experience (Hu & Wang, 2024; Hu, 2025).

Standard operating procedures, learned control strategies, and repeated exposure to sector-specific traffic patterns further structure intuitive decision-making. Recurring operational situations can become represented as experience-based decision structures that guide controllers through common sub-decisions, including which aircraft should be maneuvered, when an intervention should occur, and which trajectory parameter should be modified (Gerdes et al., 2025). With increasing expertise, many of these processes require limited conscious deliberation and impose relatively low demands on working memory. Gyles and Bearman (2025) argue that much of expert controller activity must necessarily be regulated through fast and intuitive cognitive processes because continuously deliberating over every aircraft relationship would be incompatible with the temporal demands of operational ATC. The extensive duration of controller training may partly reflect the time required to develop the regulatory patterns, habits, and domain-specific cognitive structures that support such expert decision-making.

However, expert decision-making should not be equated with exclusively intuitive processing. A defining characteristic of adaptive expertise is the ability to coordinate intuitive and analytical modes of cognition according to the demands of the evolving situation. Familiar and regular traffic patterns provide conditions in which rapid recognition-based processes can operate efficiently. When the operational environment becomes atypical, uncertainty increases, expected aircraft behaviour does not occur, or a current plan fails to produce the intended traffic configuration, continued reliance on intuitive processing may become hazardous. Under such circumstances, controllers must interrupt or reconsider established patterns of action and engage in more deliberate analytical reasoning. Thus, effective decision-making depends not simply on whether intuition or analysis is superior, but on the controller's capacity to recognize when an established cognitive strategy is no longer appropriate and to shift the level of cognitive control accordingly (Morineau et al., 2003; Gyles & Bearman, 2025).

The expert decision-making model proposed by Gyles and Bearman (2025) develops this position by conceptualizing ATC decisions as continuous goal-, plan-, and action-oriented processes regulated through automatic, intuitive, emotional, and deliberative mechanisms. As illustrated in Figure 3, the model situates decision-making within a dynamic cognitive work process that begins with orientation and situation awareness and subsequently informs the formation of goals, the selection or construction of plans, and the implementation of actions. Importantly, these components are not represented as a simple linear sequence. The regulatory architecture represented in Figure 3 is particularly relevant to understanding the interaction between intuitive expertise and cognitive vulnerability. Automatic and intuitive processes permit rapid responses in familiar operational situations, whereas metacognitive monitoring evaluates the uncertainty associated with emerging judgments and the subjective feeling of rightness. When uncertainty becomes sufficiently salient, deliberative processing may intervene to reconsider the interpretation of the situation, retrieve or modify rules, generate alternative responses, or reassess an existing plan. Deliberative processing can subsequently feed back into intuitive regulation until uncertainty is sufficiently reduced for action to proceed. From a cognitive bias perspective, this mechanism is especially important because a strong feeling of rightness attached to an intuitively generated interpretation may permit a plan or action to continue without extensive analytical reassessment. Accordingly, expert performance depends not only on the quality of intuitive pattern recognition but also on the effectiveness of metacognitive processes in detecting uncertainty, conflicting cues, and deviations from expected system behaviour (De Neys, 2023; Gyles & Bearman, 2025). Rather, feedback and feedforward mechanisms continuously connect ongoing actions with higher-order goals and plans, allowing controllers to evaluate whether the evolving traffic situation remains consistent with the anticipated system state. The model therefore conceptualizes expert ATC decision-making as a form of adaptive cognitive regulation in which operational interventions are continuously monitored and modified in response to changing environmental information (Gyles & Bearman, 2025).

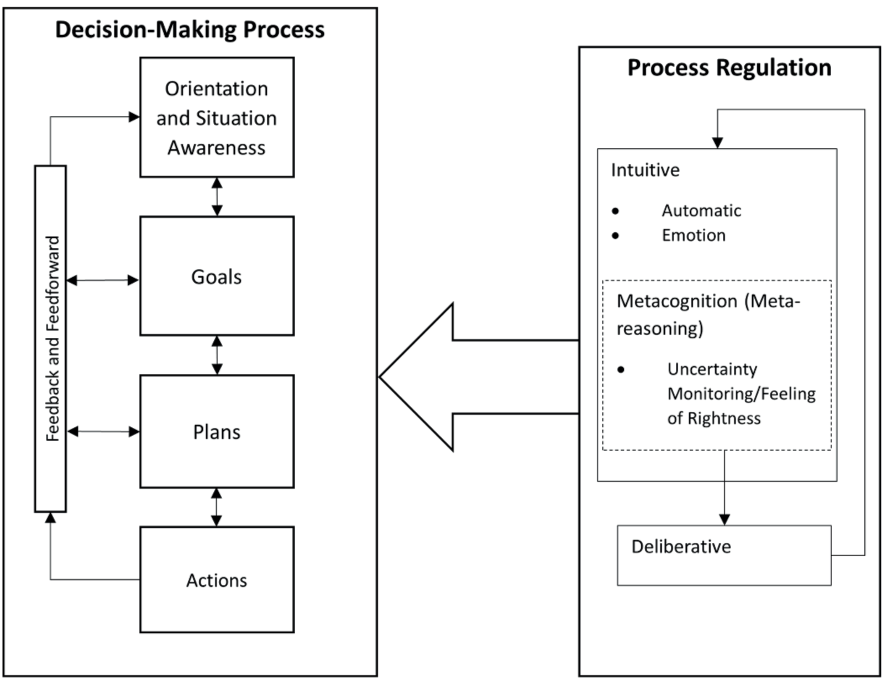

Figure 3. Integrated model of expert decision-making in air traffic control, illustrating the interaction between orientation and situation awareness, goal formation, planning, action, feedback and feedforward mechanisms, and intuitive, metacognitive, and deliberative process regulation (reproduced from Gyles & Bearman, 2025).

Recent empirical findings further indicate that cognitive regulation mechanisms extend beyond traditional decision-making models. Among professional air traffic controllers, mindfulness has been shown to improve job performance both directly and indirectly through enhanced decision-making processes. These findings suggest that maintaining attentional regulation and present-moment awareness may strengthen cognitive flexibility and decision quality under operational pressure, highlighting mindfulness as a promising human performance intervention in safety-critical environments (Çeken & Tuncal, 2025).

This dynamic account also provides a useful basis for understanding cognitive biases in air traffic control. Cognitive biases should not necessarily be interpreted as irrational departures from otherwise perfect decision-making. Many biases emerge from the same cognitive mechanisms that ordinarily enable rapid and efficient performance. Expectations, pattern recognition, selective attention, and experience allow controllers to reduce complexity and anticipate likely events; however, these processes may also constrain the interpretation of information when actual conditions differ from what is expected. The problem therefore lies not in the existence of expectations or heuristics themselves, but in the persistence of an established interpretation when discrepant evidence becomes available.

Expectation bias provides a particularly relevant example. It occurs when prior beliefs or anticipated patterns influence how incoming information is perceived and interpreted. In repetitive operational environments, what normally occurs may become a powerful cognitive reference for interpreting what is currently occurring. Controllers may therefore perceive or respond to an event in a manner consistent with routine traffic patterns even when the actual situation contains important deviations. Aviation safety literature has illustrated this mechanism through operational examples in which controllers issue habitual runway or approach clearances despite changed traffic, equipment, or environmental conditions (Skybrary, n.d.). In this sense, expectation bias may influence not only an explicit operational judgment but also the perceptual and interpretative processes through which the decision situation itself is cognitively constructed.

A particularly illustrative operational example is the February 2023 Austin-Bergstrom International Airport event involving FedEx Flight 1432 and a Southwest Airlines aircraft. Under low-visibility conditions, the controller's expectations regarding the departing aircraft's position and anticipated take-off progress influenced the developing traffic assessment. The departing aircraft required more time than expected to reach and accelerate along the runway, while the arriving aircraft continued its approach to the same runway. The subsequent investigation identified controller expectation bias as a contributing factor in the event (Skybrary, n.d.). This occurrence demonstrates how routine-based expectations can influence the interpretation of environmental cues and the projection of future system states, thereby shaping subsequent operational decisions.

Other cognitive biases identified across aviation and safety-critical decision research include confirmation bias, plan continuation bias, overconfidence, anchoring, representativeness, and broader expectancy-related effects. Confirmation bias may encourage an operator to preferentially interpret new information as supporting an existing understanding of the traffic situation. Anchoring may result in excessive reliance on an initial estimate or assessment despite subsequent changes in operational conditions. Plan continuation bias may promote persistence with an established course of action even when the original assumptions supporting that plan have weakened. Overconfidence may reduce the perceived need for additional information gathering or verification. Although these mechanisms are theoretically relevant to controller cognition, the empirical literature directly classifying specific cognitive biases in ATC remains considerably less developed than the literature on workload, situational awareness, and operational error (Reale et al., 2023; Nadri et al., 2024). Accordingly, caution is required when retrospectively assigning a particular cognitive bias to an operational event without sufficient evidence concerning the information available to the controller and the cognitive context in which the decision developed.

Workload, time pressure, and stress can further influence the balance between intuitive and analytical decision processes. Increasing task complexity modifies both cognitive workload and situational awareness, while high traffic demand may increase perceptual and interpretative errors (Hedayati et al., 2021; Yiu et al., 2025). Under substantial cognitive demand, the resources available for deliberate analysis become constrained, potentially increasing reliance on rapid pattern-based responses. Neurophysiological research similarly indicates that loss of situational awareness under high workload may involve cognitive states distinguishable from awareness degradation under normal workload conditions (Li et al., 2022). Such findings reinforce the importance of considering decision-making as the outcome of interactions among cognitive resources, environmental complexity, and operational demands rather than as an isolated mental act.

Experience modifies these relationships but does not eliminate vulnerability to error. Expert controllers generally possess richer mental models, more efficient attentional strategies, and a larger repertoire of recognized traffic patterns. These capabilities facilitate rapid identification of meaningful cues and reduce the working-memory burden associated with routine decisions. Recent evidence further suggests that experience strengthens perceived cognitive resources and may support more planful forms of control under operational pressure (Kim et al., 2026). Nevertheless, the same experience that supports intuitive expertise can strengthen expectations regarding how familiar situations normally unfold. When an atypical event resembles a familiar pattern, an expert may initially apply an otherwise effective intuitive strategy to a situation in which its underlying assumptions are invalid. Expertise therefore depends on both pattern recognition and metacognitive sensitivity to uncertainty, atypicality, and deviations from expected system behaviour.

Emotion may also contribute to the regulation of expert decision-making. Gyles and Bearman (2025) propose that affective responses can serve several cognitive functions in ATC decision processes. First, they may generate an immediate intuitive response to a developing situation. Second, emotional states may influence the accessibility and valuation of information retrieved from memory. Third, they may contribute to metacognitive judgments concerning uncertainty or the perceived *rightness* of an emerging decision. From this perspective, feelings of uncertainty are not merely undesirable consequences of operational pressure; they may provide cognitively meaningful signals that an intuitive interpretation requires further deliberative evaluation. The integration of emotion into ATC decision theory is particularly important because conventional information-processing models have often conceptualized expert judgment primarily in cognitive terms while devoting comparatively limited attention to affective and metacognitive regulation.

The increasing introduction of automation and artificial intelligence adds another layer to the decision-making architecture of air traffic control. Decision-support tools may reduce detection, memory, decision, and action-execution errors by presenting conflict information, trajectory predictions, or recommended actions. However, automation also creates new forms of cognitive vulnerability, including delayed detection of tool-related information, inappropriate reliance, and potential disruption of established controller strategies (Corver & Aneziris, 2014). Contemporary human-centered approaches therefore increasingly emphasize adaptive decision support that responds to workload and cognitive-state indicators while preserving meaningful human decision authority (Li et al., 2021).

Intelligent systems may be particularly valuable when designed to complement the limitations of intuitive expertise rather than simply automate controller decisions. For example, systems could identify aircraft behaviour that deviates from expected patterns and explicitly signal atypicality, thereby encouraging controllers to reassess an intuitive interpretation. Predictive tools may also support feedforward reasoning by presenting future spacing relationships, speed differentials, or projected traffic states at defined temporal intervals. Such information may strengthen controllers' capacity to evaluate whether an existing plan is likely to remain effective as the operational situation evolves (Gyles & Bearman, 2025). Nevertheless, the operational value of these systems depends substantially on transparency, trust, acceptance, and compatibility with controllers' existing cognitive strategies. An automated recommendation that cannot be meaningfully integrated into the controller's mental model may increase rather than reduce cognitive uncertainty.

Despite considerable progress in understanding ATC decision-making, significant research gaps remain. The literature provides a mature theoretical and empirical foundation concerning situational awareness, workload, expertise, mental models, and operational error, yet direct ATC-specific evidence concerning individual cognitive biases remains comparatively sparse. Much of the existing discussion of confirmation bias, plan continuation bias, overconfidence, and related mechanisms is derived from adjacent aviation domains or broader safety-critical environments rather than direct experimental investigation involving professional controllers. This imbalance limits the development of a comprehensive, empirically grounded taxonomy of cognitive biases specific to ATC decision-making.

A second major research gap concerns the operational validation of automation- and AI-supported decision tools. Adaptive automation, intelligent decision support, and digital ATCO concepts are advancing rapidly, yet much of the current evidence remains based on simulations, conceptual architectures, and experimental systems rather than longitudinal evaluation in live operational environments. Similarly, the expert decision-making model proposed by Gyles and Bearman (2025) remains predominantly qualitative and conceptual. The authors emphasize the need for further validation in ecologically valid ATC environments in which decisions are examined as sequences of interventions within unfolding traffic scenarios. Future research should therefore investigate how controllers construct and modify goal sets, how uncertainty influences plan selection, when analytical processing supplements intuitive cognition, and how these processes interact with team-level coordination and technological support (Gyles & Bearman, 2025).

Decision-making in air traffic control is best understood as a continuous, adaptive process through which controllers establish and maintain control of a dynamic socio-technical system. Situational awareness and mental models provide the cognitive representation upon which goals and plans are established; intuitive processes enable rapid and resource-efficient intervention in familiar situations; analytical processes support reassessment when uncertainty or atypicality emerges; and feedback and feedforward mechanisms allow controllers to evaluate whether ongoing actions remain aligned with operational goals. Cognitive biases arise partly from the same expectations, heuristics, and pattern-recognition mechanisms that normally support expert performance, making the distinction between adaptive expertise and decision error highly context-dependent. As air traffic management progresses toward closer human–AI collaboration, the central challenge will therefore be not to replace human decision-making, but to design systems capable of identifying cognitive vulnerability, supporting appropriate transitions between intuitive and analytical processing, and strengthening controllers' capacity to maintain adaptive control under increasingly complex operational conditions.

5. Mental Workload, Stress, And Human Performance

Mental workload, stress, fatigue, and vigilance represent central performance-influencing factors in air traffic control because they shape the extent to which controllers can sustain attention, maintain situation awareness, process information, communicate effectively, and make timely decisions in dynamic operational environments. In ATC, human performance is not determined solely by technical competence or procedural knowledge; rather, it emerges from the continuous interaction between task demands, cognitive resources, operator state, team processes, and environmental complexity. Performance-influencing factors are therefore especially important for understanding controller error, not because they mechanically produce unsafe behaviour, but because they alter the cognitive conditions under which safe performance must be maintained (Edwards et al., 2023).

Mental workload should be distinguished from task load, traffic volume, operational complexity, and stress. Task load refers to the objective demands imposed by the operational situation, such as the number of aircraft, frequency congestion, coordination requirements, conflict geometry, or time pressure. Mental workload, by contrast, refers to the controller's experienced cognitive demand in relation to the resources available to meet those demands. Thus, the same traffic situation may generate different levels of workload depending on controller expertise, fatigue, familiarity with the sector, available support tools, team coordination, and the strategies adopted to manage traffic. This distinction is important because observable performance or aircraft count alone may underestimate the cognitive effort required to maintain safe control (Wickens, 1984; Wickens et al., 1997; Loft et al., 2007; Fürstenau & Radüntz, 2021).

From a resource-theory perspective, workload arises when task demands require the allocation of limited attentional and cognitive resources. When task demands are low, controllers may retain spare cognitive capacity. When demands increase, more resources must be allocated to monitoring, communication, conflict detection, planning, and decision-making. If the required resources exceed those available, overload may occur, increasing the probability of delayed detection, reduced situation awareness, memory failures, communication errors, and degraded decision quality. However, workload–performance relationships are not always linear. Both underload and overload can impair performance: underload may reduce vigilance and engagement, whereas overload may produce cognitive saturation and attentional narrowing (Wickens, 1984; Cox-Fuenzalida, 2007; Edwards et al., 2023).

In ATC, high workload is closely related to complexity but cannot be reduced to traffic count alone. Traffic volume is important, yet complexity also depends on aircraft mix, convergence patterns, vertical and horizontal proximity, time-to-conflict, sector structure, number of merging points, communication load, adjacent-sector coordination, weather, abnormal events, and controller actions. Recent workload and complexity models therefore treat ATC workload as a dynamic and context-dependent construct shaped by traffic events, airspace design, controller strategy, and evolving operational uncertainty (Ibáñez-Gijón et al., 2023; Muñoz-de-Escalona et al., 2024; Göppel et al., 2024). This explains why two sectors with the same number of aircraft may impose very different cognitive demands.

This dynamic relationship between external task demands, controller cognition, and experienced workload is illustrated in Figure 4. The model distinguishes task-load factors originating from traffic and airspace complexity, interface and equipment demands, and procedural requirements from the internal cognitive processes through which controllers monitor, evaluate, formulate, and implement decisions. Importantly, workload is not conceptualised as a direct consequence of task demands. Rather, the relationship is mediated by performance-shaping factors, including skill, fatigue, strategies, and cognitive biases, which influence the allocation of attentional resources and the controller's response to operational demands (Hilburn, 2004). This framework reinforces the view that comparable traffic conditions may generate substantially different levels of cognitive workload across controllers and operational contexts.

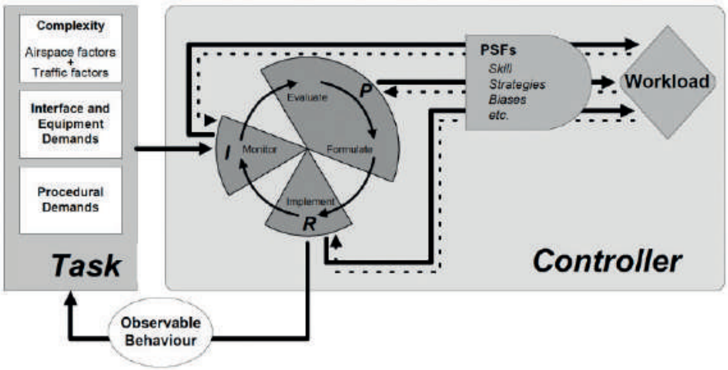

Figure 4. Proposed Model of ATC Complexity and Workload (adapted from Hilburn, 2004).

Mental workload influences performance primarily through its effects on cognitive mechanisms. Under increasing workload, controllers may have fewer resources available for sustained monitoring, prospective memory, information updating, conflict projection, and communication management. High workload can alter visual scanning patterns, reduce time spent attending to each aircraft, increase reliance on routine strategies, and weaken the maintenance of the traffic picture. Endsley and Rodgers (1997)' findings that controllers may shorten attention to individual aircraft under high task load illustrate how adaptive workload-management strategies can preserve overall monitoring while simultaneously increasing the risk of missing critical details. Thus, compensatory strategies are not inherently unsafe, but they may create new vulnerabilities when task demands exceed available cognitive capacity.

Stress is related to workload but conceptually distinct. Whereas workload concerns the cognitive demand imposed by task requirements, stress arises when operators perceive an imbalance between environmental demands and their capacity to cope with those demands. In ATC, stress may be generated by time pressure, high responsibility for safety, uncertainty, abnormal events, equipment limitations, communication congestion, and sustained exposure to demanding traffic situations. Moderate arousal may support alertness and motivation, but excessive stress can impair working memory, divided attention, cognitive flexibility, information retrieval, and decision-making. The Yerkes–Dodson framework is useful here only as a broad heuristic: performance may improve with increasing arousal up to an optimal point, but excessive arousal is especially harmful in complex cognitive tasks such as ATC, where precise attention allocation and flexible decision-making are required (Yerkes & Dodson, 1908; Hockey, 1997; LeBlanc, 2009).

Fatigue further modifies the workload–performance relationship. Controllers often work rotating shifts, night shifts, and extended duty patterns, all of which may disrupt sleep and circadian rhythms. Fatigue can also accumulate through sustained cognitive effort and time-on-task effects. In ATC, fatigue is particularly concerning because it affects sustained attention, visual perception, reaction time, vigilance, and the ability to maintain continuous monitoring over long sessions. Empirical work has shown that controller performance may decline across consecutive shifts as fatigue increases, although the relationship is moderated by task demands, motivation, compensatory effort, and operational context (Caldwell, 2001).

Vigilance is another essential component of controller performance. Controllers must maintain continuous readiness to detect rare but safety-critical events across visual and auditory channels. In en-route and terminal environments, they monitor radar displays, flight levels, speeds, trajectories, pilot readbacks, coordination messages, and potential conflicts over extended periods. Vigilance decrements over time may reduce detection accuracy and increase response time, particularly when workload is low or monotonous. Incident analyses also show that perception and detection failures, including late or missed detection, are frequent contributors to ATC-related safety events (Thackray & Mark Touchstone, 1989; Shorrock, 2007).

Controllers are not passive recipients of workload and stress. They actively regulate performance through adaptive strategies such as prioritization, attentional reallocation, task shedding, deferral of lower-priority actions, strategic simplification, increased separation margins, greater caution, and reliance on familiar routines. Expertise is central to this regulation. Experienced controllers are often better able to anticipate traffic evolution, compress complex situations into meaningful patterns, allocate attention efficiently, and select strategies that reduce unnecessary cognitive effort. However, expertise does not eliminate risk; under high workload or stress, even experts may become vulnerable to attentional narrowing, expectation-based interpretation, plan continuation, and reduced flexibility.

Measurement of workload and stress in ATC must therefore be multidimensional. Subjective measures such as NASA-TLX and ISA provide useful information about perceived demand, but they are retrospective and may not capture rapid workload fluctuations. Behavioural and performance indicators can reveal workload consequences, but often only after performance has already degraded. Physiological and neurophysiological measures, including

EEG, heart rate, heart-rate variability, electrodermal activity, fNIRS, speech markers, and eye tracking, offer promise for real-time monitoring, yet they are sensitive to individual differences, task context, equipment limitations, and interpretation problems. For this reason, multimodal approaches are increasingly recommended, especially for adaptive automation and human–AI decision support (Pagnotta et al., 2021; Li et al., 2022; Yu et al., 2025).

Automation and artificial intelligence introduce both opportunities and risks for workload management. Decision-support tools may reduce cognitive burden by assisting conflict detection, trajectory prediction, information integration, and workload monitoring. However, automation may also create new cognitive demands, including monitoring burden, mode awareness, trust calibration, automation surprise, vigilance reduction, and out-of-the-loop performance. Future ATC systems should therefore not aim simply to reduce workload, but to regulate it adaptively by supporting controller awareness, preserving meaningful human control, and providing assistance when cognitive demand approaches unsafe levels.

A recent systematic review further demonstrates that controller fatigue should not be considered an isolated physiological state but rather the cumulative outcome of workload, circadian disruption, sleep deprivation, shift schedules, and psychological stress. The interaction among these factors degrades attention, decision making, communication, and overall operational performance, emphasizing that fatigue management should be integrated into cognitive performance management rather than treated as an independent occupational health issue (Tuncal et al., 2025).

Mental workload, stress, fatigue, and vigilance should be understood as interacting components of controller human performance. Safe ATC performance depends not only on keeping workload low but on maintaining workload within a range that supports engagement, awareness, anticipation, and adaptive control. Excessive workload and stress can degrade attention, memory, situation awareness, communication, and decision-making, while very low workload may reduce vigilance and readiness. The central challenge for future air traffic management is therefore to design operational environments, staffing systems, procedures, interfaces, and automation tools that support controllers' cognitive resources, detect emerging overload or underload, and strengthen adaptive performance in increasingly complex airspace systems.

6. Communication and Team Cognition

Communication is a fundamental cognitive and operational function in air traffic control because safe traffic management depends on the timely construction, exchange, interpretation, and updating of information across multiple actors. Although ATC communication is frequently described in terms of message transmission, phraseology, and procedural compliance, such a perspective captures only part of its cognitive significance. Controllers operate within a continuously changing environment in which information acquired through surveillance displays, flight data, radio transmissions, coordination channels, and other operational sources must be selectively attended to, interpreted in relation to the current traffic picture, retained when necessary, and integrated into future-oriented decisions. Communication is therefore embedded within the broader cognitive architecture of air traffic control and is closely linked to attention, working memory, mental representation, situation awareness, anticipation, and decision-making (Niessen et al., 1999).

The cognitive demands of operational communication are particularly evident when information must be processed concurrently with other control activities. Controllers do not simply receive a verbal message and generate a response; they must identify the relevant speaker or aircraft, decode the content of the transmission, interpret its operational meaning, relate it to existing traffic conditions and ongoing plans, determine whether action is required, and maintain relevant information until the associated task has been completed. These processes occur while attention may simultaneously be required for radar monitoring, conflict assessment, coordination, and the execution of previously initiated actions. The selective nature of the controller's traffic representation is especially important in this context. Controllers appear to construct a functionally reduced traffic picture rather than maintaining an exhaustive representation of all available information, and experience influences the extent to which explicit planning information must be retained and actively processed (Niessen et al., 1999). Communication must consequently operate within finite attentional and working-memory resources.

Evidence from aviation cognition further supports this interpretation. Working memory, expertise, divided attention, and inhibitory control have been associated with situation awareness, indicating that operational information processing depends on the ability to maintain relevant information while suppressing competing or distracting inputs (Cak et al., 2019). Applied to controller–pilot communication, the safety of a transmission cannot therefore be assessed exclusively according to whether the correct words were spoken. A technically accurate instruction may still fail to support safe performance if it is missed, incorrectly attributed, incompletely retained, interpreted according to an inappropriate expectation, or insufficiently integrated into the receiver's current representation of the operational situation. The cognitive effectiveness of communication depends on both message characteristics and the information-processing state of the interacting operators.

Standardized phraseology represents an important defense against these vulnerabilities because it constrains linguistic variability and establishes predictable relationships between verbal forms and operational meanings. Concise message structure, call-sign discipline, readback and hearback procedures, and closed-loop communication are intended to reduce ambiguity and provide opportunities to detect discrepancies before they influence aircraft trajectories (Yang et al., 2023; Ziakkas et al., 2025; Arlanda et al., 2026). Nevertheless, standardization cannot entirely remove the cognitive processes involved in interpretation. The meaning of a transmission remains influenced by timing, traffic context, expectations, prior communication, and the receiver's current goals. Communication in ATC is thus simultaneously procedural and inferential: standardized language constrains possible meanings, but controllers and pilots must still integrate the message with their understanding of the evolving operational environment.

This contextual dependence is particularly relevant to the establishment of common ground. Communication between controllers and pilots, or among controllers, frequently occurs in circumstances in which the observable behaviour of another actor may be compatible with several possible intentions. Communication enables participants to reduce this ambiguity by aligning beliefs concerning the current situation, intended actions, and anticipated future states. Mutual-belief approaches to ATC coordination suggest that effective cooperation does not require all actors to possess identical knowledge. Rather, operational coordination depends on sufficient understanding of what other participants know, intend, and expect to enable compatible action

(Ogawa et al., 2019). From this perspective, communication contributes to safety by regulating the alignment of distributed cognitive representations.

This argument provides a direct conceptual bridge from individual cognition to team cognition. Air traffic control is inherently collaborative, even when an individual controller appears to be directly responsible for a particular sector or control position. Traffic management is distributed across executive and planning controllers, tower positions, adjacent sectors, pilots, supervisors, operational units, and technological artifacts. No single individual necessarily possesses all information relevant to the functioning of the overall system. Cognitive work is therefore distributed across people and technologies, with system performance emerging from the coordination of partially overlapping and role-specific information (Inoue et al., 2010; Soraji et al., 2012).

Team cognition refers broadly to the cognitive processes that enable teams to acquire, organize, exchange, and use information collectively. Within ATC, these processes include the formation of shared expectations, coordination of goals and plans, anticipation of colleagues' information requirements, task distribution, mutual monitoring, and the maintenance of a sufficiently coherent representation of the traffic environment. Team cognition should not be understood simply as the sum of individual cognitive abilities. A team composed of technically competent controllers may still experience coordination failure if information is fragmented, expectations diverge, or team members construct incompatible representations of an evolving traffic situation.

The concept of shared mental models provides one explanation for effective team coordination. Shared mental models refer to organized knowledge structures that enable team members to develop compatible expectations concerning the task, operational environment, equipment, team roles, and likely behaviour of other team members. In ATC, a sufficiently aligned mental representation can reduce the need for continuous explicit communication because controllers may anticipate what information a colleague requires or how another team member is likely to respond to a developing situation. This anticipatory capacity supports implicit coordination, particularly in experienced teams operating within familiar environments (Soraji et al., 2012).

However, effective team cognition does not necessarily require identical mental representations. Controllers occupying different operational positions have different responsibilities, information requirements, and temporal perspectives. Complete cognitive overlap would therefore be neither realistic nor necessarily desirable. A planner controller and an executive controller, for example, may attend to different aspects of the same traffic situation while contributing complementary information to a coordinated control strategy. The critical requirement is not cognitive uniformity but functional compatibility: team members must possess the knowledge required for their roles while maintaining sufficient mutual awareness to coordinate their activities. Mutual-belief models similarly emphasize alignment regarding others' knowledge, intentions, and expectations rather than complete informational equivalence (Ogawa et al., 2019).

Team situation awareness is closely related to this process. Situation awareness at the team level involves more than the parallel maintenance of individual traffic pictures. It depends on whether relevant information is appropriately distributed, whether discrepancies are detected, and whether team members can coordinate their representations through interaction. Earlier ATC team-cognition research emphasized that static accounts of shared situation awareness may inadequately explain how mutual awareness is established and revised during cooperative activity (Inoue et al., 2010). A dynamic perspective is therefore required. Team situation awareness develops through communication, observation, coordination, handovers, shared displays, flight information, and knowledge of colleagues' activities. It is continuously reconstructed as traffic and operational priorities change.

Communication consequently performs both an informational and a regulatory function within team cognition. Explicit communication can transfer information that another team member does not possess, clarify ambiguous observations, establish intentions, or correct a developing misunderstanding. At the same time, communication can regulate coordination by indicating priorities, directing attention, negotiating task distribution, or signalling that assistance is required. Once a coherent team representation has been established, some coordination may become implicit because team members can anticipate one another's actions and information requirements. Nevertheless, implicit coordination remains dependent on the continued validity of shared assumptions. When the operational situation changes unexpectedly, explicit communication may again become necessary to restore alignment.

Empirical findings concerning shared mental models reinforce their potential importance for ATC performance. In tower-control teams, the relationship between workload and team performance has been reported to operate through perceived shared mental models, suggesting that workload may become particularly detrimental when teams are unable to maintain a coherent cognitive frame for coordination (Phoompiew, 2024). This finding is theoretically important because it indicates that workload is not exclusively an individual cognitive problem. Increasing task demands may alter the frequency, timing, or completeness of information exchange and thereby affect the team's capacity to coordinate distributed cognitive resources. Team cognition may consequently function as a mechanism through which operational workload is either absorbed or amplified.

Communication itself is also a source of workload. Increasing traffic density and complexity generally produce greater demands for clearances, requests, coordination, and information exchange. Controllers must process auditory information while maintaining visual monitoring and performing concurrent cognitive tasks. Communication behaviour has therefore been investigated as a potential indicator of workload, and studies using operational voice and simulation data suggest that characteristics of controller communication can reflect changing task demands and traffic complexity (Ibáñez-Gijón et al., 2023; Muñoz-de-Escalona et al., 2025). This relationship is bidirectional. Operational complexity increases communication requirements, while communication consumes cognitive resources that might otherwise be allocated to monitoring, planning, or conflict assessment.

Under high workload, the quality of communication and team coordination may become vulnerable. Time pressure and competing tasks can reduce opportunities for elaboration, verification, and explicit information sharing. Attention may be redirected toward immediately threatening aircraft, while lower-priority coordination tasks are deferred. Information that appears obvious to one team member may not be communicated because of assumptions concerning what others already know. At the same time, the receiving operator may have insufficient attentional capacity to process or retain a transmission fully. Communication breakdown under workload should therefore not be interpreted solely as a linguistic failure; it may emerge from interactions among limited cognitive resources, task prioritization, expectations, timing, and distributed information.

Readback and hearback errors, overlapping transmissions, communication omissions, non-standard phraseology, and call-sign confusion illustrate these interactions. Such failures have been associated with loss of separation, runway incursions, and other safety occurrences (Yang et al., 2023; Arlanda et al., 2026). However, the presence of an incorrect transmission does not necessarily explain why a misunderstanding persists. Cognitive and discourse-oriented analyses indicate that phonological similarity, lexical expectation, confirmation bias, and pragmatic characteristics of communication may sustain an incorrect interpretation across several conversational exchanges (Tuncal, 2026). Once an initial message is interpreted consistently with an expected situation, subsequent information may also be processed within that interpretative frame. In such cases, both participants may believe that effective communication has occurred while their mental representations of the operational situation gradually diverge.

The relationship between communication and situation awareness is therefore recursive. Situation awareness shapes how messages are interpreted because existing mental representations provide context for incoming information. Communication, in turn, modifies situation awareness by adding, correcting, or confirming elements of those representations. If the initial traffic picture is inaccurate, expectation-driven interpretation may distort communication; if communication is incomplete or misunderstood, the traffic picture may become increasingly inaccurate. Communication failures can consequently develop through feedback processes in which an incorrect mental representation and an ambiguous exchange mutually reinforce one another.

Team cognition provides important defensive mechanisms against these failures. Mutual monitoring and backup behaviour allow team members to identify discrepancies that an individual controller may not detect. Effective teams distribute attention across tasks, anticipate emerging workload, and redistribute cognitive demands when one member becomes overloaded. Colleagues may provide reminders, clarify information, assume lower-priority tasks, or draw attention to developing conflicts. These behaviours represent forms of team adaptation in which collective performance compensates for limitations in individual cognitive capacity.

From a resilience perspective, communication and team cognition are therefore central mechanisms of adaptive performance. ATC teams must frequently respond to situations that cannot be managed through rigid procedural execution alone. Unexpected traffic behaviour, weather changes, equipment limitations, abnormal aircraft conditions, and rapidly developing conflicts may require teams to reorganize priorities and construct new control strategies. Communication allows information concerning these changes to circulate through the operational system, while shared and distributed cognitive processes enable actors to coordinate adaptive responses. Team resilience is consequently expressed not through the absence of cognitive disruption but through the ability to detect divergence, repair shared understanding, and recover coordinated control.

Training approaches increasingly reflect this broader conception of communication. Simulation-based environments can provide opportunities to practise not only standardized phraseology but also communication repair, stress management, coordination, and decision-making during complex scenarios (Ziakkas et al., 2025). Team resource management (TRM) and

Controller Resource Management (CRM) approaches similarly emphasize briefing, debriefing, mutual support, communication, and team situation awareness as essential components of operational performance (Miller & Holley, 2021; Phoompiew, 2024). Such approaches recognize that technically correct individual action is insufficient when safety depends on coordinated cognitive activity across multiple operators.

Digitalization and automation are now transforming the communication architecture of air traffic management. Data-link communication, automated coordination, digital tower systems, and advanced decision-support tools can reduce some forms of verbal communication and improve the consistency or traceability of information exchange. However, the reduction of verbal interaction does not necessarily reduce the need for cognitive coordination. Instead, information may be redistributed across visual interfaces, digital messages, and automated systems, potentially creating new attentional and integration demands. Highly automated environments may therefore alter the mechanisms through which common ground and team situation awareness are established.

Remote and digital tower environments are particularly relevant to this issue because changes in sensory information, interface configuration, and technological mediation may influence how controllers observe colleagues, infer team states, and coordinate implicitly. Similarly, automated coordination can remove routine communication while simultaneously reducing opportunities for team members to acquire information incidentally from operational conversations. Communication has an informational value beyond the literal content of a message: overheard exchanges may contribute to awareness of workload, traffic priorities, and colleagues' intentions. Removing such interactions without providing alternative mechanisms for shared awareness may create new forms of distributed cognitive fragmentation.

The emergence of artificial intelligence introduces an even more fundamental question concerning the boundaries of team cognition. Contemporary concepts of digital ATCOs and intelligent decision-support systems increasingly frame AI not merely as a tool but as a potential cognitive teammate. For such systems to participate meaningfully in joint decision-making, they must support some form of shared situation awareness and maintain a representation of the traffic environment sufficiently compatible with that of human controllers (Gerdes et al., 2025). Equally, human operators require information about the system's reasoning, intentions, uncertainty, and anticipated actions if they are to coordinate effectively with intelligent agents.

Human–AI team cognition therefore depends on transparency, predictability, trust, intent communication, and the alignment of mental models. An AI system may generate an operationally optimal recommendation yet still disrupt team performance if controllers cannot understand why the recommendation was produced or how the system expects the traffic situation to develop. Conversely, excessive explanation may increase workload and interfere with time-critical decision-making. The design challenge is therefore not simply to maximize information availability but to determine what information must be shared, with whom, and at what point in the cognitive work process to support coordinated action.

Despite growing interest in communication and team cognition, important research gaps remain. ATC team cognition is theoretically well established but comparatively less supported by longitudinal observation of intact operational teams. Many studies rely on simulations, surveys, computational models, or case-based analysis, and there remains substantial conceptual variation in the use of terms such as shared mental models, team situation awareness, shared situation awareness, and distributed cognition (Inoue et al., 2010; Ogawa et al., 2019). Measuring dynamic team cognition is particularly challenging because cognitive alignment changes over time and may not be directly observable through communication frequency or individual situation-awareness measures alone.

Human–AI team cognition represents an even more substantial empirical gap. Current research emphasizes the need for digital ATCOs to develop traffic representations, shared situation awareness, and trust-compatible interaction mechanisms, yet much of this literature remains conceptual or framework-oriented rather than validated through sustained operational deployment (Gerdes et al., 2025). Further research is needed to determine how human and artificial agents establish common ground, how divergences in their representations can be detected, and how communication should be designed to support rapid cognitive repair when joint understanding deteriorates.

Communication and team cognition should be understood as interconnected cognitive safety functions within air traffic control. Communication enables operational information to be perceived, interpreted, exchanged, and integrated, while team cognition distributes cognitive work across individuals, teams, and technological artifacts. Shared mental models, mutual awareness, team situation awareness, and coordinated information exchange allow actors to construct sufficiently compatible representations of a dynamic traffic environment and adapt their activities accordingly. Failures in communication are therefore rarely reducible to incorrect words alone; they may reflect deeper interactions among attention, memory, expectations, workload, divergent mental representations, technology, and organizational processes. As air traffic management becomes increasingly digital and AI-supported, maintaining safe performance will depend on designing communication systems that support not only information transfer but also the continuous construction, monitoring, and repair of shared cognitive understanding across human and artificial members of the operational system.

Team cognition should therefore be understood as a dynamic and continuously developing property of the operational team rather than as a fixed cognitive state. The integrative framework of team development interventions proposed by Shuffler et al. (2018), presented in Figure 5, provides a useful structure for conceptualizing this dynamic process. Within the framework, team members and the broader team and organizational contexts constitute the inputs that shape team processes and emergent states. These mediating mechanisms subsequently influence team performance, while feedback from performance episodes continuously modifies subsequent team processes and contextual conditions. The explicit incorporation of time and operational episodes is particularly relevant to ATC, where team composition, traffic conditions, workload, and coordination demands may change rapidly across shifts and operational situations.

From a cognitive perspective, communication can be positioned as a central process within the mediating component of this framework, whereas shared mental models, team situation awareness, trust, and other forms of shared cognition represent emergent states that develop through repeated interaction. Communication enables individually held information to be exchanged, interpreted, verified, and progressively aligned across controllers, pilots, adjacent units, and other operational actors. The quality of these processes affects the extent to which teams develop compatible representations of the traffic situation and anticipate one another's information and coordination requirements. Team performance, in turn, generates feedback that may reinforce effective coordination patterns or expose discrepancies in shared understanding, requiring cognitive realignment in subsequent operational episodes. Thus, the relationship between communication, team cognition, and performance is recursive rather than linear.

This dynamic perspective is especially important in aviation multiteam systems. Aviation operations involve multiple specialized teams - including cockpit crews, cabin crews, air traffic control, dispatch, maintenance, and ground operations - that maintain distinct proximal responsibilities while contributing to the overarching goal of flight safety. Shared mental models and transactive memory are therefore particularly important for understanding how knowledge is distributed and coordinated across the wider operational system. Breakdowns in coordinated decision making may emerge not because relevant information is entirely absent, but because information is not communicated or integrated in a manner that maintains compatible mental representations across distributed actors. Accordingly, effective team cognition depends on continuous communication, feedback, and adaptation across operational episodes rather than on a one-time achievement of shared understanding.

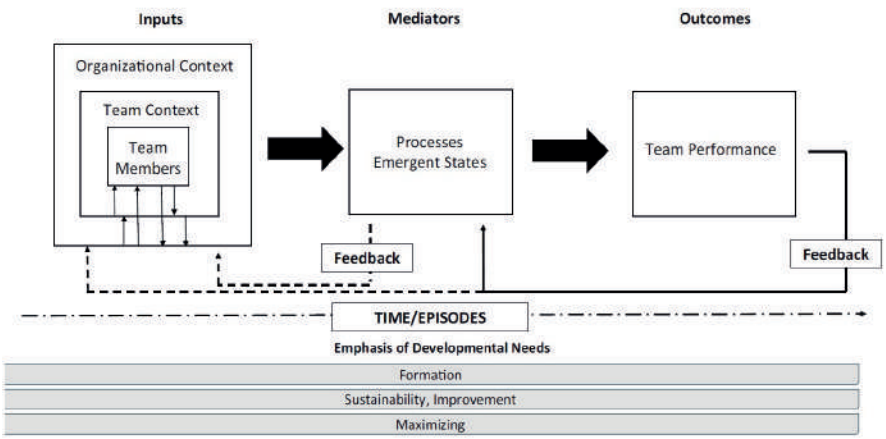

Figure 5. Integrative Framework of Team Development Interventions

Note. Adapted from Shuffler, M. L., DiazGranados, D., Maynard, M. T., and Salas, E. (2018), "Developing, Sustaining, and Maximizing Team Effectiveness: An Integrative, Dynamic Perspective of Team Development Interventions," Academy of Management Annals, 12(2), 688–724. The framework illustrates the dynamic relationships among team inputs, processes and emergent states, team performance, and feedback across time and operational episodes.

7. Human Error and Cognitive Limitations

Human error has traditionally occupied a central position in explanations of aviation accidents and incidents. In air traffic control (ATC), however, attributing an adverse event to controller error provides only a limited account of why performance deteriorated or why an unsafe action became possible. The designation of an event as a “human error” frequently identifies the point at which failure became operationally visible rather than the cognitive, technological, organizational, and contextual processes through which it developed. Contemporary human factors and safety science therefore increasingly conceptualize error as an emergent property of performance within complex socio-technical systems, in which controller cognition interacts continuously with traffic conditions, procedures, communication networks, technical interfaces, automation, supervision, and organizational arrangements (Inoue et al., 2012; Lyu et al., 2019). From this perspective, the analytical question shifts from identifying who committed an error to understanding how normally adaptive cognitive processes became insufficient or inappropriate under the conditions prevailing at the time.

This systems-oriented interpretation is particularly relevant to ATC because controllers operate in an environment characterized by continuous change, temporal pressure, uncertainty, and tightly coupled interactions among multiple agents. The controller must monitor evolving traffic, detect conflicts, retain and update operational intentions, communicate with aircraft and other control units, and intervene before unsafe traffic relationships become critical. These activities depend on cognitive systems with inherently limited capacities. Attention cannot be allocated equally to all available information; working memory cannot indefinitely retain every pending action or traffic parameter; vigilance may decline during sustained monitoring; and perceptual interpretation is influenced by prior knowledge and expectations. Human cognitive limitations should therefore not be interpreted as exceptional deficiencies of individual controllers. Rather, they represent fundamental characteristics of human information processing that become safety-relevant when operational demands, system design, and available cognitive resources are poorly aligned.

ATC error research has repeatedly demonstrated the importance of these cognitive constraints. Moon et al. (2011), for example, classified controller errors into communication, procedural, and instruction-related categories. Communication errors included failures to challenge incorrect readbacks, the use of incorrect call signs or non-standard phraseology, missed calls, call-sign omissions, and clipped transmissions. Procedural errors involved failures or delays in responding to calls or alarms, inadequate aircraft identification, omitted level verification, and failures to issue required information or clearances. Instruction errors included the transmission of incorrect information and inappropriate or delayed altitude, heading, descent, or clearance instructions (Moon et al., 2011). Importantly, their experimental investigation of 52 Korean air traffic controllers demonstrated that several categories of human error were influenced by traffic volume. This finding illustrates that error occurrence cannot be separated from the operational context in which cognition is exercised. As traffic volume increases, controllers must distribute attention across more aircraft, maintain a larger set of dynamic relationships, process more communications, and coordinate a greater number of temporally dependent tasks. The resulting increase in cognitive demand may create conditions in which otherwise effective control strategies become increasingly vulnerable to omission, delay, interference, or incorrect execution.

Table 1. Classification and Operational Elements of Human Error in Air Traffic Control

Error Category	**Cognitive/Operational Characteristic**	**Error Elements**
Communication Error	Failures occurring during controller–pilot or inter-controller communicative interaction	Incorrect readback not challenged; wrong call sign used; non-standard phraseology; missed call; call-sign omission or truncation; clipped call
Procedure Error	Failures to perform or complete required ATC procedural actions	Failure to respond to unanswered call; no or late response to alarm; no level verification; failure to identify aircraft; radar service not terminated; late or absent landing clearance; reasons for vectoring not provided
Instruction Error	Incorrect, inappropriate, or delayed control instructions	Incorrect information passed to aircraft; late descent; late flight-phase change; altitude instruction error; heading instruction error; clearance instruction error

Note. Adapted from the cognitive strategies for error detection and identification proposed by Kontogiannis and Malakis (2009).

The relationship between traffic demand and error is nevertheless more complex than a simple linear increase in mistakes as the number of aircraft rises. Controllers actively regulate their cognitive activity by changing priorities, simplifying plans, increasing separation margins, postponing non-essential actions, or reallocating attention toward emerging threats. Such adaptations are fundamental to maintaining performance in dynamic systems. Yet adaptive strategies also have boundaries. Under increasing traffic complexity, a controller may shorten the time devoted to individual aircraft, defer actions that appear less urgent, or rely more strongly on familiar traffic patterns. These strategies can preserve overall traffic management in the short term while simultaneously reducing opportunities to detect subtle changes, remember deferred intentions, or reconsider assumptions. Error may therefore emerge not because the controller ceases to act rationally, but because a locally reasonable adaptation produces unforeseen consequences as the operational environment continues to evolve.

The distinction between different forms of error is important in understanding these mechanisms. Reason's framework distinguishes slips and lapses associated primarily with the execution and memory of intended actions from mistakes involving inadequate plans, judgments, or problem representations. This distinction has particular relevance to ATC. A controller may correctly determine that an aircraft requires a heading change but inadvertently issue the instruction to the wrong call sign, representing an execution-related error. Alternatively, the instruction may be issued exactly as intended, yet the selected heading may create a new conflict because the underlying traffic assessment or plan was inadequate. The latter represents a decision-related failure rather than an execution failure. Rasmussen's skill-, rule-, and knowledge-based framework similarly demonstrates that errors may emerge at different levels of cognitive control. Highly practiced ATC activities can be performed with considerable automaticity, whereas unfamiliar or ambiguous events may require explicit rule application or knowledge-based reasoning. The mechanisms producing failure consequently differ according to the cognitive mode in which performance occurs.

Evidence from an ATC-specific application of the Human Factors Analysis and Classification System (HFACS) reinforces the importance of this distinction. An analysis conducted by the Federal Aviation Administration (FAA) (2005) found that approximately 86% of the operational errors examined were classified as skill-based errors rather than decision errors. Skill-based errors were primarily associated with habitual performance involving attention, memory, perception, and execution. Because such actions are frequently carried out with limited conscious effort, failures may arise during activities that are themselves highly familiar. In contrast, decision errors occurred when an intended action was executed as planned but the plan or selected solution was inadequate for the operational situation. Within the HFACS framework, these included procedural errors, poor choices, and problem-solving failures (Federal Aviation Administration (FAA), 2005). The distinction has direct implications for intervention. Decision-support technologies designed to improve trajectory evaluation or conflict resolution may reduce some decision errors, but their effect on memory lapses, inadequate scanning, attentional failures, or routine execution errors may be substantially more limited.

These findings challenge the assumption that increasingly sophisticated decision-support tools will necessarily eliminate the dominant sources of controller error. If a large proportion of operational failures originate in attention, perception, memory, and execution, safety interventions must address the cognitive processes through which controllers interact with information rather than focusing exclusively on decision quality. The FAA (2005), for instance, argued that perceptual scanning errors may require training environments specifically designed to strengthen scanning behaviour, whereas memory-related errors may require job-relevant exercises that progressively increase cognitive difficulty until effective strategies can be maintained under realistic operational demands. This principle reflects a broader human factors argument: training should target the mechanism of failure rather than the visible operational outcome alone.

Recent research in technologically transformed ATC environments provides further evidence of the value of cognitive error analysis. In remote apron control, Yi et al. (2026) combined hierarchical task analysis, a cognitive-behavioural model, and the Technique for Retrospective Analysis of Cognitive Errors (TRACEr) to examine human error across perception, memory, planning and decision-making, and action execution. Memory functions showed the highest error probability, with working-memory failures particularly prevalent, whereas perceptual failures were associated with the most severe consequences. Visual detection errors represented a major severity concern, while attentional deficits were among the most frequent cognitive problems. Spatial confusion and failures of information integration also exceeded defined severity thresholds (Yi et al., 2026). These findings are especially important because remote and digital tower environments do not fundamentally change the objectives of air traffic services, but they alter the perceptual and technological conditions through which controllers acquire and interpret operational information. The replacement of direct visual observation with camera-based and panoramic human–machine interfaces may therefore redistribute cognitive demands and create new configurations of error vulnerability.

Working memory represents a particularly important cognitive limitation in ATC. Controllers must temporarily maintain aircraft intentions, pending clearances, unresolved conflicts, coordination requirements, and actions that have been interrupted or deferred. This information is not static. Its operational relevance changes continuously as aircraft move and new information becomes available. Under high demand, interference between concurrent tasks may weaken the representation of a pending intention or displace information from active memory. Consequently, a controller may forget to issue a previously planned instruction, fail to return to an interrupted coordination task, or delay an intervention whose necessity had already been recognized. ATC-specific research supports the importance of memory load and working-memory constraints in dynamic control tasks, although the exact mechanisms vary across operational contexts (Smieszek et al., 2013; Zhang et al., 2026). The finding by Yi et al. (2026) that working-memory errors were particularly prevalent in remote apron operations further demonstrates that memory-related vulnerabilities remain important even as ATC becomes increasingly digitalized.

Attention is equally central to the emergence of controller error. ATC requires controllers to alternate between global monitoring of the traffic picture and focused processing of individual aircraft or conflicts. Because attentional capacity is limited, prioritizing one event necessarily reduces the cognitive resources available for others. This creates the possibility of attentional tunnelling, in which processing becomes disproportionately concentrated on a salient or urgent problem while less salient information receives insufficient attention. Importantly, the unattended information may still be operationally significant. A controller resolving a developing conflict may, for example, fail to notice a new aircraft entering a critical traffic relationship or may not detect that an earlier instruction has not produced the expected trajectory change. In such cases, error is not necessarily the consequence of a complete absence of attention, but of an allocation strategy that was locally appropriate yet insufficient for the broader traffic situation.

Vigilance and sustained monitoring create a different form of cognitive vulnerability. Errors are not restricted to periods of extreme traffic or overload. During prolonged periods of relatively stable traffic, reduced stimulation and repetitive monitoring may weaken alertness and delay the detection of infrequent or unexpected events. The cognitive demands of ATC therefore create risks at both ends of the workload continuum. Excessive demand can exceed available cognitive resources, whereas low and monotonous demand may impair sustained attention and readiness to respond. This dual vulnerability helps explain why error prevention cannot rely exclusively on reducing workload. Safe performance requires an appropriate alignment between task demands, controller engagement, and opportunities for cognitive recovery.

Expectation-driven processing also influences how controllers detect and interpret operational information. Expertise enables experienced controllers to recognize meaningful traffic patterns rapidly and to anticipate likely developments without processing every available cue analytically. Such cognitive compression is indispensable in complex traffic environments. However, the same reliance on expectations can create vulnerability when an event deviates from a familiar pattern. Information consistent with an existing traffic model may be processed rapidly, whereas contradictory or unusual cues may require greater conscious attention before they are integrated. Under time pressure, conflicting evidence may be discounted, explained away, or interpreted within an existing model rather than triggering immediate reconstruction of the situation. The potential for cognitive fixation is particularly relevant when controllers have already committed to a traffic plan and incoming information remains ambiguous.

For this reason, understanding human error requires attention not only to error production but also to error detection and recovery. Kontogiannis and Malakis argued that the complete elimination of error is unrealistic in increasingly complex technical systems. High workload, stressful decision-making, and coordination difficulties will inevitably create circumstances in which errors can occur. The central safety objective therefore becomes the detection, containment, and correction of errors before they develop into adverse system states. Within this error-management perspective, three cognitive processes are particularly important: error detection, which involves recognizing that an error may have occurred; error explanation or identification, through which the nature and possible origins of the problem are examined; and error correction, in which an existing plan is modified or replaced to restore safe system performance (Kontogiannis & Malakis, 2009).

Kontogiannis and Malakis (2009) conceptualized human performance as a nonlinear and iterative cognitive process involving situation assessment, plan formulation, action rehearsal and execution, and outcome evaluation. As illustrated in Figure 6, each stage is associated with specific cognitive challenges that may create conditions for error, including incomplete or conflicting information, competing goals, time pressure, simultaneous action and monitoring demands, and difficulties in integrating or interpreting feedback. Importantly, the model suggests that human error should not be understood solely as the failure to produce an initially correct assessment or plan. Rather, safe performance depends on the controller's capacity to continuously revise situation assessments, adapt plans, monitor ongoing actions, and evaluate emerging outcomes as operational conditions evolve.

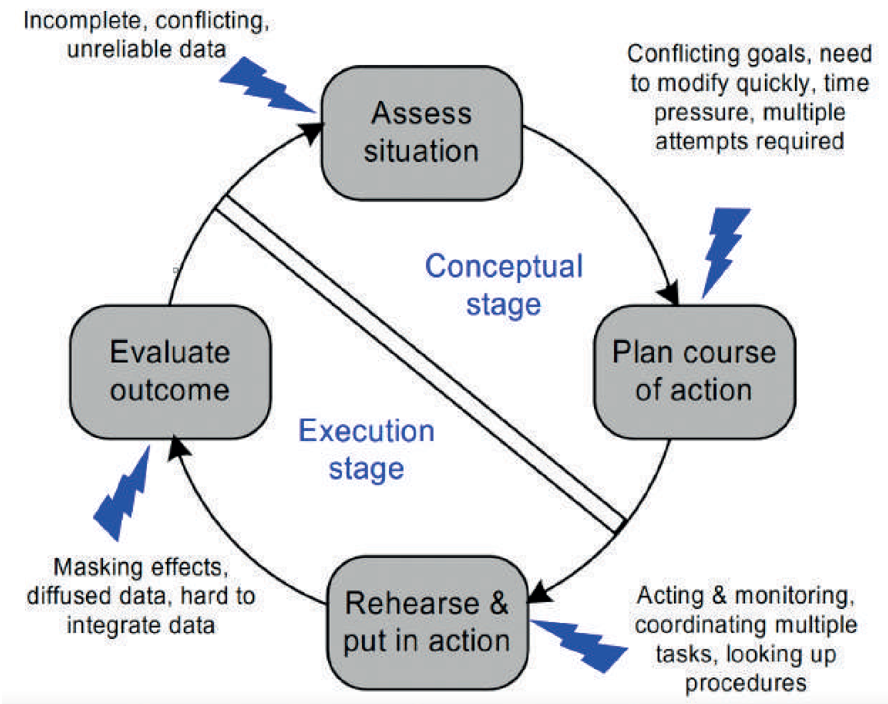

Figure 6. A simple model of human performance with four stages of error detection (adapted from Kontogiannis and Malakis, 2009).

Error detection may arise through several mechanisms. Outcome-based detection occurs when observed system behaviour differs from the effects expected by the controller. In ATC, a controller may expect an aircraft to turn, climb, or descend following an instruction and detect a problem when the radar trajectory fails to develop accordingly. Action-based detection occurs when the controller recognizes a discrepancy between an intended action and the action actually performed. A slip of the tongue during a clearance, for example, may be detected by comparing the spoken instruction with the controller's retained representation of the intended clearance. Errors may also be detected through system-generated constraints or warnings and through cross-monitoring by other controllers, pilots, or team members. The latter is particularly important for mistakes because the cognitive conditions that produced an incorrect assessment may also prevent the individual who formed it from recognizing its inadequacy (Kontogiannis & Malakis, 2009).

Error recovery itself may take different forms. Backward recovery attempts to return the system to the state preceding the failure, whereas forward recovery establishes an intermediate safe condition that provides additional time for assessment and subsequent action. Compensatory recovery uses alternative or redundant resources to achieve the intended system state. Operationally, these recovery strategies may involve stabilizing the situation, reducing the consequences of an emerging problem, establishing a temporary workaround, and subsequently developing a more permanent solution (Kontogiannis & Malakis, 2009). In ATC, the immediate objective following detection of an uncertain or deteriorating traffic situation may therefore not be to identify the complete causal chain. Increasing separation, stopping further traffic development, or simplifying the traffic configuration can create cognitive and temporal space for more detailed assessment.

A particularly valuable contribution of the error-management perspective is its emphasis on proactive cognitive strategies. Kontogiannis and Malakis proposed a cyclical model of human performance involving situation assessment, plan formulation, rehearsal and execution, and evaluation of performance outcomes. Error detection can occur throughout this cycle rather than only after an action has produced an observable consequence. Awareness-based detection involves questioning the current situation assessment, searching for missing cues, identifying hidden assumptions, and resisting the tendency to dismiss contradictory evidence. Planning-based detection involves examining weaknesses in a proposed course of action, identifying additional information needs, establishing points at which the plan should be reconsidered, and maintaining sufficient flexibility for revision. Action-based detection uses pre-action and post-action checks, rehearsal, reminders, and error barriers to identify deviations during task execution. Outcome-based detection focuses on discrepancies between expected and observed system behaviour, including relational and temporal patterns of change and the reliability of available information (Kontogiannis & Malakis, 2009).

These strategies illustrate the importance of metacognition in safe ATC performance. Experienced controllers do not merely process traffic information; they may also monitor the adequacy of their own understanding and actions. This involves recognizing uncertainty, questioning assumptions, anticipating where a plan might fail, and deciding when a current traffic model requires revision. A controller who actively searches for missing cues or tests the plausibility of an assumption creates additional opportunities for detecting mistakes before they are operationally expressed. Conversely, cognitive fixation may emerge when conflicting evidence is repeatedly reconciled with an existing interpretation rather than treated as a signal that the interpretation itself may be inadequate. Error resilience therefore depends partly on the ability to maintain a traffic picture that is sufficiently stable to guide action yet sufficiently flexible to accommodate unexpected evidence.

Expertise has a dual role in this process. Experienced controllers develop pattern-recognition capabilities, strategic routines, and efficient prioritization strategies that reduce cognitive demand and allow rapid anticipation of traffic developments. Their knowledge enables them to identify points of concern, mentally simulate likely trajectories, and maintain broad plans without specifying every action in advance. Such expertise supports what may be described as staying cognitively ahead of the traffic. At the same time, highly practiced behaviour increases reliance on automatic processing and familiar patterns. Routine actions may be performed with little conscious supervision, increasing susceptibility to slips and lapses when the operational context changes subtly. Similarly, strong expectations derived from previous experience may delay recognition of rare or atypical events. Expertise should therefore not be interpreted simply as immunity to error; rather, it changes the mechanisms through which error is likely to emerge.

The organizational and systemic context determines whether these cognitive limitations remain manageable or become operational hazards. The Swiss Cheese Model and HFACS emphasize that frontline unsafe acts occur within layers of preconditions, supervisory practices, and organizational influences. ATC-specific HFACS research has demonstrated that conventional operational error reporting may provide insufficient information about organizational factors, unsafe supervision, and the preconditions that shape controller actions (Federal Aviation Administration, 2005). Other ATC studies similarly associate performance with training adequacy, fatigue, monitoring, regulatory arrangements, resource management, and technological reliability (Lyu et al., 2019; Zhu & Chen, 2023; Pan et al., 2025a). From this perspective, a memory lapse cannot be fully understood without considering interruption patterns, interface support, staffing, traffic complexity, shift conditions, and the availability of external memory aids. Likewise, a detection failure must be examined in relation to display design, alarm characteristics, competing attentional demands, and opportunities for cross-monitoring.

Automation further complicates the relationship between cognition and error. Automated systems and decision-support tools can reduce some demands associated with conflict detection, trajectory analysis, and information management. However, automation does not simply remove human error; it may transform or redistribute it. Controllers may become less directly engaged in processes performed by automated systems, creating difficulties in maintaining an accurate understanding of system states and automation behaviour. Mode awareness problems, automation bias, inappropriate trust, reduced monitoring, and out-of-the-loop performance can introduce new pathways to failure. Furthermore, when automation performs reliably for extended periods, rare failures may occur precisely when the controller has had limited opportunity to maintain the cognitive skills required for manual diagnosis and intervention.

These concerns are increasingly important as artificial intelligence becomes integrated into air traffic management. Human–AI systems require controllers not only to interpret traffic but also to evaluate algorithmic recommendations, understand system uncertainty, and determine when automated advice should be accepted, questioned, or overridden. The safety challenge is therefore one of calibrated coordination rather than maximum automation. AI systems that provide highly accurate recommendations but obscure their informational basis may reduce opportunities for controllers to detect inconsistencies or maintain an independent traffic model. Conversely, systems that present excessive explanations or alerts may increase information-processing demand and contribute to attentional competition. Human-centred automation must consequently support cognitive engagement, meaningful monitoring, and the detection of discrepancies between human and machine assessments (Bongo & Seva, 2023; Xia et al., 2025).

Taken together, the literature suggests that human error in ATC should be understood as the observable outcome of interactions among cognitive limitations, adaptive strategies, operational demands, team processes, technological systems, and organizational conditions. Perceptual failures, memory lapses, attentional limitations, inappropriate plans, delayed interventions, and execution errors are cognitively distinguishable mechanisms, but they rarely occur independently of the environment in which controllers work. The increasing complexity and digitalization of ATC make the search for complete error elimination increasingly unrealistic. A more productive safety objective is to design systems that reduce error-producing conditions while increasing the probability that errors will be detected, contained, and recovered before safety margins are exhausted.

Accordingly, ATC safety interventions should combine mechanism-specific cognitive training, realistic simulation, effective cross-monitoring, workload and fatigue management, supportive interface design, and organizational learning. Training should develop not only correct procedures and decision strategies but also metacognitive skills for identifying missing information, questioning assumptions, anticipating plan weaknesses, rehearsing time-critical actions, and comparing expected with observed traffic developments. The fundamental safety question is therefore not simply whether controllers will make errors. In complex and dynamic systems, some degree of performance variability is inevitable. The more consequential question is whether the cognitive and socio-technical system provides sufficient opportunities to recognize emerging discrepancies, revise an inadequate understanding, and recover control before an error develops into an unsafe traffic state.

8. Human Factors Frameworks in Air Traffic Control

Human factors frameworks provide the conceptual basis for understanding how cognitive performance, operational conditions, technology, and organizational structures interact to influence safety in air traffic control. Their importance is particularly pronounced in ATC because controller performance cannot be separated from the operational context in which it occurs. Although conflict detection, sequencing, coordination, and separation assurance ultimately involve human decisions and actions, these activities are performed through continuous interaction with surveillance displays, communication systems, procedures, automation, other controllers, pilots, supervisors, and organizational arrangements. Human performance in ATM should therefore be understood as a property of the relationship between the individual and the wider work system rather than as an isolated characteristic of the controller.

This perspective represents an important departure from early interpretations of aviation accidents that focused predominantly on frontline operator error. Traditional accident analyses frequently identified the final observable action of a controller or pilot as the immediate cause of an occurrence. However, the concept of human error provides only limited explanatory value when detached from the conditions under which performance takes place. Controller actions are influenced by capabilities and experience, motivation and attitudes, as well as the systems, organizational arrangements, and environmental conditions that provide or constrain opportunities for effective performance (EUROCONTROL/FAA, 2010). In operational terms, attention, visual scanning, working memory, situation awareness, and decision-making are continuously affected by traffic complexity, fatigue, interface characteristics, procedural requirements, team coordination, and time pressure. Consequently, similar actions may lead to entirely different outcomes depending on the surrounding system conditions.

The Swiss Cheese Model provided one of the most influential conceptual shifts away from this individual-centered view of accident causation. Rather than treating accidents as the direct consequence of a single unsafe act, the model conceptualizes safety systems as multiple defensive layers, each containing weaknesses or vulnerabilities. An accident becomes possible when deficiencies across these layers temporarily align and permit a hazard to progress through the system. The distinction between active and latent failures is particularly relevant to ATC. Active failures may be observable in the form of an incorrect clearance, delayed conflict recognition, incomplete coordination, or failure to detect an emerging traffic situation. Latent conditions, by contrast, may exist within staffing practices, training systems, interface design, supervisory arrangements, procedures, or organizational safety management long before an operational occurrence becomes visible.

The value of this approach lies in redirecting analytical attention from the question of *who made the error* toward the conditions that made a particular action understandable and consequential within the operational environment. This distinction is especially important in ATC, where the same performance adaptations that support efficiency under normal conditions may contribute to vulnerability when circumstances change unexpectedly. Controllers continuously make micro-adjustments between efficiency and thoroughness, redistribute attention, defer secondary tasks, and modify control strategies in response to traffic conditions. Such adaptations are fundamental to maintaining traffic flow and are usually successful. However, a strategy that is effective under one set of conditions may become inadequate when workload, traffic complexity, equipment status, or communication demands change. Human error should therefore not automatically be interpreted as a separate abnormal category of behavior; it may emerge from the same performance variability that normally enables controllers to manage dynamic operational conditions.

The Human Factors Analysis and Classification System (HFACS) extended the systemic logic of active and latent failures by providing a structured taxonomy for examining the multiple levels at which human performance is shaped. Drawing on Reason's theoretical foundations, HFACS links unsafe acts with preconditions for unsafe acts, supervisory influences, and organizational influences. This hierarchical structure has made HFACS one of the most frequently applied human factors classification approaches in aviation accident and incident analysis (Wan et al., 2021; Nogueira et al., 2023). Rather than considering controller behavior independently, the framework permits unsafe actions to be examined in relation to cognitive and environmental preconditions, supervisory decisions, resource allocation, and organizational processes.

This multilevel perspective is highly relevant to ATC because cognitive performance is rarely independent of upstream system conditions. A failure to detect a conflict, for example, may initially appear to represent an attention or situation awareness failure. A broader HFACS-oriented analysis may reveal that the controller was operating under excessive task demand, using an interface that inadequately supported visual scanning, working within an unfavorable staffing configuration, or applying procedures shaped by supervisory and organizational practices. Empirical applications of HFACS have demonstrated significant relationships between organizational and supervisory conditions and frontline unsafe acts, reinforcing the argument that visible operational errors may represent downstream manifestations of latent system vulnerabilities (Li et al., 2008; Dönmez & Uslu, 2018). The framework is therefore valuable not simply as an error classification taxonomy but as a means of tracing relationships between organizational decisions and cognitive performance at the operational interface.

Nevertheless, hierarchical accident models alone cannot fully explain the dynamic cognitive processes through which controller performance changes during ongoing operations. ATC-specific human performance research has consequently examined performance-influencing factors such as workload, fatigue, stress, attention, vigilance, situation awareness, communication, and teamwork. These factors should not be viewed as independent variables acting on the controller in isolation. Rather, they form an interconnected cognitive ecology in which changes in one component may alter the functioning of others. Edwards et al. (2017), for example, demonstrated that workload and situation awareness may interact in their effects on controller performance and that these relationships can vary according to the level of automation. Similarly, Bongo and Seva (2021) found that fatigue influenced situation awareness and visual attention in an operational tower environment. More recent studies using eye tracking and neurophysiological measures have further demonstrated that changes in task complexity and workload are associated with identifiable patterns of situation awareness and visual attention (Li et al., 2022; Yiu et al., 2025).

A particularly important development in this area is the movement from retrospective identification of performance failures toward the detection of performance degradation while operations are still underway. Research with European and FAA air traffic controllers suggests that controllers naturally monitor both themselves and their colleagues for behavioral indicators of declining performance (Edwards et al., 2017). Indicators associated with overload may include being surprised by aircraft calls, losing a backup plan, or experiencing a sense of diminished control, whereas fatigue may become visible through concentration difficulties, distraction, or yawning. Controllers frequently respond to such indicators by changing their control strategy or adopting other compensatory mechanisms.

These findings are theoretically important because they portray controllers not as passive recipients of workload or fatigue but as active monitors and regulators of their own cognitive performance. Performance is continuously assessed, interpreted, and adjusted in relation to operational demands. The difficulty is that knowledge of behavioral indicators is often acquired informally through experience rather than systematically taught. Consequently, inexperienced controllers may have fewer internal reference points for recognizing the early signs of performance degradation, while even experienced controllers may differ in their conscious awareness of personal indicators. Human factors frameworks therefore have a practical role in translating tacit operational knowledge into training, supervisory practices, and performance-support mechanisms. The identification of behavioral indicators and compensatory strategies illustrates how human factors analysis can move beyond describing cognitive limitations to supporting early intervention before performance decline develops into a safety occurrence.

Threat and Error Management (TEM) provides a complementary operational framework by focusing on the continuous management of threats, errors, and undesired states. In contrast to approaches that seek to explain accidents primarily after they occur, TEM is concerned with how operational personnel recognize and manage conditions that may compromise safety during normal work. Within ATC, threats may include traffic complexity, adverse weather, communication problems, unexpected pilot actions, equipment limitations, or other conditions that increase operational demands. Errors may occur when controller actions or decisions deviate from operational intentions or requirements, while unmanaged threats and errors may contribute to undesired traffic states.

The conceptual significance of TEM lies in its recognition that the presence of threats or errors does not inevitably lead to an accident. Safety depends substantially on the capacity to detect, contain, and recover from developing problems. This logic closely reflects the realities of ATC, where controllers routinely resolve conflicts, correct misunderstandings, revise plans, and compensate for disturbances before they become reportable occurrences.

Performance observation, operational interviews, and analyses of controller strategies are therefore particularly valuable because they reveal not only what went wrong but also how threats were successfully recognized and managed. The TEM perspective consequently bridges cognitive performance and operational safety by focusing on the strategies through which attention, situation awareness, communication, and decision-making are used to maintain the traffic situation within safe boundaries.

Human reliability assessment (HRA) represents another important approach to integrating human performance into ATM safety analysis. Traditional safety assessments often require quantitative estimates of risk, whereas human factors analyses tend to emphasize the complexity and contextual variability of human behavior. HRA attempts to bridge these perspectives by identifying potential human failures and estimating their likelihood on the basis of empirical performance data, incident analyses, literature, expert judgement, and simulation. In ATM, this approach can be used to evaluate how alternative system designs influence the probability of delayed detection, incorrect action, or other performance-related outcomes.

The practical importance of this integration can be illustrated through controller alerting systems. A safety assessment may identify delayed detection of a runway hazard as a critical risk and propose a visual warning. A human factors analysis, however, may demonstrate that controllers are frequently directing visual attention away from the display while monitoring aircraft or other parts of the operational environment. Under such conditions, changing the color of a display symbol may provide little protection because the relevant information is not within the controller's current attentional field. An integrated human factors and reliability assessment may instead support the use of multimodal alerting, combining auditory and visual information to redirect attention rapidly. The purpose of human factors analysis in this context is not simply to assign an error probability to the controller but to determine how system design changes the conditions under which detection and action become more or less likely.

The contribution of human factors is therefore greatest when it is integrated throughout the design and safety lifecycle rather than introduced as a final validation exercise. Edwards et al. (2023) provide several operational examples illustrating this principle. The development of NASA's Dynamic Weather Routes decision-support tool demonstrated that technically efficient recommendations may have limited operational value when they do not correspond with the traffic-flow constraints and decision strategies understood by dispatchers and controllers. Routes identified algorithmically as more direct were sometimes rejected because they conflicted with established arrival and departure flows. Incorporating operational feedback and historical traffic patterns improved the operational acceptability of the tool. The case illustrates a fundamental principle of human-centered design: algorithmic optimization and operational usability are not equivalent. A decision-support system may generate technically valid solutions yet fail to improve system performance if its recommendations do not fit the cognitive and operational context of the human decision-makers expected to use them.

The same principle is evident in predictive human factors assessment for emerging airspace operations. Edwards et al. (2023) describe the use of bow-tie risk analysis to examine the potential effects of unmanned aircraft integration on ATCO performance before large-scale operational implementation. Workshops involving controllers and pilots were used to identify human-performance hazards, potential outcomes, and mitigation strategies, and the findings subsequently informed research priorities and the development of a Concept of Operations. The importance of this example lies in the timing of human factors involvement. Instead of evaluating human performance after a technological concept had already been designed, human factors analysis contributed during concept exploration, allowing performance-related risks to influence the design of the future operation itself. Such proactive integration is especially important in increasingly automated ATM environments because decisions made during early system development may determine future workload distribution, information requirements, role allocation, and opportunities for maintaining situation awareness.

Despite the analytical value of Swiss Cheese, HFACS, TEM, and HRA, contemporary ATM systems increasingly challenge models that conceptualize safety through relatively stable layers, categories, or event sequences. Air traffic management is a complex socio-technical system in which people, technologies, procedures, and organizations continuously interact and adapt. Safety outcomes may therefore emerge from combinations of individually normal activities rather than from a clearly identifiable component failure. This limitation has contributed to growing interest in systemic approaches such as the Systems-Theoretic Accident Model and Processes (STAMP) and the Functional Resonance Analysis Method (FRAM).

STAMP conceptualizes safety as a control problem. From this perspective, accidents occur when constraints necessary for safe system behavior are inadequately enforced within a hierarchical control structure. The focus consequently shifts from identifying failed components to examining control relationships, feedback processes, information flows, and interactions among system levels. This perspective is highly applicable to ATM because safe separation depends on multiple interconnected control processes involving controllers, pilots, surveillance and communication systems, automation, procedures, supervisory structures, airspace design, and regulatory oversight. A safety occurrence may arise not because any individual component completely fails but because information is delayed, feedback is incomplete, control responsibilities are poorly coordinated, or system constraints become inadequate under changing operational conditions.

FRAM extends the systemic perspective by emphasizing performance variability and functional interaction. Rather than assuming that systems normally operate according to fixed sequences, FRAM recognizes that everyday work necessarily varies in response to available time, information, resources, and operational demands. In ATM applications, this is particularly relevant because controllers continuously adapt how tasks are performed. Coordination may become shorter during periods of high workload, scanning strategies may change with traffic complexity, and attention may be redistributed toward emerging conflicts. Most of these adjustments contribute positively to operational performance. However, variability across several interconnected functions may combine or *resonate*, producing outcomes that cannot be explained through a single error or failure (Yang et al., 2017; Macchi, 2020; Carvalho, 2021).

The FRAM perspective is consistent with the recognition that performance variability is not inherently negative. The EUROCONTROL/FAA human performance framework explicitly emphasizes that controllers must vary their performance to manage variable operational conditions and continually balance efficiency and thoroughness. A controller may temporarily prioritize rapid interaction with electronic flight strips during high traffic demand or reduce attention to secondary tasks when managing an emerging conflict. These adaptations allow the ATM system to remain flexible. The same variability may, however, create vulnerability if the operational context changes faster than the controller's strategy can be adjusted. From this perspective, the analytical objective is not to eliminate variability but to understand how the system supports, constrains, detects, and recovers from its consequences.

This reasoning provides the foundation for resilience engineering and the broader transition from Safety-I toward Safety-II. Traditional Safety-I approaches primarily seek to understand why adverse outcomes occur and to reduce their recurrence. This remains essential in aviation safety; however, accident and incident data represent only a small proportion of everyday ATM performance. Most operations remain safe despite changing traffic conditions, uncertainty, technological limitations, and unexpected disturbances. Safety-II therefore directs attention toward how successful performance is produced under variable conditions and how operational personnel adapt to maintain system functioning.

Controllers are central to this adaptive capacity. They monitor changes in traffic, anticipate developing conflicts, compensate for incomplete information, coordinate with other actors, alter control strategies, and recover from both their own and others' errors. In this sense, the controller is not simply a potential source of system risk but one of the principal mechanisms through which ATM resilience is created. The behavioral-indicator studies described by Edwards et al. (2017) and Edwards et al. (2023) illustrate this principle at the level of cognitive self-regulation: controllers recognize changes in performance and implement compensatory strategies. At the system level, resilience similarly depends on the capacity to monitor current performance, respond to disturbances, learn from experience, and anticipate future conditions.

A related theoretical development is distributed cognition, which challenges the assumption that cognitive processes relevant to ATC are located exclusively within the individual controller. The operational traffic picture is constructed and maintained through interactions among controllers, pilots, displays, flight data, communication systems, procedures, and automated tools. Information is represented, transformed, transferred, and updated across this wider cognitive system. Gate-to-gate analyses using network-based approaches have demonstrated that aviation performance depends on interconnected social, task, and information networks extending across ATC, cockpit operations, dispatch, maintenance, and other operational functions (Stanton et al., 2018). Joint cognitive systems perspectives similarly emphasize that human and technical elements jointly transform information and coordinate action rather than functioning as independent system components (Adriaensen et al., 2019).

This perspective is increasingly important as automation and artificial intelligence assume more active roles in ATM decision support. The central human factors question is no longer simply whether automation reduces controller workload. It is how cognitive functions are distributed between human and technological agents, how shared situation awareness is maintained, how system recommendations are interpreted, and how controllers remain capable of intervening when automated outputs are incomplete or operationally inappropriate. The Dynamic Weather Routes example described by Edwards et al. (2023) demonstrates precisely this challenge. The technically optimal output of an algorithm did not automatically constitute an operationally meaningful decision because the broader cognitive system included local traffic-flow knowledge and constraints represented in controller and dispatcher experience. Human-centered automation must therefore be designed around the joint cognitive work of the system rather than around the isolated computational capability of the technology.

Taken together, human factors frameworks in ATC reflect a clear theoretical evolution. Swiss Cheese and HFACS demonstrated that frontline unsafe acts are embedded within deeper organizational and supervisory conditions. Cognitive-performance research clarified how workload, fatigue, attention, situation awareness, and other performance-influencing factors shape controller functioning during operations. TEM shifted attention toward the active management of threats and errors, while HRA sought to integrate human performance into formal safety assessment. STAMP and FRAM subsequently expanded the unit of analysis to dynamic socio-technical interactions, and resilience engineering and Safety-II emphasized the adaptive mechanisms through which safe performance is normally sustained. Distributed cognition further demonstrates that ATC cognition is produced across networks of people, information, artefacts, and automation.

No single framework is sufficient to explain the full complexity of human performance in contemporary ATM. Hierarchical models are particularly effective in identifying organizational and supervisory influences but may provide limited resolution of moment-to-moment cognitive adaptation. Cognitive studies offer detailed evidence regarding workload, attention, fatigue, and situation awareness but frequently isolate these processes from broader organizational conditions. Systemic models capture interaction and emergence but may be more difficult to operationalize and validate across different ATC environments. The most productive direction is therefore not the replacement of one framework by another, but their theoretical and methodological integration. Understanding safety in air traffic control requires simultaneous attention to the controller's cognitive state, the strategies used to manage operational variability, the technologies and teams through which cognition is distributed, and the organizational and system structures that shape the conditions of performance.

Accordingly, contemporary human factors analysis should move beyond explaining why controllers fail and toward understanding how the ATM system creates the conditions for both successful and unsuccessful performance. This shift is particularly critical as air traffic management becomes more automated, interconnected, and technologically complex. The future safety of ATM will depend not on eliminating human variability or removing controllers from decision-making, but on designing systems capable of supporting human adaptation, detecting emerging performance vulnerabilities, and coordinating human and technological capabilities within a resilient socio-technical system.

9. Supporting Cognitive Performance In Future Air Traffic Management (ATM)

The evolution of Air Traffic Management (ATM) is increasingly characterized by technological sophistication, distributed decision-making, and higher levels of automation. Major modernization programmes, including the Single European Sky ATM Research (SESAR) initiative and the Next Generation Air Transportation System (NextGen), envisage an operational environment in which advanced decision-support systems, trajectory-based operations, digital information exchange, and automated functions assume an increasingly prominent role. These developments are intended to increase capacity, efficiency, predictability, and safety; however, they also fundamentally alter the cognitive ecology of air traffic control. Rather than eliminating the human contribution, future ATM is expected to redistribute functions between humans and technology, between air and ground, and across increasingly interconnected operational actors. Consequently, the central human factors challenge is not simply to reduce controller workload through automation, but to ensure that future systems continue to support the cognitive processes through which controllers understand, anticipate, coordinate, and adapt to dynamic traffic situations.

EUROCONTROL (2010) emphasized that the transformation associated with SESAR represents a paradigm shift in both technological and operational terms. Although controllers and pilots will increasingly be assisted by automated functions, humans are expected to remain central decision-makers within the ATM system. This redistribution of functions has significant implications for attention, situation awareness, workload regulation, decision-making, skill maintenance, and coordination. Similarly, the NextGen philosophy of flexible and distributed decision-making relies on performance-based operations, net-centric services, and shared situation awareness. In both programmes, the limitations of existing ATM—including constraints associated with human cognitive processing and verbal communication—constitute part of the rationale for technological transformation. Nevertheless, the introduction of advanced technology does not remove cognitive limitations from the system. Instead, it changes where cognitive demands arise and how they interact with automation, information systems, and operational responsibilities.

Recent evidence from a qualitative content analysis of 232 SESAR projects further demonstrates that artificial intelligence is no longer limited to isolated decision-support applications but is becoming systematically integrated into future ATM through human–AI teaming, trajectory prediction, traffic flow optimization, communication, surveillance, safety monitoring, and AI governance. These findings indicate that the future cognitive role of controllers will increasingly shift from direct tactical control toward collaborative supervision of intelligent socio-technical systems, reinforcing the need for transparent, human-centred automation and adaptive cognitive support (Tuncal, 2025).

Increasing traffic volume, airspace complexity, digitalization, and the introduction of new airspace users are likely to place continuing demands on controller cognition. Attention, working memory, vigilance, spatial processing, and rapid decision-making remain central to effective ATC performance, although the manner in which these cognitive functions are employed may change. Mental workload is consistently identified as a major proximal constraint on controller performance and ATM capacity, and cognitive workload indicators may predict periods of degraded performance more effectively than traffic metrics alone (Muñoz-De-Escalona et al., 2024). The accumulation of simultaneous visual, auditory, and communicative demands can divide attention and place pressure on working-memory resources, particularly when controllers encounter unfamiliar or unexpected operational conditions (Holley & Miller, 2022). Importantly, cognitive performance cannot be reduced to a single construct of workload. Spatial visualization, auditory attention, oral expression, reaction time, and self-regulation have also been identified as important abilities for optimal ATC performance (Roodbandi et al., 2025). Situation awareness, communication, teamwork, vigilance, and attention similarly occupy central positions within broader models of ATC performance-shaping factors (Bongo & Seva, 2023).

Future ATM may intensify these demands by changing the structure of the controller's task. Trajectory-based operations (TBO), for example, are expected to shift control activity from predominantly tactical intervention toward more strategic traffic management and supervisory monitoring (Edwards et al., 2023). Under TBO, aircraft trajectories may be negotiated and subsequently managed through time-based constraints and narrower operational tolerances. Such arrangements may reduce the need for frequent tactical interventions and improve system predictability. However, reduced tactical involvement may also alter how controllers construct and continuously update their mental representation of traffic. Cognitive engagement in conventional control is partly sustained through active interaction with aircraft, repeated conflict evaluation, and continuous adjustment of control strategies. When these activities are increasingly performed by automation, controllers may receive fewer opportunities to maintain an active and richly updated traffic picture.

The introduction of urban air mobility, unmanned aircraft, and other new entrants creates an additional layer of cognitive and organizational complexity. Future airspace may contain traditional commercial traffic alongside drones and passenger-carrying urban air mobility vehicles, potentially managed through separate but interacting traffic-management systems. Edwards et al. (2023) note that such arrangements require clear function allocation between ATCOs and third-party traffic-management organizations, particularly during off-nominal events. From a cognitive perspective, controllers may be required to understand not only aircraft trajectories but also the operational logic, responsibilities, and limitations of other traffic-management agents. Ambiguous authority boundaries or poorly represented system states may increase uncertainty and impose additional demands on information integration and anticipatory reasoning. Supporting cognitive performance in this environment therefore requires interfaces and procedures that make distributed responsibilities, system interactions, and emerging conflicts cognitively visible.

9.1. Human-Centred Automation and Cognitive Engagement

Automation represents one of the most consequential influences on future controller cognition. When reliable and appropriately designed, automated decision aids can improve conflict-management performance and reduce mental workload. Metzger and Parasuraman (2005), for example, demonstrated that reliable conflict decision support could enhance controller performance while reducing workload. However, imperfect automation may produce different consequences. Manual control was superior to imperfect automated assistance for detecting some forms of conflict, illustrating that automation can introduce overreliance and alter controllers' allocation of attention. The cognitive benefits of automation are therefore conditional on reliability, transparency, task compatibility, and the extent to which automated support corresponds with controller strategies.

A central concern is the transition from active control to supervisory monitoring. Increasing levels of automation may reduce manual workload while simultaneously producing vigilance decrements, reduced situation awareness, and skill degradation (Di Flumeri et al., 2019). These effects are commonly associated with the out-of-the-loop performance problem. When controllers are no longer continuously involved in the control process, they may have a less complete understanding of the current traffic situation and the sequence of decisions through which that situation developed. The difficulty becomes particularly important when automation encounters an off-nominal condition and human intervention is required.

Edwards et al. (2023) emphasize that ATCOs may need to override automation when rule-based systems cannot accommodate unexpected or unusual operational conditions. A controller who has been cognitively disengaged from the control process must first reconstruct the traffic picture, identify the nature of the problem, evaluate available options, and formulate an appropriate control strategy. This reconstruction requires time, and the associated delay may have safety-critical implications. The problem is further intensified when the automation does not provide sufficient visibility into its reasoning or when the controller is unaware that a degraded condition has emerged. Under such circumstances, human intervention becomes dependent either on the automation correctly requesting assistance or on the controller independently detecting a problem while performing a predominantly supervisory role.

This issue also raises a fundamental capacity paradox. One purpose of advanced ATM automation is to increase the number of aircraft that can be safely managed by reducing controller workload and increasing precision. In nominal conditions, automation may permit narrower tolerances and higher traffic throughput. Yet if system capacity is increased precisely because automated support is available, a controller may be unable to manually manage the same traffic volume following automation degradation (Edwards et al., 2023). Thus, maintaining a nominal capacity that exceeds unaided human cognitive capability creates a potentially critical mismatch between system design and recovery requirements. Future ATM systems must therefore consider not only whether automation can control traffic effectively, but also whether the human operator can safely recover the system when automated capability is reduced.

Human-centred automation requires a shift from static task substitution toward more deliberate forms of function allocation. Rather than assigning complete classes of tasks permanently to automation, functions may be distributed dynamically according to traffic conditions, system state, and controller cognitive demands. De Rooij et al. (2022) suggest that sharing traffic between controllers and automation may offer advantages for maintaining cognitive engagement and operational skill. Delegating relatively simple flights while preserving controller involvement in more cognitively meaningful traffic may prevent the human role from becoming exclusively passive. Nevertheless, such approaches can generate new forms of interaction, including conflicts involving human-controlled and automation-controlled aircraft. Function allocation must therefore be understood as a coordination problem rather than merely a workload-reduction mechanism.

Adaptive automation presents similar opportunities and limitations. In principle, automation can be adjusted according to workload, cognitive state, or task complexity. However, increasing automated intervention does not necessarily improve the controller's experience or cognitive performance. Ijtsma et al. (2022) found that decision-based adaptive support could improve efficiency and safety compared with fully manual control, yet greater adaptive intervention was also associated with increased frustration and reduced acceptance and did not necessarily improve perceived workload. These findings suggest that cognitive support may be most effective when it facilitates information integration and anticipation rather than directly intruding into decision execution. Future systems should therefore distinguish between augmenting cognition and replacing cognitive agency.

9.2. Maintaining Situation Awareness and Meaningful Human Control

Situation awareness remains a critical requirement in highly automated ATM because controllers must retain an operationally meaningful understanding of traffic, system state, and emerging risks. The concept of keeping the controller "in the loop" extends beyond presenting information on a display. Cognitive involvement requires that controllers understand what the system is doing, why it is acting, and how current automated actions may influence future traffic states. EUROCONTROL (2010) consequently identified controller involvement, shared situation awareness, system predictability, complexity management, and appropriate trust as key human performance challenges for future ATM.

In human–AI environments, situation awareness increasingly includes awareness of the intelligent agent itself. Endsley (2022) argues that shared situation awareness in human–AI teams requires information concerning taskwork, agent state, and teamwork. Applied to ATM, controllers may need to understand not only the position and trajectory of aircraft but also the information available to the AI, the assumptions underlying its recommendations, its current intentions, and the actions it is undertaking. An automated conflict-resolution recommendation that appears as an isolated instruction may reduce the controller's ability to evaluate its appropriateness. Conversely, a system that communicates relevant constraints, anticipated consequences, and areas of uncertainty can support the controller's mental model and facilitate calibrated reliance.

Transparency is therefore closely linked to meaningful human control. If controllers are formally assigned responsibility for system outcomes but cannot understand or interrogate automated decisions, human authority becomes nominal rather than cognitively functional. Kirwan (2025) argues that human expertise is likely to remain essential in advanced aviation systems because AI continues to exhibit limitations associated with biased data, unusual edge cases, and unpredictable failures. Human oversight, however, cannot be treated as a sufficient safeguard by itself. Effective oversight requires cognitive access to the state and behaviour of the system. Controllers must have sufficient information, time, and retained competence to question automated outputs and intervene when necessary.

The relationship between humans and advanced automation may therefore be better conceptualized through joint cognitive systems and distributed cognition than through a simple supervisor–machine hierarchy. In future ATM, cognition will be distributed across controllers, automation, AI agents, interfaces, aircraft systems, and other operational actors. Tsamados et al. (2024) characterize control in advanced AI systems as a form of collaborative agency within multi-agent environments. From this perspective, the objective is not to determine whether the human or machine is universally superior, but to design interactions that enable the overall system to perceive, interpret, anticipate, and adapt effectively. Human cognitive flexibility and contextual understanding may complement the speed and computational capacity of automated systems, provided that information exchange and coordination between agents are explicitly supported.

Trust is central to this relationship. Excessive trust may promote automation bias and inappropriate reliance, whereas insufficient trust may result in disuse of effective decision support. Appropriate trust should therefore be calibrated to actual system capability and reliability. EUROCONTROL (2010) identified promoting appropriate trust as a central future human performance issue, while contemporary human–AI ATM research similarly positions trust alongside workload, situation awareness, vigilance, decision-making, teamwork, communication, and acceptance as a core human factors dimension (Xia et al., 2025). System predictability, transparent communication of uncertainty, and consistent automation behaviour are likely to be particularly important in enabling controllers to develop accurate expectations concerning automated performance.

9.3. Cognitive State Monitoring and Adaptive Support

A further direction in future ATM concerns the real-time identification of changes in controller cognitive state. Conventional workload management has often relied on traffic counts, sector complexity indicators, and subjective assessment. However, controllers experiencing similar traffic conditions may differ in cognitive demand because of expertise, fatigue, strategy, prior workload, or the specific pattern of conflicts encountered. Cognitive support systems that respond only to nominal traffic complexity may therefore fail to identify emerging performance limitations.

Recent research has examined physiological, neurophysiological, visual, and behavioural indicators of cognitive performance. In a realistic study involving professional controllers, Di Flumeri et al. (2019) found that prolonged highly automated tasks could induce vigilance decline and out-of-the-loop effects. EEG and eye-tracking measures were able to identify aspects of these changes and were used to support adaptive automation intended to maintain greater controller involvement. Similarly, Li et al. (2021) demonstrated the potential value of combining subjective and objective measures within a human-centred neuroergonomic approach to decision-support adjustment. More recent machine-learning research has explored continuous workload estimation through combinations of EEG and eye-movement data, moving beyond the classification of cognitive state into simple low- and high-workload categories (Yu et al., 2025).

Behavioural information may also provide operationally less intrusive indicators. Communication patterns derived from real controller voice data have been examined as markers of changing task demand and mental workload (Muñoz-De-Escalona et al., 2024). Such measures are particularly relevant because they may use data already generated through normal operational activity. Changes in speech rate, communication frequency, or other behavioural patterns could potentially contribute to the identification of emerging cognitive strain without requiring controllers to wear additional sensors.

The value of cognitive monitoring lies in its potential to identify performance degradation before an operational error occurs. Future systems might use workload or vigilance estimates to modify information presentation, postpone non-critical tasks, redistribute traffic, or adjust automated support. This represents a transition from reactive error management toward proactive cognitive performance support. Nevertheless, cognitive-state estimation should be approached cautiously. Workload, fatigue, and performance do not always follow simple linear relationships. Bongo and Seva (2021), for example, identified significant effects of fatigue on situation awareness and visual attention allocation but also reported a complex relationship between fatigue and perceived workload. Controllers may compensate for increasing demand by altering strategies, investing additional effort, or prioritizing specific information. A physiological signal should therefore not be interpreted as a direct and context-independent representation of performance capability.

The current evidence base also remains limited by the predominance of simulator studies, proof-of-concept systems, and relatively small samples. The operational robustness of EEG, eye tracking, functional near-infrared spectroscopy, and multimodal machine-learning models has not yet been established across sustained live ATM operations, diverse controller populations, and abnormal conditions. Yu et al. (2025), Li et al. (2021), and Di Flumeri et al. (2019) demonstrate the technological potential of cognitive-state monitoring, but the transition from experimental classification to safety-critical operational intervention requires extensive validation. False identification of cognitive overload could produce unnecessary automation, whereas failure to identify actual degradation could create misplaced confidence in the monitoring system. Future research must therefore examine not only classification accuracy but also the consequences of adaptive intervention.

9.4. Designing Interfaces to Structure Cognition

Future ATM interfaces should be designed to structure and support cognition rather than simply increase the quantity of available information. Digitalization enables controllers to access increasingly detailed traffic, weather, trajectory, system, and network information. Yet information availability does not guarantee cognitive accessibility. When multiple data streams compete for attention, additional information can increase visual search requirements and information-integration demands.

Human-centred interface design should therefore support attentional allocation, anticipation, and the rapid identification of meaningful changes. The objective is to preserve an appropriate range of cognitive demand, avoiding both overload and prolonged underload (Li et al., 2021). Under excessive demand, controllers may narrow attention, lose track of deferred tasks, or experience difficulty integrating information across multiple aircraft. Under prolonged underload, particularly during automated supervision, vigilance may decline and the traffic picture may become less actively maintained. Interface design must consequently support variable workload rather than assume that workload minimization is universally beneficial.

System predictability is particularly important. Controllers routinely anticipate how traffic will evolve and assess whether present trajectories are likely to produce future conflicts. Automated systems should support this prospective component of cognition by making temporal relationships and expected system behaviour visible. Interfaces that present only current states may be insufficient in trajectory-based and AI-supported environments. Instead, information should assist controllers in understanding the evolution of traffic, the implications of automated interventions, and areas of uncertainty.

Alert design also requires careful attention. Increasing the number of warnings may capture attention without improving understanding. Alerts should prioritize cognitively and operationally meaningful deviations and support rapid interpretation of why intervention may be required. Poorly differentiated or excessive alerts risk producing attentional capture, alarm fatigue, or inappropriate prioritization. Similarly, adaptive displays should not change so unpredictably that controllers must devote cognitive resources to understanding the interface itself. Adaptation should be transparent, stable enough to support learned expectations, and compatible with controller scanning strategies.

9.5. Training and Sustaining Cognitive Readiness

Technological transformation also requires a corresponding evolution in controller training and competence management. EUROCONTROL (2010) identified new training needs, distributed decision-making, collaboration, maintenance of rarely used but critical skills, and prevention of negative transfer as central human performance challenges. These issues become increasingly important as automation reduces the frequency with which controllers manually perform certain tasks.

The maintenance of rarely exercised skills represents a particular concern. If automation performs routine conflict detection or trajectory management, controllers may receive fewer opportunities to practise the cognitive strategies required for manual intervention. Yet these same skills may become critical during automation degradation. Training must therefore move beyond teaching normal automated operations and deliberately expose controllers to degraded modes, unexpected system behaviour, and transitions between automated and manual control. The aim is not simply to preserve procedural recall but to maintain the capacity to reconstruct traffic situations, prioritize rapidly, and adapt control strategies under uncertainty.

Adaptive expertise is particularly relevant in this context. Expert controllers do not apply a single conflict-management strategy across all situations. They modify their approach according to workload and operational demands, employing more monitoring-intensive strategies when cognitive resources are available and more economical strategies under higher workload (Ijtsma et al., 2022). Future training should therefore support flexible strategy selection rather than over-standardize cognitive behaviour. Controllers need opportunities to understand when a familiar strategy is no longer appropriate and to develop alternative approaches for novel or rapidly changing conditions.

Automation and AI literacy should also form part of future competence frameworks. Controllers must understand the capabilities and limitations of intelligent systems sufficiently to form realistic expectations of their performance. This does not require detailed knowledge of algorithmic architecture, but it does require an operational mental model of when the system is reliable, where uncertainty may arise, and what forms of failure are possible. Training should include situations in which automated recommendations are incomplete, inappropriate, or conflicting so that controllers practise questioning and overriding system outputs.

Collaboration training will similarly become more important as decision-making becomes distributed across humans and technological agents. SESAR and NextGen both envisage more distributed operational structures, while new entrants may introduce additional organizations and traffic-management actors. Controllers may therefore need to coordinate across conventional sector boundaries and with unfamiliar human or automated agents. Training for future ATM should address shared situation awareness, authority transitions, communication of uncertainty, and recovery from coordination breakdowns.

9.6. From Error Prevention to Cognitive Resilience

Supporting cognitive performance in future ATM ultimately requires a broader conception of safety. Technological systems have traditionally been designed partly around the reduction of human error. However, the controller's contribution to safety extends beyond error avoidance. Controllers continuously adapt to traffic variability, incomplete information, unexpected behaviour, and competing operational goals. The ability to detect weak signals, revise plans, compensate for system limitations, and coordinate with other actors constitutes an important source of system resilience.

The expertise embedded in controller performance can be underestimated when automation is designed primarily around nominal operations. Edwards et al. (2023) caution that the extent of the ATCO's contribution to system safety may become visible only when automated systems encounter conditions they cannot manage. A future ATM system that reduces human involvement without preserving the cognitive conditions necessary for adaptation may achieve high efficiency under normal conditions while becoming increasingly brittle during disruption.

For this reason, human factors should be integrated into ATM development from the earliest stages of system design. EUROCONTROL (2010) emphasized the need to integrate human performance considerations into safety cases, system engineering processes, user requirements, design specifications, and performance indicators. Human performance cannot remain a final validation activity conducted after technological architecture has been determined. Decisions concerning automation, role allocation, interface structure, staffing, procedures, and training directly shape the cognitive resources available to the ATM system.

The future of cognitive support in ATM therefore lies neither in preserving traditional controller work unchanged nor in progressively removing the human from operational control. Instead, future systems should be designed as adaptive socio-technical environments in which human and technological capabilities are deliberately coordinated. Automation should reduce unnecessary cognitive burden while preserving active engagement; interfaces should make complex system states and automation behaviour understandable; cognitive monitoring should support rather than surveil or prematurely replace human performance; and training should maintain adaptive expertise for both nominal and degraded operations.

Accordingly, the central design question for future ATM is not simply how much can be automated, but how cognitive functions should be distributed across controllers and intelligent systems so that the overall system remains understandable, adaptable, and resilient. Future ATM safety will depend on maintaining controllers' capacity to anticipate, interpret, question, and intervene even as their operational role evolves. Human cognitive performance should therefore be treated not as a limiting constraint to be engineered out of ATM, but as a dynamic system capability that must be actively supported through human-centred technology, appropriate function allocation, cognitive readiness, and organizational design.

10. Case Study - The Ronald Reagan Washington National Airport Mid-Air Collision (2025): A Human Factors and Organizational Culture Analysis of Collision Risks in Complex Terminal Airspaces

Case Overview

The exponential growth of air traffic in modern aviation systems has rendered the management and safety of Terminal Control Areas (TCAs) increasingly complex and vulnerable. This case study examines the systemic human and organizational vulnerabilities underlying aviation safety through the fatal mid-air collision that occurred near Ronald Reagan Washington National Airport (DCA) on January 29, 2025, involving PSA Airlines Flight 5342, a CRJ700 regional jet, and a U.S. Army UH-60L Black Hawk helicopter operating under the call sign PAT25. The accident resulted in the loss of all 67 occupants aboard both aircraft, making it one of the most significant aviation disasters in recent U.S. history.

The primary objective of this study is to analyze the structural limitations of the "See-and-Avoid" principle within the context of human cognitive and visual constraints, the phenomenon of normalization of deviance in air traffic control (ATC) operations, and deficiencies in Threat and Error Management (TEM). Drawing upon accident investigation findings, the study explores how situational awareness degradation among controllers operating under elevated workload conditions, expectation bias during nighttime flight operations, and latent organizational failures interacted to create the conditions for catastrophe.

The accident is examined through the lenses of Reason's Swiss Cheese Model and Leveson's Systems-Theoretic Accident Model and Processes (STAMP), providing a multi-layered understanding of how active failures and latent organizational conditions converged. Furthermore, parallels are drawn with historical aviation accidents, including the Überlingen mid-air collision and the LaGuardia airspace conflict events, highlighting recurring patterns in the management of complex airspace environments.

The findings suggest that traffic management strategies relying predominantly on human performance and visual separation are increasingly unsustainable in congested and operationally complex airspace systems. The study underscores the urgent need for proactive Safety Management Systems (SMS), robust Threat and Error Management practices, and a just reporting culture capable of identifying and mitigating emerging systemic risks before they result in catastrophic outcomes. Ultimately, the case demonstrates that aviation accidents are rarely the consequence of isolated human errors; rather, they emerge from the interaction of cognitive limitations, operational pressures, technological dependencies, and organizational vulnerabilities within a complex socio-technical system.

10.1. Introduction to the Case

Over the past several decades, aviation safety has evolved from reactive, rule-based approaches toward proactive, systems-oriented philosophies emphasizing risk management, organizational learning, and resilience. Contemporary Safety Management Systems (SMS) recognize that accidents rarely result from isolated operator errors; rather, they emerge from the interaction of human, technological, environmental, and organizational factors operating within complex socio-technical systems (Reason, 1990; ICAO, 2018; Leveson, 2012). Despite significant advances in aircraft technology, automation, surveillance systems, and air traffic management, terminal control areas (TCAs) remain among the most cognitively demanding and operationally vulnerable environments in aviation.

TCAs accommodate dense concentrations of commercial airliners, general aviation traffic, military operations, and rotary-wing aircraft, often within geographically constrained airspace and under considerable time pressure. Consequently, air traffic controllers and flight crews must continuously allocate attention, process large volumes of information, maintain situational awareness, manage workload, communicate effectively, and make time-critical decisions. The increasing growth of air traffic, coupled with airport capacity limitations, has intensified operational complexity and placed greater reliance on visual separation procedures and the "See-and-Avoid" principle to maintain traffic flow efficiency. However, these procedures ultimately depend on the perceptual, cognitive, and physiological capabilities of human operators. Research has repeatedly demonstrated that human visual detection and threat recognition capabilities are constrained by workload, attentional limitations, expectancy effects, environmental conditions, and the inherent limitations of human vision (Endsley, 1995; Morris, 2005; Wickens et al., 2015).

The fatal mid-air collision that occurred on January 29, 2025, near Ronald Reagan Washington National Airport (DCA) provides a compelling illustration of these systemic vulnerabilities. The accident involved PSA Airlines Flight 5342, a Bombardier CRJ700 regional jet conducting a scheduled passenger service, and a United States Army UH-60L Black Hawk helicopter operating under the call sign PAT25. The collision resulted in the deaths of all 67 occupants aboard both aircraft and occurred within one of the most operationally complex and politically sensitive airspaces in the United States (National Transportation Safety Board [NTSB], 2026). According to the National Transportation Safety Board (NTSB), the accident took place in an environment characterized by dense traffic flows, constrained airspace geometry, mixed civil-military operations, and significant operational pressures, all of which increased the complexity of traffic management and reduced available safety margins (National Transportation Safety Board [NTSB], 2026). Figure 7 illustrates the overall geometry of the accident by depicting the reconstructed flight paths of PSA Airlines Flight 5342 and the U.S. Army UH-60L Black Hawk helicopter (PAT25) during the final phase of flight. As shown in the figure, both aircraft followed independently authorized flight trajectories that gradually converged within the confined terminal airspace surrounding Ronald Reagan Washington National Airport (DCA). The visualization highlights the spatial proximity between the Runway 33 arrival corridor and Helicopter Route 4, illustrating how two operationally legitimate traffic flows ultimately intersected within a limited airspace volume. Rather than representing an isolated operational error, the reconstructed trajectories demonstrate the systemic complexity of the DCA terminal environment and provide an essential spatial context for understanding the subsequent cognitive, operational, and organizational factors discussed throughout this case study (National Transportation Safety Board [NTSB], 2026).

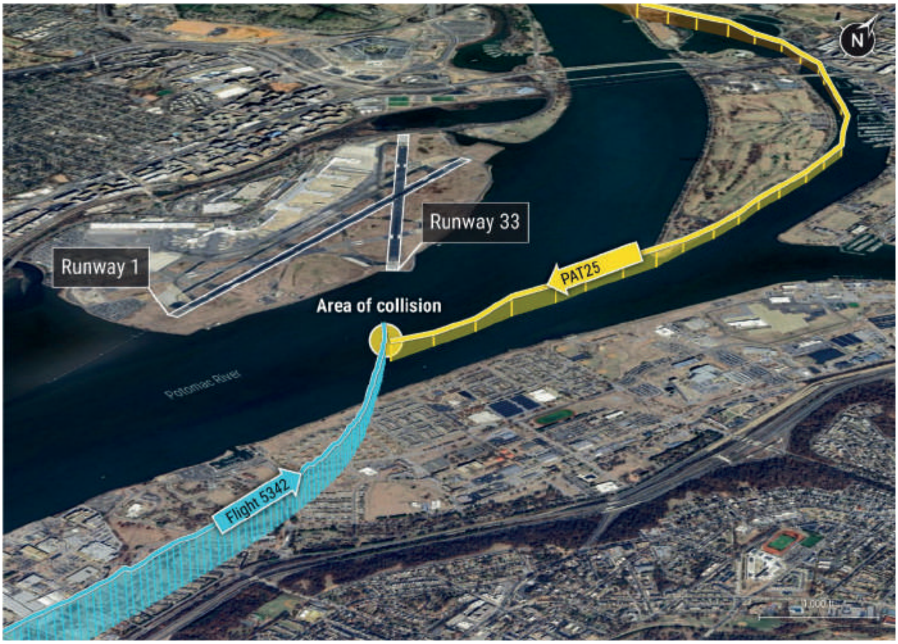

Figure 7. Reconstructed flight trajectories of PSA Airlines Flight 5342 and U.S. Army Priority Air Transport Flight 25 (PAT25) during the final approach phase near Ronald Reagan Washington National Airport (DCA), illustrating the convergence of commercial and military flight paths immediately prior to the mid-air collision. (Adapted from National Transportation Safety Board [NTSB], 2026).

Importantly, the investigation revealed that the accident cannot be adequately explained through the traditional lens of pilot error or controller error alone. Rather, the event emerged from the interaction of multiple latent organizational conditions, operational pressures, communication vulnerabilities, workload-related challenges, and cognitive limitations that gradually eroded the system's defensive barriers (NTSB, 2026). The NTSB investigation identified longstanding concerns regarding the interaction between helicopter routes and fixed-wing arrival procedures, increasing traffic density, the frequent use of visual separation techniques, and operational workarounds that had become normalized over time (NTSB, 2026). These findings align closely with contemporary safety science literature, which emphasizes that accidents are often the product of organizational drift, system migration toward the boundaries of safe performance, and the normalization of deviance rather than isolated unsafe acts (Reason, 1990; Vaughan, 1997; Dekker, 2017).

From a cognitive perspective, the DCA accident provides a unique opportunity to examine how human performance deteriorates under conditions of elevated workload, uncertainty, and time pressure. Situational awareness (SA), defined as the perception of environmental elements, comprehension of their meaning, and projection of their future status (Endsley, 1995), represents one of the most critical cognitive competencies in both air traffic control and flight operations. According to the investigation findings, the controller responsible for local control operations was simultaneously managing fixed-wing and helicopter traffic through combined operational positions while communicating with multiple aircraft in a highly compressed operational environment (NTSB, 2026). Such conditions are known to increase cognitive workload, promote attentional narrowing, reduce information-processing capacity, and elevate the likelihood of situational awareness degradation (Wickens et al., 2015).

Communication difficulties further compounded these cognitive challenges. The NTSB report documented frequency congestion and a blocked radio transmission that prevented the helicopter crew from receiving a critical instruction during the final moments preceding the collision (NTSB, 2026). Research on Team Situational Awareness suggests that communication failures in high-tempo operational environments can significantly impair the development of a shared understanding of evolving traffic situations, thereby increasing operational risk (Salas et al., 1995).

The accident also highlights the limitations of visual perception during nighttime operations. According to the investigation, the helicopter crew requested visual separation after incorrectly identifying surrounding traffic, while the CRJ700 crew was simultaneously conducting a high-workload circling approach to Runway 33 under nighttime conditions (NTSB, 2026). Environmental factors such as city lighting, visual clutter, night vision device usage, perceptual ambiguity, and expectation bias appear to have influenced how both crews interpreted the traffic picture. These findings are consistent with extensive human factors research demonstrating that pilots may experience "look-but-failed-to-see" phenomena, inattentional blindness, and expectancy-driven perceptual errors, particularly under conditions of elevated workload and degraded visual environments (Morris, 2005; Wickens & Hollands, 2000).

Beyond frontline operational performance, the DCA collision raises critical questions regarding organizational safety culture and the effectiveness of Safety Management Systems. The investigation identified previously reported concerns regarding the interaction between helicopter routes and arrival procedures, yet these hazards remained insufficiently mitigated despite repeated operational exposure (NTSB, 2026). Furthermore, evidence suggested that both civil and military organizations possessed safety reporting structures that failed to translate operational knowledge into meaningful risk-reduction actions (NTSB, 2026). These findings strongly reflect Vaughan's (1997) concept of normalization of deviance, whereby repeated exposure to risk without adverse consequences gradually transforms unsafe practices into accepted operational norms. Similarly, they illustrate how organizational learning failures and weak safety cultures can permit hazards to persist until catastrophic outcomes occur.

Consequently, the DCA mid-air collision should not be viewed merely as a tragic operational failure but rather as a manifestation of deeper systemic vulnerabilities involving cognition, workload management, visual perception, organizational culture, safety governance, and airspace design. The case therefore offers an exceptionally valuable opportunity to explore how cognitive processes influence performance in safety-critical environments and how interactions between human and organizational factors shape safety outcomes in modern air traffic management systems.

The significance of the DCA collision extends far beyond the immediate circumstances of the event. The accident occurred within an operational environment that increasingly resembles the future of global air traffic management, characterized by rising traffic volumes, constrained infrastructure, mixed civil-military operations, and growing efficiency demands. Consequently, understanding the cognitive and organizational contributors to this accident offers valuable lessons for air traffic controllers, regulators, safety managers, and aviation researchers.

The case highlights the central role of situational awareness, workload management, communication effectiveness, visual separation procedures, and decision-making under uncertainty. Furthermore, it demonstrates how organizational influences, safety culture, and operational pressures shape frontline performance and contribute to the erosion of safety margins. As such, the DCA accident represents not only a human factors event but also a systems safety event, illustrating the interconnected nature of cognition, technology, organizational culture, and operational performance.

This case study has been developed to provide readers with an applied understanding of cognitive processes in air traffic control through the analysis of a real-world aviation accident. Specifically, the case seeks to:

1. Examine the role of situational awareness in complex terminal airspace operations.
2. Analyze the effects of workload, attention management, and cognitive overload on air traffic controller performance.

3. Explore the influence of expectation bias, visual perception limitations, and decision-making processes on pilot performance.
4. Evaluate the operational limitations of the "See-and-Avoid" principle in congested airspace environments.
5. Investigate the influence of organizational culture, normalization of deviance, and Safety Management System effectiveness on aviation safety outcomes.
6. Apply contemporary human factors frameworks -including the Swiss Cheese Model, Threat and Error Management (TEM), and STAMP-to understand accident causation from a systems perspective.
7. Identify lessons learned for future air traffic management systems, controller training programs, and organizational safety strategies.

Through these objectives, the case demonstrates that aviation accidents emerge not from isolated mistakes but from the interaction of cognitive limitations, operational demands, technological systems, and organizational influences within a complex socio-technical environment.

10.2. Operational Context of Ronald Reagan Washington National Airport (DCA)

10.2.1. Airspace Complexity Around DCA

Ronald Reagan Washington National Airport (DCA) is widely recognized as one of the most operationally complex terminal airspace environments in the United States. Unlike many major airports that benefit from expansive surrounding airspace, DCA operates within a geographically constrained and highly regulated environment shaped by the presence of prohibited areas, restricted airspace, governmental facilities, military operations, and dense metropolitan infrastructure. As a result, aircraft arriving and departing from DCA must comply with highly structured procedures while maintaining separation within relatively limited maneuvering space (NTSB, 2026).

From an air traffic management perspective, airspace complexity extends beyond simple traffic density. Complexity emerges from the interaction of traffic volume, traffic mix, airspace structure, operational constraints, and uncertainty (Histon & Hansman, 2008). DCA exemplifies this phenomenon. Controllers operating within the Washington terminal area must simultaneously manage commercial airline traffic, general aviation flights, military operations, helicopter corridors, and special security restrictions. Such environments require continuous information processing, dynamic prioritization, and anticipation of future traffic states, thereby imposing substantial cognitive demands on both controllers and flight crews (EUROCONTROL, 2019).

Research in air traffic control consistently demonstrates that increasing airspace complexity is associated with elevated mental workload, reduced spare attentional capacity, and a greater likelihood of situational awareness degradation (Endsley, 1995; Alzughibi et al., 2021). These effects become particularly pronounced in terminal airspace environments where traffic trajectories converge, and separation margins are continuously compressed. The DCA operational environment therefore represents a valuable example of how airspace design itself can influence human cognitive performance.

Figure 8 illustrates the spatial configuration of the Ronald Reagan Washington National Airport (DCA) terminal airspace and highlights the geographical and regulatory constraints that distinguish it from conventional terminal environments. As shown in the figure, the airport operates within a highly constrained airspace surrounded by the Washington Flight Restricted Zone (FRZ), prohibited areas, the Potomac River helicopter routes, and closely spaced commercial arrival and departure corridors. The figure further demonstrates the close spatial interaction between fixed-wing approach paths and helicopter operations, illustrating how multiple traffic streams with fundamentally different operational characteristics are required to coexist within a limited volume of airspace. Consequently, the complexity of DCA extends beyond traffic density alone and reflects the interaction of airspace structure, security restrictions, traffic heterogeneity, and operational constraints that collectively increase cognitive workload and coordination requirements for both controllers and flight crews (NTSB, 2026).

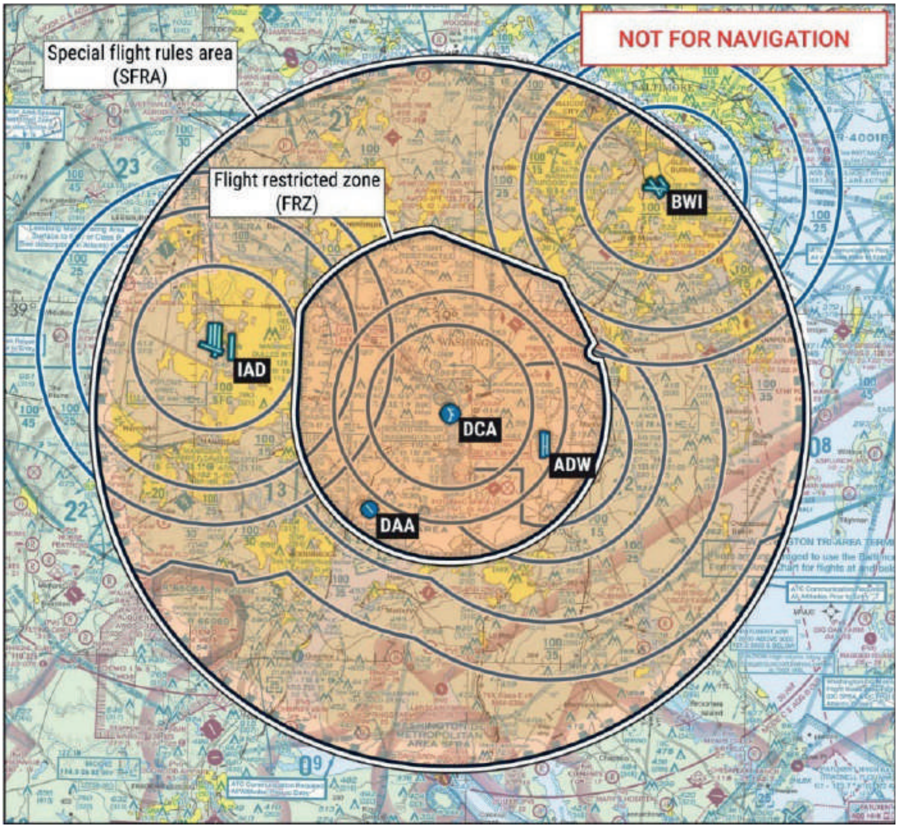

Figure 8. Annotated sectional chart of the Ronald Reagan Washington National Airport (DCA) terminal airspace showing the Washington Flight Restricted Zone (FRZ), Potomac River helicopter routes, prohibited areas, and principal commercial arrival and departure corridors, illustrating the spatial constraints contributing to the operational complexity of the DCA terminal environment. (Adapted from National Transportation Safety Board, 2026).

In addition to its physical and procedural constraints, DCA presents a unique operational challenge because it lies within one of the most politically sensitive and security-restricted regions in the world. Controllers must simultaneously account for conventional air traffic management requirements and a range of security-driven operational restrictions that influence aircraft routing, sequencing, and separation practices. Consequently, the complexity of the DCA environment should be understood not merely as a function of traffic volume but as the product of multiple interacting operational, regulatory, and organizational factors that collectively increase cognitive demands on aviation personnel.

10.2.2. Interaction Between Commercial and Military Traffic

A defining characteristic of the DCA operational environment is the routine coexistence of commercial airline traffic and military helicopter operations within a highly constrained terminal airspace structure. Unlike many airports where traffic categories are separated through dedicated procedures or airspace segmentation, DCA requires controllers to continuously manage aircraft with fundamentally different performance characteristics, operational objectives, flight profiles, and maneuvering capabilities.

From a systems perspective, such coexistence introduces a level of complexity that extends beyond conventional traffic management challenges. Fixed-wing transport aircraft typically operate within highly standardized arrival and departure procedures, whereas military helicopter operations often involve greater operational flexibility and route variability. Consequently, controllers must simultaneously maintain multiple mental models of aircraft behavior and anticipate interactions between traffic streams that evolve at different speeds and under different procedural assumptions.

The DCA accident illustrates how mixed-operation environments can create latent vulnerabilities that remain largely invisible during routine operations but become critical when workload increases or operational margins are reduced. According to the NTSB investigation, helicopter routes and fixed-wing arrival procedures intersected within the same operational environment, creating conditions in which traffic separation increasingly relied on accurate perception, communication, and shared situational awareness among controllers and pilots (NTSB, 2026). Rather than viewing the collision as the consequence of a single failed visual acquisition, it may be more appropriate to interpret the event as evidence of a system in which operational complexity gradually exceeded the capacity of its human operators to maintain an accurate and shared understanding of the evolving traffic situation.

From a cognitive standpoint, heterogeneous traffic environments demand continuous attention switching and increase the likelihood of expectation-driven processing. Operators naturally develop mental models regarding where traffic should be located and how it is expected to behave. When actual traffic behavior diverges from those expectations, the probability of misidentification, delayed recognition, and incorrect assumptions may increase substantially, particularly under conditions of elevated workload and time pressure. These cognitive challenges become even more pronounced when operators must simultaneously integrate information originating from multiple aircraft categories, communication channels, and operational procedures.

The DCA case therefore highlights a broader challenge confronting modern air traffic management systems: how to safely integrate increasingly diverse traffic types within finite airspace resources while ensuring that operational complexity remains compatible with human cognitive capabilities.

10.2.3. Traffic Density and Capacity Constraints

The relationship between traffic demand and operational capacity represents one of the most significant challenges facing contemporary air traffic management systems. While increasing traffic density is often discussed as a quantitative problem, its consequences are fundamentally cognitive in nature. As traffic demand approaches the practical limits of available infrastructure, the task of maintaining safe separation becomes progressively more dependent on human information processing, decision-making, and workload management.

The DCA investigation suggests that operational practices had gradually evolved in response to persistent capacity pressures generated by traffic demand, airport infrastructure limitations, and arrival sequencing challenges (NTSB, 2026). Importantly, these pressures did not manifest as a single operational failure. Instead, they appear to have created a context in which controllers were required to manage increasingly compressed traffic situations while simultaneously preserving traffic flow efficiency.

This distinction is critical from a human factors perspective. Air traffic controllers do not experience traffic density merely as a greater number of aircraft on a radar display. Rather, complexity emerges through the increasing number of interactions, coordination requirements, communication exchanges, conflict assessments, and future-state predictions that must be processed simultaneously. Research consistently demonstrates that workload increases disproportionately as complexity rises, often producing abrupt reductions in spare cognitive capacity and situational awareness rather than gradual declines in performance (Alzughibi et al., 2021; Histon & Hansman, 2008).

The NTSB investigation further identified operational conditions in which arrival spacing and traffic sequencing frequently reduced the tactical flexibility available to controllers, thereby increasing workload and limiting opportunities for proactive conflict management (NTSB, 2026). Under such circumstances, operators are often forced to rely on short-term adaptations and rapid decision-making strategies to maintain traffic flow. Although these adaptations may be effective in the short term, they can gradually create conditions in which safety margins become increasingly dependent on individual performance rather than systemic resilience.

The accident therefore raises broader questions regarding the relationship between efficiency and safety. As operational demand increases, organizations often develop adaptive practices intended to preserve throughput. While such adaptations may initially appear successful, they can gradually become embedded within routine operations without a corresponding evaluation of their long-term safety implications. In this sense, the DCA accident illustrates how capacity management challenges can evolve from operational concerns into systemic safety concerns when human cognitive limitations are not explicitly incorporated into system design and operational planning.

10.2.4. Runway Configuration and Operational Pressures

Runway configurations are often viewed as technical or operational variables; however, from a human factors perspective, they also shape the cognitive demands placed upon controllers and flight crews. The configuration in use on the evening of the accident illustrates how operational adaptations designed to improve efficiency may inadvertently increase complexity within an already demanding environment.

According to the NTSB investigation, aircraft arriving at DCA were frequently reassigned from standard arrival procedures to circling approaches for Runway 33 in order to alleviate congestion and maintain traffic flow efficiency (NTSB, 2026). While operationally practical, this adaptation required flight crews to perform additional maneuvering, increased trajectory variability, and introduced new interactions between arriving fixed-wing aircraft and helicopter traffic operating in the surrounding area.

Although Runway 33 became a focal point of the accident investigation, it did not represent the primary arrival runway during routine DCA operations. Rather, its use was typically associated with specific traffic management strategies intended to improve operational efficiency under particular traffic and environmental conditions. The operational significance of Runway 33 therefore stems not from its frequency of use but from the distinctive traffic interactions and coordination demands it creates. Table 2 summarizes the proportion of arrivals conducted to Runway 33 during the period examined by the NTSB investigation, providing quantitative context for interpreting its role within the broader operational environment (NTSB, 2026).

Table 2. Percentage of aircraft arrivals conducted to Runway 33 during the operational period examined by the NTSB investigation.

Landing runway	2018	2019	2023	2024	2025[a]	Total
1	92.56	91.98	92.89	93.43	94.41	92.84
33	7.44	8.02	7.11	6.57	5.59	7.16
Total (%)	100.0	100.0	100.0	100.0	100.0	100.0

a Data as of April 2025.

Source. Adapted from National Transportation Safety Board (NTSB). (2026).

From a cognitive perspective, such procedures significantly alter task demands. Controllers require continuous monitoring of dynamically changing traffic relationships and the anticipation of future aircraft positions. For pilots, circling approaches involve the simultaneous management of aircraft control, visual references, navigation, communication, and traffic monitoring under time-constrained conditions. These competing demands place considerable pressure on attentional resources and working memory, particularly during nighttime operations.

The accident investigation suggests that the use of Runway 33 procedures was not an isolated operational decision but part of a broader adaptation to recurring capacity constraints within the DCA environment (NTSB, 2026). This observation is particularly important because it highlights how local operational practices can evolve in response to systemic pressures. Over time, procedures initially adopted as practical solutions to operational bottlenecks may become normalized components of daily operations, even when they introduce additional complexity or reduce available safety margins.

Safety science literature has long recognized that organizations operating near capacity limits frequently develop informal practices that allow systems to continue functioning efficiently despite underlying constraints (Vaughan, 1997; Dekker, 2017). Although such practices are rarely intended to compromise safety, they may gradually normalize increased levels of risk and reduce opportunities for error recovery. In the DCA environment, the routine use of operational adaptations designed to preserve efficiency may have inadvertently increased the cognitive demands placed upon both controllers and pilots, thereby creating conditions more susceptible to human performance limitations.

Viewed through this lens, the significance of the Runway 33 operation extends beyond its immediate role in the accident sequence. It represents a manifestation of how operational pressures, organizational priorities, and human cognitive limitations can interact within complex aviation systems. The DCA accident therefore serves as a reminder that efficiency-driven adaptations must be evaluated not only in terms of operational effectiveness but also in terms of their impact on human performance, situational awareness, and overall system resilience.

10.3. Air Traffic Controller Cognitive Processes During the Event

The collision between PSA Airlines Flight 5342 and the U.S. Army UH-60L Black Hawk helicopter near Ronald Reagan Washington National Airport (DCA) provides a valuable opportunity to examine the role of cognitive processes in air traffic control under conditions of elevated complexity, workload, and operational uncertainty. While accident investigations often focus on procedural deviations and operational decisions, contemporary human factors research emphasizes that such actions can only be fully understood by examining the cognitive environment in which they occur. Air traffic controllers continuously engage in complex cognitive activities, including attention management, information integration, workload regulation, communication processing, anticipation, and the maintenance of situational awareness. When these cognitive processes become overloaded or disrupted, the probability of operational error increases significantly (Endsley, 1995; Wickens et al., 2015).

The DCA accident occurred within an environment characterized by dense traffic flows, mixed civil-military operations, compressed arrival sequencing, and multiple simultaneous communication demands (NTSB, 2026). These conditions created a setting in which controllers were required to allocate limited cognitive resources across multiple concurrent tasks while maintaining an accurate and continuously updated representation of the traffic situation. Consequently, the event provides a compelling case through which to examine the interaction between attention, workload, situational awareness, communication, and team cognition in a safety-critical environment.

Before examining the specific cognitive mechanisms underlying controller performance during the DCA accident, it is necessary to understand the operational responsibilities assigned to each control position within the DCA Air Traffic Control Tower (ATCT). Air traffic control does not represent the work of a single controller but rather a distributed cognitive system in which multiple specialists perform complementary tasks while maintaining a shared representation of the operational environment. Consequently, the cognitive demands experienced during the accident can only be interpreted within the context of each controller's assigned responsibilities.

As summarized in Table 3, the DCA ATCT is organized into several operational positions, each responsible for distinct aspects of aircraft movement, separation, coordination, and communication. Although these responsibilities are formally divided, controllers continuously exchange information and update one another's understanding of the traffic situation. This distributed allocation of responsibilities reduces individual workload under normal operating conditions but simultaneously requires continuous coordination and shared situational awareness to ensure safe operations (NTSB, 2026).

Table 3. Primary operational duties and responsibilities associated with controller positions at Ronald Reagan Washington National Airport Air Traffic Control Tower (DCA ATCT).

Position	**Primary duties and responsibilities**
LC (Local Control)	• Provide initial separation between successive departures. • Provide separation between arrivals and departures. • Coordinate with the final controller if the tower issues any control instruction that affects the sequence or separation established by the final controller. • Initiate corrective action and coordinate with appropriate sectors if a loss of standard separation may occur within the tower's airspace.
HC (Helicopter Control)	• Separate VFR traffic from DCA arrivals and departures. • Issue safety alerts and traffic advisories as required. • Clear VFR aircraft on routes or into zones as depicted on the Baltimore-Washington Helicopter Route Chart.
ALC (Assistant Local Control)	• Alert LC of any unusual situations or traffic conflicts. • Maintain surveillance of the local traffic pattern and landing area. • Assist LC with monitoring traffic on final via control tower radar display (CTRD).
Operations Supervisor (OS)	• Provide operational supervision and direct the tower operation to ensure an efficient flow of air traffic. • Make necessary notifications of: • Suspected operational errors • Pilot deviations • Near midair collision (NMAC) reports • Other incidents requiring notifications • Combine and de-combine positions.

Ground Control (GC)	• Control aircraft and vehicles operating on movement areas, excluding runways. • When Airport Resource Management Tool (ARMT) is out of service, verbally request departure releases from the TMC, FD, or OS. • Review proposed departure times and ensure that flight plans do not time out. • Notify the OS/controller in charge (CIC) of ODO requests.
Clearance Delivery (CD)	• Review proposed flight plans for anomalies. • Issue ATC clearances, traffic management initiatives, Expect Departure Clearance Time (EDCT) times and any other pertinent information as necessary. • Mark strips in accordance with Chapter 3, Strip Marking. • When duplicate flight plans are received, verify the requested flight plan with the pilot and remove the undesired flight plan.

Source: Adapted from National Transportation Safety Board (NTSB) (2026).

10.3.1 Attention Allocation Under High Traffic Demand

Attention represents one of the most critical cognitive resources in air traffic control. Controllers must continuously distribute their attention across multiple aircraft, communication channels, potential conflict points, runway operations, and future traffic developments while prioritizing information according to operational relevance. Unlike static monitoring tasks, attention in ATC is dynamic and must be continuously reallocated as traffic conditions evolve (Wickens, 2008).

According to the NTSB investigation, the controller responsible for local operations at DCA was simultaneously managing both fixed-wing and helicopter traffic within a compressed and highly dynamic traffic environment during the period preceding the collision (NTSB, 2026). Under such circumstances, attentional resources become fragmented across competing operational demands. Rather than focusing on a single traffic situation, controllers must repeatedly switch attention among multiple aircraft, communication exchanges, runway operations, and anticipated future conflicts.

Research on selective and divided attention demonstrates that human attentional capacity is inherently limited. As task demands increase, operators become more vulnerable to attentional tunneling, a phenomenon in which attention becomes concentrated on specific tasks while other critical cues receive insufficient processing (Wickens et al., 2015). Recent experimental studies further suggest that frequent task interruptions and attention switching significantly degrade controllers' situational awareness and increase the cognitive costs associated with task resumption (Zhou et al., 2024). In complex environments characterized by dense communication traffic and multiple simultaneous operational demands, these interruptions may reduce the likelihood of timely conflict recognition and compromise overall traffic monitoring performance.

Recent eye-tracking research has also demonstrated that increasing traffic complexity alters controllers' visual scanning strategies, reduces gaze efficiency, and affects the allocation of visual attention across the operational environment (Li et al., 2023). These findings indicate that attention allocation in air traffic control should be conceptualized as a dynamic cognitive process influenced not only by traffic volume but also by information distribution, task complexity, and environmental demands. Within the DCA operational context, the coexistence of multiple traffic categories and communication streams likely increased attentional fragmentation and reduced opportunities for proactive monitoring of emerging hazards.

Although attentional allocation is generally described as an internal cognitive process, it can also be inferred from observable operational behaviour. During real-time air traffic control, attention is continuously redirected toward aircraft requiring immediate communication, conflict resolution, sequencing, or coordination. Consequently, communication behaviour provides an indirect but valuable indicator of attentional demands imposed on controllers. The NTSB communication analysis presented in Figure 9 illustrates how the local controller's attention was dynamically distributed across aircraft during the twenty-minute period preceding the collision. Rather than reflecting evenly distributed cognitive resources, the communication pattern demonstrates substantial variations in communication frequency, duration, direction, and spatial distribution, indicating the continuously changing attentional priorities imposed by the operational environment (NTSB, 2026).

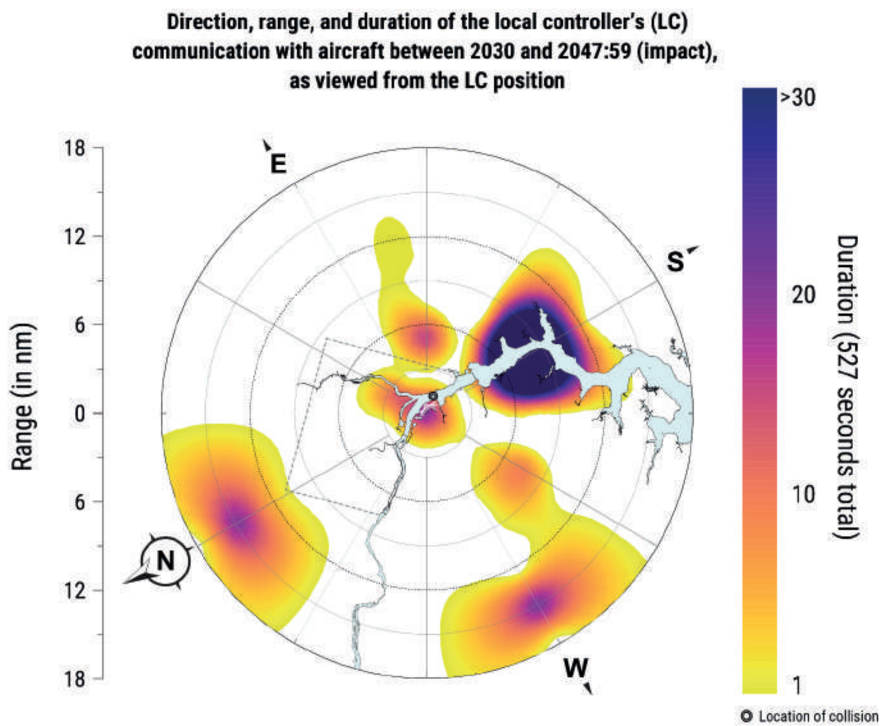

Figure 9. Heatmap illustrating the direction, distance, and duration of communications between the local controller and aircraft from 2030 until the collision. The visualization demonstrates the dynamic distribution of controller communication activity and attentional demands across the DCA terminal airspace.

Source: Adapted from National Transportation Safety Board (NTSB) (2026).

10.3.2 Mental Workload and Cognitive Saturation

Mental workload refers to the proportion of cognitive resources required to perform a task relative to the resources available to the operator (Wickens, 2008). In air traffic control, workload is influenced not only by traffic volume but also by traffic complexity, coordination requirements, communication demands, procedural constraints, and time pressure. Consequently, workload should be viewed as an emergent property of the interaction between the operator and the operational environment rather than a simple function of aircraft count.

The DCA investigation suggests that workload levels during the accident sequence were elevated by several interacting factors, including compressed arrival flows, mixed traffic operations, runway management demands, communication activity, and concurrent helicopter operations (NTSB, 2026). Under such circumstances, controllers may approach cognitive saturation, a condition in which available mental resources become insufficient to process all relevant information effectively.

Contemporary workload research increasingly recognizes that controller workload is not determined solely by traffic density. Instead, workload emerges from the interaction between traffic complexity, sector design, communication requirements, operational uncertainty, and human-centered factors (Suárez et al., 2024). This distinction is particularly important because operators often experience abrupt increases in cognitive demand when complexity reaches a critical threshold. Research has consistently shown that workload increases nonlinearly as complexity rises, producing reductions in spare cognitive capacity, planning ability, conflict detection performance, and situational awareness (Rodgers & Nye, 1993; Histon & Hansman, 2008).

Recent advances in neuroergonomics have further strengthened our understanding of workload dynamics. Studies utilizing electroencephalography (EEG), physiological monitoring, and machine-learning techniques have demonstrated that cognitive workload can be measured in real time and that elevated workload is associated with slower response times, diminished operational efficiency, and reduced conflict detection performance (Hui et al., 2024). These findings support the argument that workload management should be viewed as a critical safety issue rather than merely an operational concern.

When workload approaches cognitive capacity limits, operators typically adopt adaptive strategies such as prioritization, simplification, and selective information processing. While these strategies may maintain short-term operational continuity, they can also reduce sensitivity to emerging threats and limit the ability to anticipate future traffic developments. The DCA accident therefore illustrates how excessive workload can become a systemic vulnerability when organizational and operational conditions place sustained demands on human cognitive resources.

10.3.3 Situational Awareness Breakdown

Situational awareness (SA) is widely regarded as one of the most important cognitive constructs in aviation safety. According to Endsley (1995), SA consists of three hierarchical levels: perception of relevant environmental elements, comprehension of their significance, and projection of their future status. Effective air traffic control depends upon maintaining accurate situational awareness across multiple aircraft, traffic flows, and evolving operational conditions.

The DCA accident provides a clear example of how situational awareness can deteriorate under conditions of elevated workload and operational complexity. The NTSB investigation indicates that the controller was required to manage multiple aircraft categories, monitor converging traffic trajectories, and process numerous communication exchanges within a constrained operational environment (NTSB, 2026). Such demands increase the likelihood that critical information may be perceived but not fully integrated into an accurate mental representation of the developing situation.

Situational awareness failures rarely result from a complete absence of information. More commonly, they emerge when operators possess relevant information but fail to integrate it effectively into a coherent understanding of the operational environment (Endsley & Garland, 2000). In dynamic environments, the challenge lies not simply in observing aircraft individually but in continuously predicting how those aircraft will interact in the future.

Recent research has expanded traditional views of situational awareness by emphasizing its distributed nature. Rather than existing solely within the mind of an individual operator, situational awareness increasingly appears to emerge through interactions among controllers, pilots, technological systems, and organizational processes (Pan et al., 2025b). Studies conducted in remote tower environments suggest that changes in information presentation, interface design, and technological mediation can significantly influence operators' ability to maintain accurate traffic representations and anticipate future system states.

From this perspective, the DCA accident should not be interpreted solely as an individual loss of situational awareness. Instead, it may be viewed as a system-level failure in which multiple actors possessed partial information but were unable to collectively develop a sufficiently accurate understanding of the evolving traffic situation. Such an interpretation aligns with contemporary socio-technical approaches to safety and highlights the importance of considering situational awareness as both an individual and an organizational phenomenon.

10.3.4 Communication Management and Information Processing

Communication serves as the primary mechanism through which air traffic controllers acquire, distribute, verify, and update operational information. Effective communication supports situational awareness, coordination, and decision-making, whereas communication failures can disrupt information flow and increase uncertainty throughout the operational system.

The NTSB investigation documented communication-related challenges during the accident sequence, including frequency congestion and a blocked radio transmission that prevented the helicopter crew from receiving a critical instruction shortly before the collision (NTSB, 2026). Although communication failures are often interpreted as isolated operational events, human factors research suggests that they frequently reflect broader information-processing challenges associated with workload and cognitive demand.

Controllers must continuously encode, transmit, receive, interpret, and integrate information originating from multiple aircraft and operational sources. As workload increases, communication itself becomes a cognitively demanding activity requiring attentional resources, working memory capacity, and rapid decision-making. Under high-demand conditions, the probability of missed transmissions, delayed responses, incomplete information processing, and misunderstandings increases substantially (Wickens et al., 2015).

Recent research suggests that communication behavior itself may serve as a useful indicator of controller workload and operational complexity. Variations in speech patterns, communication density, and interaction strategies have been shown to reflect underlying cognitive demands and changes in workload levels (Muñoz-de-Escalona et al., 2025). Furthermore, advances in artificial intelligence and automated communication monitoring systems indicate that communication anomalies may increasingly be detected in real time, potentially supporting controllers in managing information-intensive environments.

Communication effectiveness depends not only on message transmission but also on message interpretation. Operators frequently interpret information through the lens of existing expectations and mental models. Consequently, expectation bias may influence how messages are understood and acted upon, particularly when time pressure limits opportunities for verification. The DCA accident illustrates how communication management and information processing should be viewed as interdependent cognitive processes that directly influence operational safety.

10.3.5 Team Situation Awareness Challenges

Air traffic control operations rarely depend upon the cognitive performance of a single individual. Instead, safe operations emerge from the collective ability of controllers, pilots, supervisors, and supporting personnel to develop and maintain a shared understanding of evolving operational conditions.

This concept is commonly referred to as Team Situational Awareness (TSA) (Salas et al., 1995).

The DCA accident highlights the challenges associated with maintaining shared situational awareness across multiple actors operating within a complex socio-technical system. The controller, helicopter crew, airline flight crew, and supporting organizational structures each possessed different pieces of information regarding the traffic situation. However, the effectiveness of the system depended upon these actors developing a sufficiently common understanding of traffic relationships to support coordinated action.

Research on team cognition suggests that breakdowns in shared situational awareness frequently occur when communication becomes fragmented, assumptions diverge, or individual mental models evolve differently over time (Salas et al., 1995). Such breakdowns are particularly likely in environments characterized by elevated workload, compressed timelines, and operational uncertainty.

Recent studies increasingly emphasize that air traffic control safety depends on distributed and shared forms of situational awareness rather than individual awareness alone (Gerdes et al., 2025). Emerging ATM concepts involving remote operations, digital towers, decision-support tools, and human–AI teaming require controllers to coordinate not only with other human operators but also with increasingly sophisticated technological systems. Consequently, maintaining common operational understanding across both human and technological agents has become a critical challenge for next-generation air traffic management.

The NTSB findings suggest that the actors involved in the DCA accident sequence may have operated with partially different understandings of the traffic environment (NTSB, 2026). From a cognitive perspective, this does not necessarily indicate a lack of competence or effort. Rather, it reflects the inherent difficulty of maintaining synchronized mental models within a dynamic and information-rich operational environment.

Ultimately, the DCA collision demonstrates that air traffic control safety depends not only on individual cognition but also on collective cognition. The ability to create, maintain, and update shared situational awareness remains one of the most important—and most challenging—requirements of modern air traffic management systems. By illustrating the interaction between attention, workload, communication, situational awareness, and team cognition, the DCA accident provides important insights into how cognitive processes shape safety outcomes in complex aviation environments.

10.4. Pilot Cognitive Processes and Perceptual Limitations

10.4.1. Pilot Cognitive Processes and Perceptual Limitations

The DCA mid-air collision highlights not only the cognitive challenges faced by air traffic controllers but also the perceptual and decision-making limitations experienced by flight crews operating in complex, dynamic, and time-constrained environments. Contemporary aviation safety research increasingly recognizes that pilots do not function as passive observers who simply receive and process sensory information. Rather, they actively construct an understanding of their environment through the interaction of perception, attention, memory, expectations, prior experience, and operational goals (Endsley, 1995; Wickens & Hollands, 2000). Consequently, perception is not a purely objective process but a constructive cognitive activity influenced by both environmental stimuli and internal mental models.

The collision between PSA Airlines Flight 5342 and the U.S. Army UH-60L Black Hawk helicopter occurred during nighttime operations within a highly complex terminal airspace characterized by multiple traffic streams, mixed civil-military operations, visual clutter, and compressed decision timelines. According to the NTSB investigation, both crews were operating in an environment requiring continuous integration of visual information, traffic monitoring, communication management, navigation, and aircraft control while simultaneously anticipating future traffic developments (NTSB, 2026). Under such circumstances, the limitations of human perception and cognition become particularly relevant. Rather than emerging from a single visual failure, the accident sequence appears to reflect the interaction of expectation bias, selective attention, predictive cognition, inattentional blindness, perceptual ambiguity, and elevated workload operating simultaneously within a demanding operational context.

10.4.2. Expectation Bias During Night Operations

Expectation bias refers to the tendency of individuals to interpret information in ways that confirm their existing beliefs, expectations, or mental models rather than objectively evaluating all available evidence (Wickens et al., 2015). In aviation environments, expectation bias frequently emerges because operators must continuously anticipate future events in order to maintain safety and efficiency. Pilots routinely construct predictive mental models regarding aircraft positions, traffic flows, weather developments, and procedural outcomes. While these models generally support effective decision-making, they may also increase susceptibility to misinterpretation when environmental cues are ambiguous or incomplete.

According to the NTSB investigation, the PAT25 helicopter crew accepted visual separation responsibilities after reporting traffic in sight; however, evidence suggests that the crew may have identified a different aircraft than the CRJ700 involved in the subsequent collision (NTSB, 2026). This possibility highlights one of the most important characteristics of human cognition: operators frequently perceive what they expect to see rather than what is objectively present.

Night operations further amplify the influence of expectation bias. Reduced visual contrast, degraded depth perception, artificial lighting, and incomplete visual information increase reliance on top-down cognitive processing. Under such conditions, expectations become increasingly important in shaping perception because the visual system receives less reliable sensory information from the environment. Research has consistently demonstrated that expectation-driven errors become more likely when workload is elevated and opportunities for information verification are limited (Orasanu & Martin, 1998; Wickens & Hollands, 2000).

Loft (2009) argued that aviation operators routinely employ predictive cognitive strategies to manage uncertainty and maintain safety margins. These strategies generally improve operational performance because they allow operators to anticipate future developments rather than react solely to current events. However, predictive mental models may also contribute to confirmation biases when operators interpret ambiguous information in ways that support existing expectations. Within the DCA accident sequence, the helicopter crew's traffic identification process appears to have occurred under precisely such conditions. Consequently, expectation bias should not be viewed merely as a perceptual limitation but as an adaptive cognitive mechanism that, under certain circumstances, may contribute to inaccurate threat assessment and decision-making.

10.4.3. Selective Attention and Visual Search

Visual search represents one of the most fundamental cognitive activities performed by pilots. During flight operations, pilots must continuously monitor aircraft instruments, navigation displays, communication systems, external traffic, terrain, weather conditions, and runway references. Because attentional resources are inherently limited, it is impossible to process all available information simultaneously. As a result, pilots must selectively allocate attention according to operational priorities (Wickens, 2008).

Selective attention enables efficient performance by allowing operators to focus on task-relevant information while filtering irrelevant stimuli. However, this mechanism also creates vulnerabilities. As workload increases, attentional resources become increasingly concentrated on specific tasks, potentially reducing awareness of peripheral or unexpected events. Consequently, the effectiveness of visual search depends not only on what is visible but also on where attentional resources are directed.

Recent eye-tracking research demonstrates that increasing workload significantly alters visual scanning behaviour. Under high-demand conditions, pilots exhibit narrower scanning patterns, longer fixation durations, and reduced monitoring of peripheral information sources (Li et al., 2023). Such changes may reduce the likelihood of detecting unexpected hazards, particularly in visually complex environments.

Importantly, visual search involves not only detecting objects but also predicting where relevant objects are likely to appear. Boudes and Cellier (2000) demonstrated that aviation operators frequently exhibit systematic response biases when estimating the future positions of moving aircraft. These predictive tendencies influence attentional allocation by directing visual search toward anticipated locations rather than promoting entirely objective scanning behaviour. While such strategies generally improve efficiency, they may also reduce the probability of detecting unexpected traffic appearing outside anticipated search areas.

The DCA accident occurred within an environment requiring simultaneous monitoring of approach guidance, aircraft configuration, runway alignment, external traffic, and communications (NTSB, 2026). Under these conditions, visual attention was necessarily divided across multiple competing demands. Consequently, even if the conflicting aircraft were physically visible, successful detection depended upon whether attentional resources were allocated toward the appropriate region of the visual environment at the appropriate time. These findings suggest that visual acquisition failures cannot be understood solely as deficiencies in visual capability; rather, they emerge through the interaction of attention, prediction, workload, and environmental complexity.

10.4.4. Inattentional Blindness

One of the most influential findings in cognitive psychology is that visibility does not guarantee awareness. Individuals may fail to perceive highly visible objects when attentional resources are allocated elsewhere, a phenomenon known as inattentional blindness (Mack & Rock, 1998).

In aviation environments, inattentional blindness represents a significant safety concern because pilots frequently perform multiple cognitively demanding tasks simultaneously. Aircraft control, navigation, communication management, weather assessment, checklist execution, and traffic monitoring compete for limited attentional resources. Consequently, operators may fail to consciously register unexpected hazards despite directing their gaze toward them.

Research has repeatedly demonstrated that inattentional blindness contributes to so-called "look-but-failed-to-see" events in aviation, whereby pilots visually scan an area but fail to consciously recognize critical traffic information (Haines, 1991; Wickens & Hollands, 2000). Such failures become particularly likely when operators are focused on highly demanding tasks or when unexpected objects do not match existing expectations.

Importantly, inattentional blindness is closely related to predictive cognition. Pilots do not merely observe their environment; they continuously generate expectations regarding future developments and allocate attentional resources accordingly. When attention becomes strongly guided by these expectations, unexpected hazards may remain undetected even when physically visible. Loft et al. (2009) suggested that operators frequently rely on predictive strategies to manage uncertainty and maintain safety margins. Although such strategies are generally adaptive, they may also increase vulnerability to failures in detecting unexpected conflicts that fall outside anticipated traffic patterns.

The DCA accident provides a compelling context for inattentional blindness. The CRJ700 crew was simultaneously managing aircraft control, runway acquisition, circling approach procedures, communication requirements, and traffic monitoring. Similarly, the helicopter crew was responsible for maintaining visual separation while monitoring multiple aircraft operating within a complex airspace environment (NTSB, 2026). Under such circumstances, attentional resources may have been concentrated on expected operational priorities at the expense of detecting an emerging collision threat. Consequently, the accident illustrates why collision avoidance cannot depend solely on visual acquisition; successful threat detection requires not only seeing but also cognitively recognizing and correctly interpreting relevant information.

10.4.5. Visual Illusions and Night-Time Perception

Night operations present unique challenges for human perception. The human visual system evolved primarily for daylight conditions and performs substantially less effectively in low-light environments. At night, visual acuity, colour discrimination, depth perception, contrast sensitivity, and motion detection capabilities are significantly reduced, increasing susceptibility to perceptual errors and visual illusions (Gibb et al., 2011).

The DCA accident occurred against the backdrop of a densely illuminated urban environment. Numerous stationary and moving light sources—including city lights, roadway traffic, illuminated buildings, reflections, and airport lighting systems—created a visually cluttered scene that may have complicated aircraft identification and distance estimation (NTSB, 2026). Such conditions reduce the salience of critical traffic cues and increase the cognitive demands associated with visual target acquisition.

Research has identified several visual illusions relevant to nighttime aviation operations, including false horizon illusions, autokinesis, relative motion misperception, size-distance illusions, and closure-rate misjudgments (Federal Aviation Administration [FAA], 2023). Furthermore, visual clutter can produce contour interaction effects, whereby background illumination interferes with the accurate detection and identification of airborne traffic. In the DCA operational environment, the visual complexity surrounding the Potomac River corridor may have contributed to difficulties in distinguishing aircraft lighting from numerous competing light sources.

The use of night vision devices introduces additional perceptual challenges. Although such systems enhance visibility under low-light conditions, they may reduce field of view, alter contrast relationships, and modify depth perception. Consequently, pilots may experience difficulties in accurately assessing aircraft positions, relative motion, and closure rates.

Modern research increasingly emphasizes that perception should be understood as an interaction between sensory information and cognitive interpretation rather than as a purely sensory process (Wickens et al., 2015). Thus, perceptual errors often emerge not because information is absent but because available information is ambiguous, degraded, or interpreted incorrectly. The DCA accident demonstrates how environmental complexity and nighttime conditions may amplify these challenges and contribute to degraded traffic perception.

10.4.6. Cognitive Challenges During Circling Approaches

Circling approaches represent one of the most cognitively demanding phases of flight. Unlike standard straight-in instrument approaches, circling procedures require pilots to transition from instrument-based navigation to visually guided maneuvering while simultaneously maintaining terrain awareness, aircraft control, runway orientation, traffic monitoring, and communication management.

According to the NTSB investigation, Flight 5342 was reassigned from a standard Runway 1 arrival to a nighttime circling approach for Runway 33, a procedure routinely used to alleviate traffic congestion at DCA (NTSB, 2026). Although operationally effective from a traffic management perspective, such procedures substantially increase pilot workload because they require continuous integration of multiple information sources during a time-critical phase of flight.

From a cognitive perspective, circling approaches place considerable demands on working memory, attention management, predictive processing, and situational awareness. Pilots must continuously maintain awareness of aircraft position relative to the runway while simultaneously monitoring airspeed, altitude, traffic, weather conditions, aircraft configuration, and external visual references. These competing demands increase the likelihood of cognitive overload and reduce the cognitive resources available for detecting unexpected threats.

Research consistently demonstrates that the approach and landing phases are associated with some of the highest workload levels encountered during flight operations (Kaber & Endsley, 2004). When nighttime conditions, traffic complexity, communication demands, and visual separation responsibilities are added, cumulative workload may approach or exceed available cognitive capacity.

The reassignment of Flight 5342 to a nighttime circling approach therefore introduced an additional layer of cognitive complexity into an already demanding operational environment. Rather than focusing solely on aircraft control and approach stabilization, the crew was required to continuously integrate runway acquisition, visual navigation, traffic monitoring, communication management, and aircraft configuration tasks. Such competing demands likely reduced the cognitive resources available for unexpected threat detection.

The DCA accident should therefore not be interpreted as the consequence of a single perceptual failure. Rather, it reflects the interaction of expectation bias, selective attention, predictive cognition, inattentional blindness, visual perception limitations, and elevated workload operating simultaneously under conditions of uncertainty and environmental complexity. The accident demonstrates that collision avoidance depends not only on whether a threat is visible but also on how pilots perceive, interpret, anticipate, and cognitively integrate information within a dynamic operational environment. In this sense, the collision represents a failure of perception, prediction, attention, and cognitive integration rather than a simple failure to see another aircraft.

10.5. The Failure of See-and-Avoid

The principle of *See-and-Avoid* has historically served as one of the fundamental safety barriers against mid-air collisions, particularly during Visual Flight Rules (VFR) operations and pilot-maintained visual separation procedures. At its core, the concept assumes that pilots can visually acquire conflicting traffic and execute timely avoidance manoeuvres before a hazardous convergence develops. However, an expanding body of evidence from aviation psychology, cognitive science, and human factors research demonstrates that this assumption is fundamentally constrained by the physical characteristics of collision geometry, the biological limitations of human vision, and the cognitive architecture underlying attention and perception (Morris, 2005; Wickens & Hollands, 2000).

Contemporary literature increasingly argues that successful visual traffic acquisition is not merely a matter of eyesight but rather the outcome of a complex sequence of cognitive operations involving visual search, selective attention, object recognition, expectation management, predictive processing, and decision-making. Failures at any stage of this sequence may result in an otherwise visible aircraft remaining cognitively undetected. Importantly, these limitations become substantially amplified under conditions of elevated workload, distraction, visual clutter, and when conflicting traffic does not conform to the operator's expectations (White & O'Hare, 2021; Zivony & Eimer, 2022).

The collision between PSA Airlines Flight 5342 and the U.S. Army UH-60L Black Hawk helicopter near Ronald Reagan Washington National Airport (DCA) illustrates these limitations in a real-world operational setting. According to the National Transportation Safety Board (NTSB, 2026), the helicopter crew accepted responsibility for maintaining visual separation after reporting traffic in sight. Nevertheless, the subsequent collision demonstrates that the successful application of See-and-Avoid requires considerably more than simply having an unobstructed line of sight. Detection, identification, interpretation, prediction, and decision-making constitute an integrated cognitive process, each stage of which may fail under conditions of operational complexity and uncertainty.

Morris (2005) argued that the See-and-Avoid concept possesses "striking physical and behavioral limitations." In a classic constant-bearing collision geometry, the conflicting aircraft remains relatively small, exhibits minimal apparent lateral movement across the observer's visual field, and often blends into the surrounding background until only seconds before impact. Because the human visual system relies heavily on relative motion to attract attention, such trajectories inherently reduce the likelihood of successful threat detection. Moreover, Morris' modelling studies demonstrated that detection-and-avoid performance deteriorates rapidly as aircraft speed increases. At a closure speed of approximately 300 knots, a realistically scanning pilot who devotes only one-third of visual attention to external traffic may successfully avoid a converging aircraft in only about 16% of encounters. These findings suggest that the limitations of See-and-Avoid are rooted not merely in operator error but also in the physical constraints imposed by high-speed aviation environments.

Subsequent research has reinforced this conclusion. Reviews focusing on both manned and unmanned aviation systems have consistently identified visual sensing and distance estimation limitations as major obstacles to the reliable implementation of See-and-Avoid strategies (McFadyen & Mejias, 2015; Skowron et al., 2019). Even under ideal environmental conditions, accurately detecting, identifying, and predicting the future trajectory of another aircraft remains an inherently difficult perceptual task. In dense terminal airspace, where multiple aircraft operate simultaneously and closure rates are high, these difficulties become even more pronounced.

Beyond the physiological limits of vision, contemporary cognitive research emphasizes the critical role of attention. Inattentional blindness refers to the phenomenon whereby clearly visible but unexpected objects remain unnoticed because attentional resources are allocated elsewhere (Mack & Rock, 1998). Experimental studies have repeatedly demonstrated this effect in realistic operational contexts. White and O'Hare (2021) showed that inattentional blindness can occur in flight simulation environments, while studies in applied transportation settings indicate that dual-task conditions substantially narrow effective visual search behaviour and increase the likelihood of missing hazards (Recarte & Nunes, 2003; Wiczorek & Protzak, 2022). These findings are particularly relevant to aviation because pilots rarely perform visual scanning as an isolated task; rather, they simultaneously manage aircraft control, navigation, communications, checklist execution, and traffic monitoring.

The DCA accident occurred under precisely such circumstances. The NTSB investigation indicates that the CRJ700 crew was conducting a nighttime circling approach to Runway 33 while simultaneously managing aircraft configuration changes, runway acquisition, communication tasks, and external traffic monitoring (NTSB, 2026). Concurrently, the helicopter crew was responsible for maintaining visual separation while operating within a highly complex mixed civil-military traffic environment. Under these conditions, attentional resources were necessarily divided among multiple competing tasks, increasing susceptibility to inattentional blindness and failures of visual acquisition.

Closely related to attentional limitations is the role of expectation and predictive cognition. Modern theories of visual cognition argue that perception is fundamentally predictive; the brain continuously generates expectations regarding future events and interprets incoming sensory information through the lens of these expectations (Summerfield & Egner, 2009). Although predictive processing generally improves efficiency by reducing ambiguity, it may also bias perception away from unlikely or unexpected events. Zivony and Eimer (2022) introduced the concept of "expectation-based blindness," demonstrating that even attended targets may fail to reach conscious awareness when they violate existing expectations about what should appear in the environment.

Recent predictive-processing research further suggests that violations of expected task difficulty interact with attentional control mechanisms and distractor salience, slowing responses and degrading visual search performance (Ozsu & Urgen, 2024). In aviation contexts, these findings imply that pilots may preferentially allocate attention toward anticipated traffic locations while under-sampling areas considered less relevant or less likely to contain hazards.

Wickens et al. (2001) similarly proposed that pilot visual scanning behaviour is driven by both expectancy and the perceived value of available information channels. Pilots actively direct their gaze toward locations where they anticipate important operational events, meaning that traffic which falls outside these expected patterns may receive insufficient attentional sampling. From this perspective, the DCA collision may not simply represent a failure to see another aircraft, but rather a failure of predictive attention in which visual resources were allocated according to an incomplete or inaccurate mental representation of the surrounding traffic picture.

The operational environment itself further compounds these vulnerabilities. Complex and visually crowded scenes reduce an operator's capacity to suppress irrelevant stimuli, increasing the likelihood that critical hazards will be overlooked (Matias et al., 2021). The DCA accident occurred against the backdrop of a densely illuminated urban environment, where airport lighting systems, city lights, roadway traffic, and reflections along the Potomac River collectively created substantial visual clutter (NTSB, 2026). Such conditions reduce the salience of aircraft lighting cues and complicate the discrimination of relevant traffic from background stimuli.

Research on visual approaches similarly demonstrates that accident sequences frequently emerge under conditions characterized by elevated task saturation, degraded visual awareness, visual illusions, and fatigue (Misra, 2020). Within such environments, theoretical constructs such as change blindness and inattentional blindness become operationally significant because they directly influence the probability that pilots will detect and correctly interpret conflicting traffic.

Taken together, the contemporary literature suggests that the See-and-Avoid principle should not be regarded as a fully reliable collision avoidance mechanism in complex terminal environments. Rather than representing a simple sensory task, visual traffic acquisition emerges from the interaction of physical collision geometry, biological limitations of human vision, selective attention, predictive cognition, expectation, workload, and environmental complexity. The DCA collision illustrates that even highly trained and motivated flight crews may fail to detect conflicting traffic when these factors converge. Consequently, modern aviation safety increasingly requires collision avoidance strategies that complement, rather than rely exclusively upon, the inherent limitations of human visual and cognitive performance.

10.6. Workload, Stress, and Decision Making

The collision between PSA Airlines Flight 5342 and the U.S. Army UH-60L Black Hawk helicopter demonstrates that workload, stress, and decision-making are not isolated psychological constructs but deeply interconnected elements of aviation safety. In modern human factors theory, workload is understood not simply as the quantity of work assigned to an operator but as the dynamic relationship between task demands, available cognitive resources, environmental complexity, uncertainty, and time pressure (Wickens, 2008). In both air traffic control and flight operations, excessive workload directly influences attention allocation, situational awareness, communication quality, task prioritization, and ultimately the ability to recognize and mitigate emerging hazards.

Recent research increasingly identifies workload escalation, time pressure, and stress as some of the most significant human-factor risks in terminal airspace operations. Studies involving both pilots and air traffic controllers consistently demonstrate that elevated mental workload degrades operational performance, alters attentional strategies, and reduces situational awareness, thereby increasing the probability of human error and safety-critical events (Masi et al., 2023; Mohan et al., 2024; Alaydi & Ng, 2024). Rather than resulting from isolated individual mistakes, many aviation accidents emerge when operational demands exceed the cognitive capacity of otherwise highly skilled professionals.

The DCA accident occurred within precisely such an environment. According to the NTSB investigation, controllers and flight crews were simultaneously required to manage dense traffic flows, mixed fixed-wing and helicopter operations, multiple communication exchanges, nighttime conditions, and rapidly evolving aircraft trajectories (NTSB, 2026). Consequently, the accident should be interpreted not simply as a procedural failure but as a case illustrating how excessive cognitive demand can degrade human performance within a complex socio-technical system.

10.6.1 ATC Workload Escalation

Air traffic controller workload is shaped by numerous interacting factors, including traffic density, traffic complexity, communication load, runway configuration, sector design, coordination requirements, weather conditions, and staffing levels. Contemporary workload research increasingly argues that traffic volume alone provides an insufficient explanation of controller workload. Rather, workload emerges through the interaction of operational complexity, communication demands, uncertainty, and human-centered factors (Suárez et al., 2024).

The DCA accident sequence illustrates this principle clearly. Although traffic volume itself was manageable, the simultaneous management of commercial airline traffic and military helicopter operations within a constrained terminal environment substantially increased cognitive demand. According to the NTSB investigation, the controller was responsible for monitoring converging aircraft trajectories, managing runway operations, issuing traffic advisories, maintaining communication across multiple aircraft categories, and anticipating future traffic interactions (NTSB, 2026). These concurrent demands fragmented available attentional resources and increased the complexity of maintaining an accurate operational picture.

Recent survey and simulator studies further demonstrate that subjective and objective measures of mental workload predict controller performance more accurately than aircraft count alone (Alaydi & Ng, 2024). Operational complexity, communication density, and uncertainty frequently produce workload peaks that are not adequately reflected by traditional traffic metrics. This finding is particularly relevant to the DCA accident because the principal challenge did not arise solely from the number of aircraft but from the interaction between mixed traffic types, compressed sequencing, communication requirements, and the necessity to continuously project future aircraft trajectories.

Moreover, workload escalation exhibits nonlinear characteristics. Small increases in operational complexity may generate disproportionately large increases in cognitive demand once available mental resources approach their limits (Wickens, 2008). Under such conditions, controllers possess less spare capacity for anticipation, error detection, and proactive conflict management. Contemporary neuroergonomic research supports this interpretation by demonstrating that elevated controller workload can be detected through physiological indicators such as electroencephalography (EEG) and is associated with measurable reductions in operational efficiency and conflict detection capability (Li et al., 2022; Shao et al., 2024).

10.6.2 Time Pressure and Decision Quality

Time pressure represents one of the defining characteristics of terminal airspace operations. Controllers and pilots must frequently make decisions under conditions in which available information is incomplete and the opportunity for intervention rapidly diminishes. Decision quality under such circumstances depends heavily upon situational awareness, expertise, mental models, and the ability to rapidly prioritize competing demands (Orasanu & Connolly, 1993; Klein, 1998).

During the DCA accident sequence, the available window for effective intervention narrowed considerably as the CRJ700 and UH-60L converged. Under severe time constraints, decision-making increasingly shifts from deliberate analytical reasoning toward recognition-primed strategies, whereby operators rely on previously acquired experience and pattern matching (Klein, 1998). Although this approach often supports effective performance in dynamic environments, it may also increase susceptibility to incomplete information integration and premature closure when the operational picture is ambiguous.

Evidence from pilot populations similarly suggests that increasing mental workload exerts a small but statistically significant negative influence on decision quality (Mohan et al., 2024). While some aspects of perceived task performance may remain stable, overall cognitive load reduces the capacity for careful evaluation and increases dependence upon heuristic processing. Within the DCA context, both controllers and flight crews were required to interpret rapidly changing traffic relationships under considerable uncertainty, making them particularly vulnerable to these effects.

The NTSB investigation identified the absence of timely safety alerts and incomplete traffic advisories as important components of the accident sequence

(NTSB, 2026). From a cognitive perspective, these findings suggest that the operational environment constrained the transition from routine monitoring to decisive intervention. Operators may continue to manage evolving situations procedurally while failing to recognize that a critical threshold requiring immediate corrective action has already been crossed.

10.6.3 Cognitive Overload and Task Prioritization

Cognitive overload occurs when operational demands exceed the cognitive resources available to the operator. Importantly, overload does not necessarily result in a complete performance breakdown. More commonly, operators adapt by simplifying the environment, prioritizing immediate tasks, postponing less salient activities, and selectively processing information (Hockey, 1997; Wickens et al., 2015). Although these strategies often preserve short-term operational continuity, they may simultaneously reduce sensitivity to emerging threats.

Task prioritization is therefore fundamental to air traffic control performance. Controllers must continuously determine which aircraft, communication exchange, or operational issue requires immediate attention. However, under conditions of excessive workload, prioritization increasingly favors the most immediate or visually salient demands, potentially leaving less obvious hazards insufficiently monitored.

The DCA operational environment created these conditions precisely. The combination of mixed helicopter and fixed-wing operations, combined control responsibilities, communication activity, runway management, and compressed sequencing generated a cognitively demanding environment in which task prioritization became increasingly difficult (NTSB, 2026). The controller was required to manage ongoing traffic flow while simultaneously monitoring a developing conflict. Under such circumstances, cognitive resources may become focused on maintaining current operations rather than anticipating future hazards.

Research further indicates that workload alters operators' subjective perception of time. Balta et al. (2023) demonstrated that controllers operating during high-workload landing phases systematically overestimated elapsed time, perceived time as passing more rapidly, and exhibited physiological indicators associated with elevated arousal. These temporal distortions may encourage reactive rather than anticipatory operational behaviour, reducing opportunities for proactive conflict resolution.

Mental workload and situational awareness are also closely interconnected. Eye-tracking studies have demonstrated that increasing task complexity alters gaze allocation patterns, increases cognitive load, and reduces situational awareness during radar monitoring tasks (Yiu et al., 2025). Similarly, EEG and eye-tracking investigations have identified distinct neurophysiological signatures associated with the loss of situational awareness under high-workload conditions and have successfully classified low-SA states using machine-learning approaches (Li et al., 2022). These findings suggest that cognitive overload directly interferes with the operator's ability to continuously update and maintain an accurate mental representation of the traffic picture.

Working memory limitations further contribute to this process. Controllers and pilots must continuously retain and update information concerning aircraft positions, altitudes, headings, clearances, intentions, and future trajectories. As working memory approaches saturation, the ability to integrate information and project future system states deteriorates. Consequently, overload directly compromises the projection component of situational awareness described by Endsley (1995).

10.6.4 Stress Effects on Human Performance

Although closely related to workload, stress represents a distinct construct reflecting the psychological and physiological response to perceived demands, uncertainty, responsibility, and potential threat (Lazarus & Folkman, 1984). In aviation environments, stress may emerge from time pressure, ambiguous information, conflicting operational priorities, and the recognition that errors may carry catastrophic consequences.

The relationship between stress and performance follows a nonlinear pattern. Moderate levels of activation may enhance alertness and task engagement, whereas excessive stress impairs attention flexibility, working memory, communication, and decision-making. One important consequence of stress is attentional narrowing, sometimes referred to as cognitive tunneling, in which operators become excessively focused on a limited subset of available information while neglecting other relevant cues (Wickens et al., 2015).

Within the DCA accident context, both controllers and pilots were operating under conditions requiring rapid interpretation of uncertain information while managing dense traffic and maintaining visual separation. Such circumstances likely increased psychological stress and encouraged greater reliance on dominant cognitive strategies rather than flexible information processing. Research examining decision-making under stress suggests that these conditions reduce cognitive flexibility and increase dependence upon habitual response patterns (Starcke & Brand, 2012).

Interruptions further exacerbate these effects. Experimental studies involving simulated landing sequencing and conflict resolution tasks have demonstrated that interruptions occurring under time pressure significantly reduce situational awareness, particularly when interruption modality matches the primary task (e.g., visual interruptions during visually demanding tasks) (Zhou et al., 2024). Such interruptions consume available cognitive resources and impair the operator's ability to maintain continuous updating of the traffic situation.

Recent survey data further indicate that traumatic experiences combined with ongoing workload significantly reduce situational awareness among air traffic controllers (Sonhaji et al., 2024). Fatigue, which often coexists with stress and workload, further amplifies these effects by degrading vigilance, reducing attentional control, and increasing susceptibility to error (Masi et al., 2023).

10.6.5 Missed Opportunities for Intervention

A missed opportunity for intervention occurs when a system contains sufficient information to support corrective action, yet that information is not recognized, prioritized, communicated, or acted upon before the situation becomes unrecoverable. In complex aviation accidents, such failures rarely reflect complete ignorance of the situation. Rather, they emerge because relevant information is distributed across individuals, technologies, and communication channels without being integrated into a sufficiently urgent shared understanding.

The DCA accident illustrates this phenomenon. Multiple indicators of developing risk were present within the operational system, including converging trajectories, dependence upon visual separation, communication complexity, and elevated workload (NTSB, 2026). Nevertheless, the accident sequence progressed without effective intervention sufficient to prevent collision.

Emerging evidence suggests that mental overload and attentional entropy represent relatively rare but highly consequential operational states. Survey studies among professional controllers indicate that these conditions are perceived primarily as safety threats because they increase susceptibility to inattentional blindness and failures to recognize critical cues (Migliorini et al., 2022). Similarly, research involving student air traffic controllers demonstrates that escalating workload progressively increases the frequency of situational awareness losses, delayed responses, and separation-related errors (Pilmannová et al., 2023).

From a human factors perspective, missed interventions are closely linked to situational awareness, workload, stress, and decision thresholds. Operators may perceive isolated cues but fail to integrate them into a coherent understanding requiring immediate action. Alternatively, they may recognize some degree of risk but continue relying on existing assumptions because the situation has not yet crossed their subjective threshold for intervention.

Importantly, intervention should be viewed as a system-level function rather than merely an individual responsibility. Controllers, pilots, supervisors, operational procedures, technological systems, and organizational safety cultures collectively determine whether emerging hazards are recognized and mitigated. When workload is excessive, communication is fragmented, and responsibility is distributed across multiple actors, the probability of delayed or missed intervention increases substantially.

Recent research also suggests that the adverse effects of workload are not inevitable. Mindfulness and social support have been shown to buffer the negative relationship between workload and operational performance among air traffic controllers, reducing performance degradation under demanding conditions (Alaydi & Ng, 2024). Situation-awareness prompts embedded within automated ATC systems appear capable of attenuating workload spikes following automation failures (Kim et al., 2022), while emerging Controller Resource Management approaches emphasize teamwork, communication, and shared cognition as mechanisms for reducing cognitive overload in future terminal and tower operations (Miller & Holley, 2021).

Therefore, the principal lesson of the DCA accident is not simply that an individual operator should have acted differently. Rather, the accident demonstrates that increasingly complex terminal airspace systems must be designed to support timely intervention under conditions of workload, uncertainty, and stress. Effective staffing policies, fatigue-risk management, robust communication structures, real-time decision support systems, Threat and Error Management (TEM) training, and organizational cultures that explicitly recognize workload as a central determinant of safety are essential for enhancing resilience in modern aviation systems.

10.7. Organizational Influences on Human Performance

The DCA mid-air collision demonstrates that aviation accidents cannot be fully understood through the actions of frontline operators alone. Contemporary safety science increasingly recognizes that human performance is shaped by organizational structures, management practices, safety culture, resource allocation decisions, training systems, supervisory processes, and organizational learning mechanisms long before an accident becomes visible at the operational level (Reason, 1997; Leveson, 2012; Dekker, 2014). Consequently, modern accident investigations rarely attribute catastrophic events solely to pilot or controller error. Instead, they seek to identify the latent organizational conditions that create the context within which frontline decisions are made.

A growing body of empirical evidence supports this perspective. Across flight operations, maintenance activities, and ground handling environments, research consistently demonstrates that the majority of accident-contributing factors originate at the organizational level rather than at the level of individual operators. In a recent multi-case analysis of aviation accidents, No and Cha (2025) reported that approximately 87% of identified contributing factors were organizational in nature, including deficiencies related to human resource management, supervision, operational processes, and organizational culture, whereas only 13% were directly attributable to individual or task-level factors. These findings reinforce the argument that frontline performance often reflects deeper systemic influences rather than isolated human shortcomings.

The DCA accident reflects many of these characteristics. Although the final collision occurred between two aircraft crews operating within a complex terminal environment, the NTSB investigation identified multiple organizational deficiencies involving both the Federal Aviation Administration (FAA) and the U.S. Army. The report highlighted shortcomings in safety risk management, safety assurance, safety data utilization, organizational communication, and hazard identification processes. Importantly, these deficiencies existed long before the accident occurred and influenced how risk was managed on a daily basis (NTSB, 2026).

Research examining aviation accidents through the Human Factors Analysis and Classification System (HFACS) framework has repeatedly demonstrated that organizational influences exert a significant indirect effect on frontline unsafe acts. Studies of both commercial and general aviation accidents have identified statistically significant relationships between organizational factors, supervisory deficiencies, adverse preconditions, and operational errors committed by frontline personnel (Li et al., 2008; Dönmez & Uslu, 2018). These findings suggest that unsafe acts should not be viewed as independent causes of accidents but rather as the final manifestations of systemic weaknesses distributed throughout the organizational hierarchy.

One of the most consistent findings within the aviation safety literature concerns the role of inadequate procedures, unclear objectives, and ineffective documentation. Analyses of commercial aviation accident databases indicate that procedural deficiencies represent some of the most frequently occurring organizational contributors to adverse events (Von Thaden et al., 2006). When procedures are unclear, difficult to apply, or insufficiently aligned with operational realities, frontline personnel inevitably develop local adaptations to accomplish their tasks. While such adaptations may initially improve efficiency, they can gradually alter the balance between safety and production pressures.

This phenomenon is closely related to the concept of normalization of deviance. Vaughan (1997) described how deviations from intended safety practices gradually become accepted as normal when they repeatedly occur without immediate negative consequences. In complex aviation environments, repeated exposure to operational conditions that appear successful despite reduced safety margins can create a false perception that existing practices are safe. Over time, organizations become less sensitive to warning signals because routine success masks underlying vulnerabilities. The DCA operational environment exhibited several characteristics consistent with this process. The continued coexistence of high-density commercial traffic and military helicopter operations, combined with frequent reliance on visual separation procedures, may have contributed to a gradual organizational acceptance of risk conditions that were not fully appreciated until the accident occurred.

The NTSB investigation provides empirical evidence supporting this interpretation. As summarized in Table 4, multiple encounters involving commercial airplanes and helicopters were documented in the DCA terminal area between October 2021 and December 2024 through the Aviation Safety Information Analysis and Sharing (ASIAS) system. These events involved recurring operational concerns, including inadequate traffic separation, communication difficulties, helicopter altitude deviations, uncertainty during Runway 33 operations, and near mid-air collision scenarios. Importantly, many of these occurrences reflected safety concerns remarkably similar to those identified in the present accident. Rather than representing isolated operational anomalies, the accumulated reports suggest the existence of persistent systemic vulnerabilities that remained embedded within routine operations long before the fatal collision occurred (NTSB, 2026).

Table 4. Selected safety events involving commercial airplanes and helicopters in the DCA terminal area (October 2021–December 2024), illustrating recurring operational hazards identified through the ASIAS reporting system.

Lateral separation	Vertical seperation	Total # of events	Average # per month	% of all operations	% on arrival
<1 nm	<400 ft	15.214	390.1	1.6%	96%
<600 ft	<400 ft	210[a]	5.4	0.02%	99.5%
<1.500 ft	<200 ft	85[a]	2.2	0.004%	100.0%

Source: Adapted from National Transportation Safety Board (2026).

The literature further suggests that operational drift represents a natural consequence of organizational adaptation. According to Dekker (2014), organizations rarely fail because personnel intentionally violate procedures; rather, they drift toward the boundaries of safe performance through incremental adaptations designed to achieve operational goals under real-world constraints. In aviation, such drift often emerges through informal workarounds, local procedural modifications, and efficiency-oriented adjustments that allow operations to continue despite limitations in staffing, infrastructure, or procedures. The DCA case illustrates how operational pressures associated with runway utilization, traffic flow management, mixed aircraft operations, and capacity demands may gradually shape local practices in ways that increase system complexity and dependence upon human judgment.

Safety Management Systems (SMS) are intended to counteract these tendencies by providing structured mechanisms for hazard identification, risk assessment, safety assurance, and organizational learning. However, the effectiveness of SMS depends not on its formal existence but on its practical implementation. The NTSB investigation concluded that FAA safety management processes did not adequately identify or mitigate operational challenges associated with helicopter and fixed-wing interactions in the DCA airspace. Similarly, deficiencies within Army safety monitoring and reporting systems limited the organization's ability to identify recurring operational risks and altitude deviations before they contributed to the accident sequence (NTSB, 2026). These findings illustrate a critical distinction frequently emphasized within safety science: organizations may possess extensive safety documentation while simultaneously failing to transform safety information into effective risk controls.

Research focusing on general aviation organizations reaches similar conclusions. Xue and Fu (2018) found that weak or absent SMS implementation, inadequate organizational processes, and limited safety oversight represented major contributors to organizational vulnerability. Such findings are particularly important because they demonstrate that organizational deficiencies are not confined to large commercial operators but emerge across diverse aviation sectors whenever safety management processes fail to evolve alongside operational complexity.

Safety culture represents another critical dimension of organizational influence. Studies conducted within flight training organizations, airlines, and ground operations environments consistently associate accidents, incidents, and under-reporting behaviours with weak safety cultures characterized by poor communication, ineffective safety programs, limited professionalism, and insufficient management commitment to safety (Silcox et al., 2022). Similarly, analyses of airport ground operations have identified inadequate organizational and safety culture as significant contributors to operational accidents and incidents (Muecklich et al., 2023). These findings reinforce the notion that safety culture directly influences how organizations perceive risk, communicate concerns, and respond to emerging threats.

The relationship between safety culture and human performance becomes particularly evident when examining procedural non-compliance and decision-making errors. Kharoufah et al. (2018) reported that aviation accidents frequently involve decision errors, failures to adhere to procedures, and breakdowns in Crew Resource Management (CRM). Rather than viewing these events solely as individual shortcomings, the authors argued that they may reflect a gradual organizational tolerance for rule-bending behaviours. When deviations repeatedly produce acceptable outcomes, organizations may implicitly reinforce practices that progressively erode safety margins.

Historical analyses of major disasters further support this interpretation. Orr (2021) argued that many catastrophic accidents should be understood as organizational accidents rather than purely operational failures. Such events are frequently rooted in weak leadership commitment, inadequate supervision, ineffective training systems, and organizational structures that fail to prioritize safety over competing operational demands. Importantly, these accidents often become catalysts for cultural change precisely because they reveal latent vulnerabilities that had remained invisible during routine operations.

The DCA accident exhibits many of the characteristics associated with organizational accidents. Multiple weak signals existed prior to the collision, including known operational complexities, recurring interactions between helicopter and fixed-wing traffic, dependence on visual separation, and safety concerns identified through operational experience. However, these signals were not effectively integrated into a proactive organizational response. From a systems perspective, the collision therefore reflects not only the actions of controllers and pilots during the final moments of the event but also the cumulative effects of organizational decisions, supervisory practices, safety management deficiencies, and learning failures that evolved over time.

Ultimately, the DCA accident reinforces a central principle of contemporary safety science: human performance is shaped by organizational conditions long before an operator commits a visible error. Frontline personnel function within systems designed, managed, and governed by organizations. When safety culture weakens, deviations become normalized, operational drift remains unrecognized, safety management processes fail to identify emerging hazards, and organizations do not effectively learn from weak signals, frontline human performance becomes the final fragile barrier protecting the system from failure. Therefore, improving safety in complex terminal airspace environments requires not only enhancing individual competence but also strengthening organizational learning, safety culture, risk management, leadership commitment, and the capacity to identify and mitigate latent hazards before they manifest as accidents.

10.8. Accident Analysis Through Human Factors Frameworks

The collision between PSA Airlines Flight 5342 and the U.S. Army UH-60L Black Hawk helicopter near Ronald Reagan Washington National Airport represents a complex socio-technical failure that cannot be adequately explained through a single causal lens. Contemporary accident investigation research increasingly recognizes that aviation accidents emerge from interactions among human cognition, operational practices, technological systems, supervisory processes, organizational culture, and regulatory environments rather than from isolated errors committed by frontline operators. Consequently, modern safety science advocates the use of multiple complementary analytical frameworks to understand how accidents develop within complex systems (Reason, 1997; Leveson, 2012; Bills et al., 2023).

The DCA accident illustrates this principle particularly well. The collision involved issues related to visual separation, workload, communication, situational awareness, organizational safety management, military-civilian operational integration, and risk governance. No single framework fully captures all of these dimensions. Instead, the combined application of Reason's Swiss Cheese Model, Human Factors Analysis and Classification System (HFACS), Systems-Theoretic Accident Model and Processes (STAMP), and Threat and Error Management (TEM) provides a more comprehensive understanding of how multiple interacting failures aligned to produce the accident.

From a Swiss Cheese perspective, the accident can be interpreted as the alignment of multiple defensive failures across different organizational layers. Reason (1997) argued that accidents occur when weaknesses within successive safety barriers align, allowing hazards to penetrate the system. In the DCA case, several protective layers that should have prevented a collision were either weakened or bypassed. These included airspace design controls, risk assessment processes, controller monitoring functions, visual separation procedures, pilot traffic acquisition, communication safeguards, and organizational oversight mechanisms. The NTSB investigation identified deficiencies in FAA safety risk management, Army safety assurance processes, safety data utilization, and operational monitoring, suggesting that the accident was not solely the result of frontline actions but rather the culmination of latent organizational vulnerabilities that had accumulated over time (NTSB, 2026).

Contemporary accident research continues to support this interpretation. Reason-based models, including HFACS, ICAM, and Tripod, remain among the most widely applied frameworks in aviation investigations because they provide a structured approach for identifying both active failures and latent organizational conditions (Bills et al., 2023). HFACS, in particular, has become the most frequently used human factors taxonomy in aviation accident analysis because it explicitly links unsafe acts to supervisory influences, organizational processes, environmental factors, and preconditions for unsafe behavior (Wan et al., 2021; Nogueira et al., 2023). Applying this perspective to the DCA accident reveals how controller actions, pilot decisions, workload conditions, visual limitations, supervisory practices, and organizational safety deficiencies were interconnected rather than independent causal factors.

Within the HFACS framework, the collision can be understood as the interaction of active failures and latent conditions. Active failures included the unsuccessful maintenance of visual separation, limitations in traffic acquisition, incomplete conflict recognition, and missed opportunities for intervention during the final stages of the event. However, these visible actions occurred within a broader context shaped by latent organizational factors, including insufficient hazard identification, incomplete safety monitoring, procedural assumptions regarding visual separation, and inadequate integration of safety management processes. Research examining aviation accidents consistently demonstrates that organizational influences, supervisory deficiencies, and adverse operational preconditions significantly predict frontline unsafe acts (Li et al., 2008; Dönmez & Uslu, 2018). Thus, the actions observed immediately before the collision should be viewed as symptoms of deeper systemic weaknesses rather than independent causes.

Although Swiss Cheese and HFACS provide valuable explanations regarding barrier failures and organizational influences, they offer limited insight into how complex socio-technical interactions evolve dynamically over time. For this reason, STAMP provides an important complementary perspective. Developed by Leveson (2012), STAMP conceptualizes safety as a control problem rather than a component reliability problem. Accidents occur when safety constraints are inadequately enforced within hierarchical control structures, allowing unsafe system states to emerge. Rather than focusing primarily on human error, STAMP examines how interactions among regulators, organizations, managers, procedures, technologies, and operators shape system behavior.

From a STAMP perspective, the DCA accident reflects failures in safety control and feedback mechanisms operating across multiple organizational levels. The FAA, Army aviation authorities, local air traffic facilities, operational supervisors, controllers, and flight crews each represented components within a larger control structure intended to maintain safe separation between aircraft. The NTSB findings indicate that risk information regarding helicopter operations, altitude deviations, traffic interactions, and collision hazards was not consistently transformed into effective safety constraints or organizational action (NTSB, 2026). Consequently, the accident can be interpreted as a breakdown in safety control rather than merely a breakdown in operator performance.

Recent systematic reviews demonstrate that STAMP, AcciMap, and Functional Resonance Analysis Method (FRAM) are increasingly applied to aviation accidents because they capture organizational complexity, control flaws, and interactions between system components more effectively than traditional linear models (Patriarca et al., 2022; Delikhoon et al., 2022). Furthermore, integrated Swiss Cheese–STAMP analyses have shown that failures in engineering, training, regulatory oversight, and organizational governance frequently align with frontline operational errors to produce catastrophic outcomes (David et al., 2026). This interpretation is particularly relevant to the DCA accident, where organizational risk management, operational procedures, staffing decisions, and visual separation practices collectively shaped the environment in which controllers and pilots operated.

Threat and Error Management (TEM) provides an additional layer of understanding by focusing on how operational threats and human errors are managed in real time. Unlike Swiss Cheese and STAMP, which emphasize organizational structures and systemic interactions, TEM examines how operators detect, respond to, and recover from threats during ongoing operations. Within the DCA accident sequence, multiple operational threats were present, including nighttime operations, mixed fixed-wing and helicopter traffic, visual separation requirements, high workload, communication complexity, and compressed decision-making timelines. These threats increased the probability of operational errors and created conditions under which undesired aircraft states could emerge.

A TEM analysis suggests that the collision did not result from a single error but from the accumulation of unmanaged threats and ineffective recovery opportunities. The system remained dependent upon the successful adaptation of controllers and pilots to increasingly complex conditions. Recent research integrating TEM with Safety-II perspectives argues that the same adaptive processes that usually enable safe operations may contribute to failure when workload, organizational pressures, and competing operational goals exceed available system capacity (Sharma et al., 2025). This perspective is particularly important because it shifts attention away from asking why operators failed and toward understanding why a system that normally functions successfully became unable to adapt effectively under specific circumstances.

The DCA accident also illustrates the increasingly recognized coupling between human and organizational factors. Contemporary human factors research emphasizes that individual performance cannot be separated from organizational and environmental context (Wan et al., 2021). Controllers and pilots operate within systems that shape workload, communication patterns, decision authority, procedural flexibility, and available safety margins. Neural-network analyses have demonstrated that human-factor variables remain among the strongest predictors of fatal accident outcomes, while simultaneously highlighting the influence of organizational context on human performance (Lázaro et al., 2024; Nogueira et al., 2023).

This perspective is especially relevant in the context of air traffic control. Recent research examining loss-of-separation events indicates that controllers frequently shift operational priorities from efficiency toward safety when conflicts emerge. However, nearly half of these goal-transition interactions are suboptimal, affecting communication quality, workload management, and coordination effectiveness during developing hazards (Gyles & Bearman, 2025). Such findings align closely with the DCA accident sequence, where the system increasingly relied upon controller judgment, adaptive expertise, and real-time problem solving under conditions characterized by uncertainty and elevated cognitive demand.

The growing integration of conceptual and quantitative accident models further reinforces the systemic nature of aviation safety. Recent studies have converted Swiss Cheese and HFACS frameworks into probabilistic and predictive tools capable of estimating accident likelihood and evaluating the effectiveness of alternative safety interventions (Koshekov et al., 2025). Similarly, hybrid HFACS–system dynamics approaches have demonstrated how organizational feedback loops, supervisory practices, and safety interventions influence accident trends over time (Wu et al., 2023). Systematic reviews increasingly conclude that the most promising future direction for accident investigation lies in combining traditional human factors frameworks with predictive analytics, Bayesian modeling, and machine-learning approaches (Vargová et al., 2025).

Viewed through these complementary frameworks, the DCA accident emerges not as the consequence of a single mistake but as the product of interacting human, technological, organizational, and regulatory factors operating within a complex socio-technical system. Swiss Cheese and HFACS reveal how active failures aligned with latent organizational weaknesses. STAMP highlights deficiencies in safety control, feedback, and risk governance. TEM explains how operational threats accumulated and exceeded the adaptive capacity of frontline operators. Together, these frameworks demonstrate that aviation accidents rarely result from isolated human error; rather, they emerge when multiple defensive layers, organizational processes, and adaptive mechanisms fail simultaneously. Consequently, the primary lesson of the DCA collision is that sustainable aviation safety depends not only on improving individual performance but also on strengthening the organizational, technological, and regulatory systems that shape human behavior long before an accident occurs.

10.9. Historical Comparisons

The collision between PSA Airlines Flight 5342 and the U.S. Army UH-60L Black Hawk helicopter is often perceived as a contemporary accident occurring within a technologically advanced aviation system. However, when examined through the lens of aviation safety history, the event reveals striking similarities to earlier accidents involving air traffic control, collision avoidance, communication breakdowns, and organizational deficiencies. Despite substantial technological progress, sophisticated surveillance systems, increasingly formalized Safety Management Systems (SMS), and decades of regulatory development, many of the underlying human and organizational factors observed in historical accidents continue to reappear in contemporary aviation systems.

This persistence raises an important question: why do similar failures continue to emerge despite continuous improvements in technology and regulation? Contemporary safety science increasingly argues that aviation accidents should not be understood as isolated failures of individual operators but as manifestations of systemic interactions occurring across people, technologies, organizations, and regulatory structures (Leveson, 2012; Dekker, 2014). Consequently, the recurrence of similar accident patterns reflects not the failure of a particular individual or technology but the enduring complexity of socio-technical systems.

The DCA collision exhibits notable parallels with the 2002 Überlingen mid-air collision involving a DHL Boeing 757 and a Bashkirian Airlines Tupolev Tu-154 over southern Germany. Although separated by more than two decades and differing operational contexts, both accidents involved breakdowns in separation assurance, communication challenges, conflicting expectations, and the interaction between human decision-making and organizational conditions. In the Überlingen accident, a reduced staffing configuration, maintenance activities affecting warning systems, delayed conflict recognition, and communication challenges contributed to a situation in which controllers and pilots were forced to make time-critical decisions under uncertainty. Similarly, the DCA accident occurred within an environment characterized by high operational complexity, workload demands, reliance on visual separation, and limitations in organizational risk management. In both cases, the visible actions of frontline operators represented only the final stage of a longer chain of systemic vulnerabilities.

The DCA accident also shares important characteristics with more recent runway and traffic conflict events occurring within increasingly congested terminal environments. The LaGuardia accident and other contemporary incidents have highlighted the growing importance of workload management, communication quality, situational awareness, and organizational resilience in preventing accidents within high-density airspace systems. Although the specific operational details differ, these events collectively demonstrate that aviation safety challenges increasingly emerge from interactions among multiple system components rather than from isolated technical failures.

A review of accident investigation literature reveals several recurring human factors themes across major aviation accidents. Among the most consistent findings is the central role of human performance limitations. Human factors continue to contribute to the majority of aviation accidents across commercial, military, general aviation, and ground operations sectors. Recent studies estimate that approximately 70–80% of aviation accidents involve significant human-factor components, making human performance one of the most persistent contributors to operational risk (Kharoufah et al., 2018; Muecklich et al., 2023). Importantly, contemporary research increasingly emphasizes that so-called "human error" should not be interpreted as a root cause but rather as a symptom of deeper systemic weaknesses (Uzun et al., 2025; Clarke, 2025).

This perspective aligns closely with the findings of the DCA investigation. Throughout the accident sequence, controller workload, pilot visual acquisition challenges, communication complexities, and decision-making demands played important roles. However, the NTSB investigation also identified deficiencies in safety management, hazard identification, organizational oversight, and risk assessment processes that existed independently of the individuals involved in the final event sequence (NTSB, 2026). Similar patterns have been observed in numerous historical accident investigations, reinforcing the conclusion that human performance is strongly shaped by organizational context.

Organizational influences represent another recurring theme across aviation accidents. Research examining accident causation through frameworks such as HFACS consistently demonstrates that inadequate supervision, ineffective safety oversight, weak organizational processes, and insufficient resource management create conditions that increase the likelihood of operational errors (Wang et al., 2022; Li et al., 2008). These organizational deficiencies often remain latent for extended periods because they rarely produce immediate negative consequences. Instead, they gradually shape operational environments, influencing how personnel perceive risk, allocate attention, and make decisions.

The DCA accident reflects many of these characteristics. The NTSB identified shortcomings in FAA safety risk management processes and Army safety assurance activities, indicating that opportunities to identify and mitigate hazards existed long before the collision occurred (NTSB, 2026). Similar organizational patterns have been documented across historical accident investigations, suggesting that deficiencies in organizational learning and risk governance remain persistent challenges despite advancements in safety management practices.

Safety culture represents a particularly important recurring theme. Studies conducted across airlines, flight training organizations, maintenance operations, and airport environments consistently associate weak safety culture with increased accident risk, under-reporting of hazards, ineffective communication, and inadequate implementation of safety programs (Silcox et al., 2022; Muecklich et al., 2023). When safety culture weakens, organizations become less capable of detecting emerging hazards and less likely to respond effectively to warning signals. Consequently, risks that could otherwise be mitigated may gradually become normalized within everyday operations.

The concept of normalization of deviance provides an important explanation for why similar accident patterns continue to recur. As described by Vaughan (1996), repeated exposure to unsafe conditions without immediate adverse consequences can gradually transform deviations from intended procedures into accepted operational practices. Over time, organizations become accustomed to operating with reduced safety margins because previous outcomes appear successful. Clarke (2025) similarly argues that incremental declines in safety are often difficult to detect, allowing unsafe practices to become normalized despite formal regulatory oversight. This phenomenon helps explain why accident precursors frequently remain unnoticed even within highly regulated industries such as aviation.

Another recurring lesson concerns the limitations of technological and regulatory solutions. Historically, major improvements in aircraft design, navigation systems, surveillance technologies, and regulatory frameworks have significantly reduced accident rates. However, research suggests that once major technical failures are addressed, further safety improvements become increasingly dependent upon managing human and organizational factors rather than introducing additional technological safeguards (Kelly & Efthymiou, 2019). In other words, technological progress alone cannot eliminate risks that originate from decision-making, communication, organizational culture, supervision, or safety governance.

The DCA accident provides a contemporary example of this challenge. The aircraft involved were operating within an environment supported by advanced surveillance systems, sophisticated procedures, and established regulatory frameworks. Nevertheless, the collision occurred because safety depended not only upon technology but also upon the successful interaction of humans, procedures, organizations, and operational practices. Similar observations have emerged from studies of unmanned aircraft systems, remotely piloted aircraft operations, and modern commercial aviation environments, all of which demonstrate that human errors remain tightly coupled with technological, environmental, and managerial influences (Wu et al., 2023).

Recent accident research increasingly emphasizes the importance of viewing aviation systems as adaptive socio-technical systems. Controllers, pilots, supervisors, organizations, and technologies continuously adjust their behavior to balance safety, efficiency, capacity, and operational demands. In most situations, these adaptations contribute positively to system performance. However, under conditions of elevated workload, conflicting goals, uncertainty, or organizational pressure, the same adaptive mechanisms may produce unintended consequences. Research examining air traffic control operations indicates that controllers frequently shift priorities from efficiency toward safety when conflicts emerge, yet nearly half of these goal-transition processes are suboptimal, creating vulnerabilities in communication, coordination, and workload management (Gyles & Bearman, 2025). Such findings closely mirror the challenges observed during the DCA accident sequence.

Across the DCA, Überlingen, and other contemporary aviation accidents, several consistent lessons emerge. First, human performance remains a critical determinant of safety, but human error alone rarely explains accident causation. Second, organizational conditions—including safety culture, supervision, training, risk management, and learning processes—strongly influence frontline performance. Third, normalization of deviance and operational drift can gradually erode safety margins without triggering immediate warning signs. Fourth, technology and regulation, while essential, cannot fully compensate for weaknesses in organizational learning and safety culture. Finally, aviation safety increasingly depends upon understanding and managing the interactions among humans, technologies, organizations, and regulatory systems rather than focusing on individual actions in isolation.

Viewed through this historical lens, the DCA accident should not be interpreted as an isolated failure. Rather, it represents the latest manifestation of recurring socio-technical challenges that have appeared throughout aviation history. The persistence of these themes underscores a central lesson of contemporary safety science: sustainable safety improvement requires not only technological innovation and procedural compliance but also continuous attention to organizational learning, safety culture, human performance, and the complex interactions that shape behavior within modern aviation systems.

10.10. Lessons for Cognitive Performance in Air Traffic Control

The collision between PSA Airlines Flight 5342 and the U.S. Army UH-60L Black Hawk helicopter highlights a fundamental reality of modern air traffic management: aviation safety depends not only on technology, procedures, and regulatory compliance but also on the ability of human operators to sustain cognitive performance under conditions of uncertainty, complexity, and time pressure. Throughout the accident sequence, the interaction of workload, situational awareness, communication, visual perception, decision-making, and organizational influences demonstrated how even highly trained professionals may become vulnerable when operational demands approach the limits of human cognitive capacity. Consequently, the lessons derived from the DCA accident extend beyond the specific circumstances of the event and provide broader implications for supporting cognitive performance in air traffic control systems.

One of the most important lessons concerns the central role of situational awareness (SA). Situational awareness represents the foundation of effective air traffic control because it enables controllers to perceive relevant environmental information, comprehend its significance, and project future system states (Endsley, 1995). Numerous studies have demonstrated that degraded situational awareness is associated with operational errors, delayed conflict detection, and accident involvement. Chi et al. (2023) and Friedrich et al. (2018) emphasize that situational awareness remains one of the strongest determinants of safe and timely decision-making in aviation environments and that losses of situational awareness are implicated in a substantial proportion of aviation accidents. The DCA accident illustrates this challenge clearly. Controllers and flight crews were required to maintain awareness of multiple aircraft, changing trajectories, visual separation responsibilities, and future traffic interactions while simultaneously managing communication demands and operational constraints. As complexity increased, maintaining an accurate mental representation of the traffic picture became increasingly difficult.

Research further demonstrates that situational awareness and workload are inseparably linked. Experimental studies show that situational awareness tends to be highest under moderate workload conditions and deteriorates significantly when task demands exceed available cognitive resources (Chi et al., 2023). Similarly, Edwards et al. (2017) and Bongo and Seva (2021) found that workload and fatigue interact to produce compound effects on performance that are greater than the sum of their individual influences. These findings are particularly relevant in terminal environments such as DCA, where multiple aircraft interactions, communication requirements, and operational constraints frequently coexist. The accident therefore reinforces the need for proactive workload management rather than relying solely on controller expertise to compensate for increasing complexity.

Modern research suggests that controllers continuously adapt their cognitive strategies to maintain situational awareness under changing operational conditions. Eye-tracking studies demonstrate that controllers modify information-gathering strategies, gaze allocation patterns, and visual scanning behavior as workload, visibility, and traffic complexity increase (Yiu et al., 2025). Such adaptive behavior represents an important source of resilience within the air traffic system. However, the DCA accident also illustrates that adaptive strategies have limits. When task demands exceed available cognitive resources, even experienced controllers may become vulnerable to attentional narrowing, delayed conflict recognition, and incomplete integration of critical information.

The findings of the accident also highlight the importance of systematic workload monitoring and regulation. Traditional approaches often rely on subjective judgments regarding controller workload. However, contemporary workload research increasingly supports predictive and multimodal assessment approaches. Models such as COMETA have demonstrated the ability to estimate mental workload using traffic density, airspace complexity, and operational characteristics, allowing organizations to anticipate workload peaks before performance degradation occurs (Ibáñez-Gijón et al., 2023). Similarly, recent reviews emphasize the value of combining subjective measures such as NASA-TLX and Instantaneous Self-Assessment (ISA) with physiological indicators including EEG activity, heart-rate variability, skin conductance, and eye-tracking metrics to create more comprehensive assessments of controller cognitive state (Yazgan et al., 2021). Such approaches may offer opportunities for real-time detection of elevated workload and proactive intervention before safety margins are compromised.

Another major lesson concerns the importance of team cognition and communication resilience. Air traffic control is frequently described as an individual cognitive task; however, contemporary research increasingly emphasizes that safe performance emerges from distributed cognition shared across controllers, supervisors, pilots, technologies, and organizational structures. Expert analyses of performance-shaping factors consistently identify communication, teamwork, vigilance, attention, and situational awareness as among the most influential determinants of controller performance, with communication often emerging as the highest-priority factor (Bongo & Seva, 2023). In the DCA accident, multiple actors shared responsibility for maintaining safety, yet the effectiveness of the system ultimately depended on the successful exchange, interpretation, and integration of information across operational boundaries.

Research examining aviation risk management similarly emphasizes the importance of standard phraseology, effective coordination, and rapid communication during high-workload situations (Hoika & Korechi, 2024). Communication failures rarely occur because information is entirely absent; rather, they emerge because information is misunderstood, delayed, incompletely processed, or insufficiently integrated into operational decision-making. The DCA accident underscores this reality by demonstrating how communication quality and timing directly influence conflict recognition and intervention opportunities.

The concept of Controller Resource Management (CRM) offers an important framework for addressing these challenges. Building upon principles originally developed within Crew Resource Management, contemporary Controller Resource Management approaches emphasize teamwork, collaborative decision-making, communication quality, and shared situational awareness as mechanisms for reducing cognitive overload and enhancing system resilience (Milley & Holley, 2021). As air traffic systems become increasingly complex, the development of collective cognitive capabilities may prove as important as the enhancement of individual technical skills.

Psychological resilience represents another critical lesson emerging from both the accident and contemporary literature. Controllers routinely operate in environments characterized by uncertainty, time pressure, and high consequences for error. Under such conditions, resilience becomes essential for maintaining performance during periods of elevated stress. Research conducted within air traffic control populations demonstrates that cognitive flexibility is positively associated with psychological resilience and enables controllers to adapt more effectively to changing operational demands (Çeken, 2025). Individuals with greater cognitive flexibility appear better able to sustain performance under pressure, recover from unexpected events, and maintain effective decision-making despite uncertainty.

Similarly, recent studies indicate that mindfulness and perceived social support buffer the negative effects of workload on performance (Alaydi & Ng, 2024). These findings suggest that resilience should not be viewed solely as an individual characteristic but also as an organizational resource that can be developed through supportive work environments, effective leadership, and targeted training interventions. The DCA accident illustrates the importance of creating systems that support human performance rather than assuming that operators will consistently perform optimally under all conditions.

The accident also provides important lessons regarding training and competency development. Subject-matter experts consistently identify spatial visualization, oral expression, rapid reaction capability, auditory attention, self-control, and persistence among the most important abilities associated with successful controller performance (Roodbandi et al., 2025). These competencies extend beyond technical knowledge and reflect the complex cognitive and interpersonal demands of air traffic control. Importantly, recent evidence suggests that generic cognitive training interventions may have limited transfer to operational performance. Black et al. (2022) found that multitasking training improved performance within the training environment itself but did not significantly improve situational awareness, workload management, or performance in simulated air traffic control scenarios. This finding reinforces the importance of context-specific training that closely replicates operational conditions.

Simulation-based training therefore remains one of the most effective approaches for enhancing cognitive performance in air traffic control. Advanced simulation environments provide opportunities to develop communication skills, standard phraseology, conflict detection abilities, workload management strategies, and decision-making under stress within realistic operational contexts (Ziakkas et al., 2025). Such training allows controllers to experience rare but high-consequence scenarios that cannot be safely replicated in live operations while simultaneously strengthening cognitive resilience and adaptive expertise.

The growing integration of automation and artificial intelligence within air traffic management introduces additional opportunities and challenges for cognitive performance. Recent research examining digital "ATCO teammates" emphasizes the importance of establishing shared mental models and shared situational awareness between human operators and automated systems (Gerdes et al., 2025). Rather than replacing human decision-makers, future technologies are increasingly envisioned as cognitive partners capable of supporting workload management, conflict detection, and information integration. The effectiveness of these systems, however, will depend upon their ability to complement rather than disrupt human cognitive processes.

Finally, the DCA accident underscores the importance of proactive workload regulation and risk management. Emerging research suggests that workload can be estimated in real time using behavioral indicators derived from voice communications, operational data, and physiological measures (Muñoz-De-Escalona et al., 2025). Such systems may enable organizations to identify periods of elevated cognitive demand and redistribute tasks before performance degradation occurs. Risk management research similarly recommends structured workload regulation, stress-management programs, fatigue mitigation strategies, and recurrent emergency-response training as mechanisms for preserving attention, decision-making quality, and resilience in high-traffic environments (Hoika & Korechi, 2024).

Taken together, the lessons derived from the DCA accident reinforce a central principle of contemporary aviation human factors: maintaining safety in increasingly complex airspace systems depends on preserving cognitive performance under pressure. Situational awareness, workload management, communication resilience, team cognition, psychological resilience, and adaptive expertise should not be viewed as independent constructs but as interconnected components of a broader system supporting human performance. Future air traffic management systems will therefore require not only technological innovation but also organizational strategies, training approaches, and operational designs explicitly intended to strengthen the cognitive capabilities of the humans who remain at the center of aviation safety.

10.11. Implications for Future Air Traffic Management

The collision between PSA Airlines Flight 5342 and the U.S. Army UH-60L Black Hawk helicopter represents more than an isolated operational failure. Rather, it serves as a warning regarding the limitations of contemporary air traffic management systems that continue to rely heavily on human cognition as the final barrier against collision. Throughout the accident sequence, workload, visual separation, situational awareness, communication, organizational oversight, and risk management processes interacted in ways that exposed the vulnerabilities of a complex socio-technical system. Consequently, the lessons emerging from the DCA accident extend beyond local operational procedures and raise broader questions concerning the future design of air traffic management (ATM) systems.

Contemporary ATM research increasingly argues that future systems must be designed around human cognitive capabilities and limitations rather than assuming that human operators can continuously compensate for increasing operational complexity. Historically, advances in aviation safety have focused on improving technological reliability and procedural standardization. While these efforts have significantly reduced technical failures, accident investigations continue to demonstrate that many remaining risks originate from workload, communication failures, situational awareness degradation, decision-making limitations, and organizational deficiencies rather than equipment malfunction alone (Brooker, 2007). The DCA accident reflects this trend. Despite advanced surveillance technologies, established separation procedures, and regulatory oversight mechanisms, the system ultimately depended upon the successful cognitive performance of controllers and pilots operating under complex conditions.

A central implication for future ATM systems concerns the adoption of human-centered design principles. Human-centered ATM recognizes that operators are not merely users of technology but integral components of the safety system. Accordingly, technologies, procedures, interfaces, and airspace structures should be designed to support human cognition rather than increase cognitive burden. Research suggests that future ATM environments should explicitly aim to reduce information clutter, prevent cognitive overload, and enhance situational awareness through improved interface design, decision support systems, and adaptive workload management tools (Ortner et al., 2022). Such approaches align with the findings of the DCA accident, where operators were required to process multiple streams of information while maintaining awareness of complex and rapidly evolving traffic interactions.

The importance of situational awareness support is particularly evident. Studies indicate that approximately 85% of aviation accidents involve some form of situational awareness degradation, making SA one of the most critical determinants of safety performance (Gerdes et al., 2025). Future ATM systems must therefore move beyond simply providing information and instead support the continuous perception, comprehension, and projection of operational states. This requirement applies not only to human operators but also to emerging AI-enabled decision-support systems. As human-machine teaming becomes increasingly common, maintaining shared situational awareness between controllers and automated systems will become a fundamental design objective.

The DCA accident also highlights the limitations of visual separation as a primary safety barrier in increasingly complex terminal environments. For decades, visual separation and the See-and-Avoid principle have served as important operational tools for maintaining traffic flow and reducing controller workload. However, as discussed throughout this case study, extensive human factors research demonstrates that visual traffic acquisition is constrained by perceptual limitations, attentional resources, expectation bias, workload, and environmental complexity. In dense terminal airspace, these limitations become increasingly significant.

Future ATM systems must therefore move beyond exclusive reliance on visual separation and adopt multilayered collision avoidance architectures. Such architectures should integrate surveillance technologies, predictive conflict detection systems, automated alerts, trajectory-based operations, and collaborative decision-support tools. Rather than assuming that pilots or controllers will consistently detect and resolve conflicts through visual observation alone, future systems should proactively identify emerging hazards before they reach the limits of human perception. The DCA accident illustrates the potential consequences of a system that continues to rely heavily upon successful visual acquisition as a critical safety defense.

Artificial intelligence represents one of the most promising developments in this transition. Recent ATM research increasingly focuses on AI-supported decision aids capable of assisting controllers in monitoring traffic, predicting conflicts, managing workload, and identifying anomalous operational conditions. Importantly, these technologies are not intended to replace human decision-makers but rather to function as cognitive partners capable of augmenting human performance (Gerdes et al., 2025). This perspective is consistent with contemporary approaches to human-AI teaming, which emphasize complementary rather than competitive relationships between humans and automation.

Future AI-enabled systems may provide real-time conflict prediction, adaptive workload management, communication monitoring, weather hazard identification, and dynamic decision support. Research examining shared situational awareness between controllers and AI systems suggests that appropriately designed digital teammates can improve awareness and support decision-making without increasing workload (Gerdes et al., 2025; Yiu et al., 2022). Such capabilities are particularly relevant in complex terminal environments where multiple interacting traffic flows challenge human cognitive capacity.

Communication resilience constitutes another critical implication. Accident investigations repeatedly demonstrate that communication failures remain among the most persistent contributors to operational risk. The DCA accident, like many previous aviation accidents, illustrates that effective communication depends not only on message transmission but also on timing, interpretation, shared understanding, and coordination among multiple actors. Emerging digital communication technologies provide opportunities to strengthen this process.

Research examining Data Communications (Data Comm) systems suggests that digital communication technologies may reduce mid-air collision risk by approximately 25% by minimizing misunderstandings, reducing frequency congestion, and improving information consistency (Bauranov & Rakas, 2023). Such findings suggest that future ATM systems should combine traditional voice communication with intelligent communication-support technologies capable of monitoring phraseology, identifying ambiguities, and supporting communication quality assurance. Rather than replacing human communication, these systems may enhance communication resilience by providing additional safeguards against information loss and misunderstanding.

The DCA accident also underscores the importance of data-driven safety management. One of the most significant findings of contemporary safety research is that organizational factors frequently dominate accident causation, even though corrective actions often focus disproportionately on individual operators. Recent analyses suggest that approximately 87% of accident-contributing factors originate at the organizational level, including deficiencies related to supervision, organizational processes, safety culture, and risk management (No & Cha, 2025). These findings highlight the limitations of reactive safety approaches that focus primarily on operator behavior after accidents occur.

Future ATM systems must therefore embrace proactive, data-driven safety management strategies. Advances in artificial intelligence, natural language processing, Bayesian modeling, and ontological reasoning systems provide unprecedented opportunities for identifying emerging hazards before accidents occur (Insaurralde & Blasch, 2022). Safety reports, operational communications, traffic patterns, controller workload indicators, and incident databases can be integrated to support predictive risk assessment and real-time safety monitoring. Such capabilities would allow organizations to identify weak signals and latent hazards long before they develop into catastrophic failures.

The implementation of such data-driven safety management depends fundamentally on the availability and integration of multiple surveillance and aircraft-position data sources. Rather than relying on a single surveillance technology, contemporary ATM systems combine complementary tracking systems that differ in their operational purpose, positional accuracy, update rate, and coverage. Understanding these data sources is essential for appreciating how future decision-support systems can transform raw surveillance information into proactive safety interventions. Table 5 summarizes the principal aircraft position data systems discussed in the NTSB investigation and their respective operational characteristics (NTSB, 2026).

Table 5. Overview of aircraft position data systems supporting surveillance, aircraft tracking, and operational decision-making.

Name	Managing organization	Primary sources	Position data	Availability
Flight Operations and Quality Assurance (FOQA)	Operators	Aircraft data recorders	TCAS RAs and limited TCAS TAs	Operators, ASIAS
Automatic Dependent Surveillance–Broadcast (ADS-B)	FAA ATO	ADS-B squitter	TCAS RAs	FAA ATO, public

Aviation Risk Identification and Assessment (ARIA)	FAA ATO and ASIAS with contractor support	National Offload Program,148 radar, ADS-B	Aircraft proximities	FAA ATO, ASIAS, publicly available via open source software
Performance Data Analysis and Reporting System (PDARS)	FAA ATO with contractor support	National Offload Program, radar, ADS-B	Aircraft proximities	FAA ATO

Source: Adapted from National Transportation Safety Board (2026).

Equally important is the need to strengthen organizational learning. Traditional Safety-I approaches focus primarily on understanding and preventing failure. While essential, this perspective captures only part of operational reality. Contemporary resilience engineering and Safety-II approaches argue that organizations must also understand why operations succeed under varying conditions and how frontline personnel adapt to maintain safety in the presence of complexity and uncertainty (Hollnagel et al., 2022). The DCA accident demonstrates the consequences of organizational systems that fail to recognize and respond effectively to weak signals. Future ATM organizations should therefore integrate Safety-I and Safety-II principles by learning simultaneously from accidents, incidents, near misses, and everyday successful performance.

The concept of resilience engineering provides perhaps the most comprehensive framework for future ATM development. Resilience engineering recognizes that complex systems cannot anticipate every possible operational scenario. Instead, resilient systems are designed to adapt effectively when unexpected situations emerge. According to Brooker (2007), resilience requires systems capable of maintaining performance despite uncertainty, workload fluctuations, communication disruptions, and information degradation. Such systems rely upon flexible human operators, adaptive technologies, robust organizational processes, and effective feedback mechanisms.

Within future ATM environments, resilience may be enhanced through integrated safety architectures combining predictive analytics, automated safety monitoring, shared situational awareness tools, workload management systems, and human-AI collaboration. Research examining AI-enhanced weather awareness and adaptive instruction systems suggests that technological support can improve hazard recognition without increasing workload, thereby strengthening both individual and collective resilience (Yiu et al., 2022).

Similarly, adaptive staffing models, fatigue-risk management programs, and psychological support systems may help preserve controller performance during periods of elevated operational demand.

Ultimately, the DCA accident reinforces a central lesson for future air traffic management: safety can no longer depend primarily on the ability of individual controllers and pilots to compensate for system complexity. Future ATM systems must be explicitly designed to support human cognition, anticipate emerging risks, facilitate communication, enhance situational awareness, and strengthen organizational learning. Human-centered design, AI-supported decision aids, data-driven safety management, and resilience engineering should therefore be viewed not as independent initiatives but as interconnected components of a broader strategy for building safer, more adaptive, and more sustainable air traffic management systems. The future of aviation safety will depend not on eliminating human involvement but on creating systems that enable humans and technologies to work together more effectively in managing the complexities of modern airspace.

11. Conclusion

Air traffic control cognition cannot be adequately understood through isolated models of attention, memory, workload, or decision-making. As demonstrated throughout this study, controller performance emerges from the continuous interaction of perceptual processes, attentional allocation, working memory, mental representations, situation awareness, adaptive decision-making, communication, and team cognition within a complex socio-technical system. These cognitive processes are further shaped by workload, fatigue, automation, organizational conditions, and the operational structure of the airspace.

The analysis of the DCA mid-air collision provides an applied illustration of this interdependence. The accident cannot be reduced to a single perceptual failure, controller decision, or pilot action. Rather, the event demonstrates how cognitive limitations, increasing operational demands, visual separation dependencies, communication constraints, expectation-based processing, and latent organizational vulnerabilities may progressively interact and erode safety margins. This interpretation reinforces the importance of moving beyond retrospective attribution of human error toward systemic analyses of the conditions under which human performance is produced.

As ATM evolves toward trajectory-based operations, advanced automation, artificial intelligence, and increasingly distributed decision-making, the central human factors challenge will not be to remove human cognition from the system but to support its adaptive capabilities. Future ATM systems should preserve meaningful cognitive engagement, facilitate shared situation awareness, support calibrated interaction with automation, and strengthen controllers' capacity to detect, interpret, and respond to emerging operational variability. Accordingly, cognitive performance should be regarded not merely as a human limitation to be managed, but as a fundamental source of system adaptability and resilience. Integrating cognitive science and human factors into the earliest stages of ATM design, training, safety management, and organizational decision-making is therefore essential for developing safer, more resilient, and genuinely human-centred air traffic systems.

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