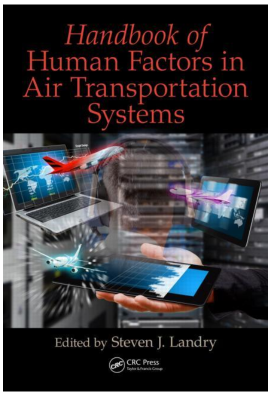

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Steven J. Landry

Situation Awareness in Air Traffic Control

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CONTENTS

Air traffic control (ATC) is a highly complex activity that requires air traffic controllers (ATCos) to interact with various technical and social elements of a system (e.g., radar screens, Ultra High Frequency/Very High Frequency (UHF/VHF) radios, automation tools, pilots, other ATCos, and air traffic management [ATM] personnel). This challenges their information processing abilities as they seek to acquire and maintain their situation awareness (SA) regarding the ongoing traffic situation (Durso & Alexander, 2010; Endsley & Smolensky, 1998; O'Brien & O'Hare, 2007; Prevot, Homola, Martin, Mercer, & Cabrall, 2012). For example, to ensure that aircraft (AC) are not in danger of losing separation, ATCos have to scan their 2D radar screens to assess the current and future 3D locations of various AC. In projecting these locations, they have to take into account multiple factors such as wind speed, weather, and the performance characteristics of the AC. Despite being a challenging task, aviation remains one of the safest areas in transportation (see accidents rates from the National Transportation Safety Board; http://www.ntsb.gov/). This is due to the fact that human factors has played an important part in shaping the roles, tasks, training, and technology used by ATCos (Roske-Hofstrand & Murphy, 1998). This continues to be the case under the airspace modernization plan known as the Next Generation Airspace System, the goal of which is to increase the capacity of the airspace without compromising its safety (JPDO, 2011). We begin the chapter by outlining some of the changes that are envisioned as part of the NextGen ATM system. Then, we discuss some of the key areas of human factors research that have been carried out, focusing on SA and best practices for training student ATCos in the use of NextGen technologies.

NEXTGEN AND CHANGES TO THE AIR TRAFFIC MANAGEMENT SYSTEM

The main functions of an ATCo include maintaining the safety of flight by keeping AC separate from each other, making traffic flow efficiently, and providing traffic and weather information to pilots (Nolan, 2010). There are three general types of ATCos, operating at different altitudes. First, there are Tower Controllers, who manage traffic on the ground and until AC are a few thousand feet from the ground. Second, there are Terminal Radar Approach Control ATCos, who handle AC from 30 to 50 miles around an airport, and up to 10,000 feet. Third, there are *en route* ATCos who control AC during the high-altitude phases of flight (Durso & Manning, 2008). ATC services are provided only in specified airspaces (i.e., in controlled and positively-controlled airspace). In the United States, the National Airspace System (NAS) is divided into a series of 3D sectors. Each sector is managed by one or more ATCos, and the responsibility for providing services to an AC is passed from one sector controller to the next. Sectors with little traffic often do not need the support of a highly technical ATM system, but traffic in major cities and commercial hubs requires complex coordination and control of AC. Due to the workload placed on controllers in these high-density sectors and the projected increase in traffic demand brought about from passenger travel and e-commerce transport at the start of the millennium, the number of AC estimated to be operating in the U.S. NAS in 2025 is likely to exceed the capacity of the current ATM system. As a result, the Joint Planning and Development Office was formed in 2003 to develop the Next Generation Air Transportation System (NextGen; JPDO, 2011).

NextGen reflects a transformation of the current, radar-based ATM system to a state-of-the-art, satellite-based system for improving the efficiency, security, maintenance, and safety of the airspace. NextGen innovations are already being introduced into the system and will continue to be incrementally implemented over the next several decades. The innovations include changes to existing airspace structures and increased reliance on automation (JPDO, 2011; Kopardekar & Quon, 2011). As automation becomes more complex and capable of higher information-processing tasks, however, it does not replace humans but rather changes the nature of the work they carry out (Parasuraman, Sheridan, & Wickens, 2008). A human operator is typically required to interact with automation as a supervisor and collaborator/team member. Successful implementation of automation for achieving NextGen goals demands that operators use the tools appropriately, taking into account characteristics of the automation and of human operators themselves (Lee & Moray, 1994; McCarley & Wickens, 2005).

Effective operations in complex environments such as NextGen thus require that ATCos rely heavily on automated components of the system. *Automation* refers to when functions that would otherwise be carried out by a human are allocated to a machine (Parasuraman, et al., 2008; Sheridan, 1992). Functions that are candidates for automation span the full range of human information-processing: Information acquisition and analysis, decision-making, and action implementation (Parasuraman, Sheridan, & Wickens, 2000). Automated tools are expected to reduce ATCo workload, a major bottleneck limiting the capacity of current day operations (Kopardekar & Quon, 2011). Successful implementation of these automation solutions for achieving NextGen goals, however, demands that operators use these tools appropriately. In particular, for optimal use, the operator must be aware of, and understand, several characteristics of an automation tool such as its current reliability, false alarm rate, and miss rate (Lee & See, 2004; Manzey, Reichenbach, & Onnasch, 2012; Metzger & Parasuraman, 2005; Parasuraman & Riley, 1997). Less than optimal usage occurs when the operator is not calibrated with respect to the reliability of the automation tool. Overreliance on automation introduces problems such as complacency, loss of SA, and the out-of-the-loop syndrome (e.g., Onnasch, Wickens, Li & Manzey, 2014; Parasuraman et al., 2008; Wickens, 1999). Underreliance prevents automated systems from achieving the purpose for which they were designed. Therefore, to be effective in achieving the goals of NextGen, it is critical that proper human–automation teaming mechanisms and training strategies are in place to ensure that the increased traffic demands being made on the NAS are achieved in a safe and efficient manner.

Several strategies for automating ATC tasks have been proposed to assist controllers in NextGen environments (e.g., Prevot et al., 2012; Willems & Heiney, 2002). For example, a critical automation tool for ATC operations is the conflict detection and resolution (CD&R) system that will partly relieve ATCos of the separation assurance task. The CD&R system, however, can be configured so as to feature different levels of automation, depending on how much autonomy and responsibility is allocated to the machine and how much cognitive and physical activity is required of the human operator (e.g., Endsley & Jones, 2012; Parasuraman et al., 2008). For instance, the tool could be formatted to only alert the ATCo to potential conflicts but leave the ATCo responsible for resolving them. Another possible implementation of the tool is that it could alert the ATCo and suggest conflict resolutions that the controller could accept (management by consent) or reject (management by exception). Furthermore, a fully automated CD&R tool could alert the ATCo of conflicts, but the system would resolve them by sending commands to the pilot without any human intervention. The latter concept would produce the greatest reductions in workload, depending on the extent to which the ATCo trusts and uses the CD&R system.

It is important, however, to examine broader consequences of adopting different levels of automation. In their meta-analysis, Onnasch et al. (2014) found that higher degrees of automation tended to lead to improved performance and lower workload when the automation functioned properly, but it also compromised SA. Moreover, when automation failed, the higher the degree of automation, the greater the negative impact on performance, especially when automation supported action selection. Designers therefore need to consider not only how a tool will improve workload and performance when it is functioning normally but also how performance will be affected when automation fails. As automation-related problems can arise under many conditions, it is important for designers to take into account the entire human–automation system, including level of automation, operator training requirements, and human–automation interfaces (Lee & Seppelt, 2009; Madhavan & Wiegmann, 2007; Vu & Chiappe, 2015).

This type of system approach therefore calls for a user-centered design philosophy (Salvendy, 2012; Maguire, 2001). That is, rather than expecting users to conform to the characteristics of the system, design is based on the needs, wants, and limitations of the end user, in this case, the ATCos. These factors are taken into account during each stage of the system design and development lifecycle, not just at the end. In this way, product development and lifecycle costs are minimized, whereas operator performance is optimized (Vu & Chiappe, 2015). For example, with respect to ATCo displays, instead of presenting information in a way that is organized around the sensors and tools that generate it, information is displayed with an understanding of the goals and tasks of the ATCo. It is also important to keep in mind that ATCos may have multiple operational goals to satisfy at any given time, and goals may quickly change as a task unfolds. A user-centered design approach is one that is sensitive to the dynamics of user goals and involves ensuring that displays organize information around the multiple goals of the user (Endsley & Jones, 2012).

In what follows, we will describe two different areas of human factors concern in ATC operations. We begin with an overview of SA and its measurement and how the concept has been applied to evaluation of potential NextGen concepts and technologies for ATC, and we end with a review of a series of training studies we have conducted with students studying to be ATCos, and how their training can be affected by the introduction of NextGen Tools and Concepts. We acknowledge that human factors researchers have contributed to other areas of ATC operations, but we limit our focus to these two topics in the present chapter.

AIR TRAFFIC CONTROLLER SITUATION AWARENESS

SITUATION AWARENESS IN AIR TRAFFIC CONTROLLER ACTIVITIES

A critical human factors concern in ATC is designing displays, tools, concepts of operation, and training regimens that enhance and do not undermine SA (Endsley & Smolensky, 1998). SA is an operator's dynamic understanding of what's going on as he or she is managing a complex system

(Chiappe, Strybel, & Vu, 2012, 2015; Durso, Rawson, & Girotto, 2007; Endsley, 1995a, 2015). *En route* ATCos, for example, need to possess an ongoing awareness of traffic, which they refer to as *the picture*, so they can move AC safely and efficiently through the sector and detect whether any problems are developing (Endsley & Smolensky, 1998). Most importantly, these controllers need to be aware of conflicts between AC. If any AC are in danger of losing separation, ATCos need to issue commands to pilots to change speed, heading, or altitude. In planning maneuvers, ATCos also need to assess whether a proposed maneuver will create any secondary conflicts. Thus, route planning requires having a global picture of the traffic; a narrow focus on specific AC is not an effective strategy. ATCos maintain their SA by scanning their Digital System Replacement (DSR) display, by communicating with pilots, and by communicating with other controllers and ATM personnel. A high level of SA is therefore important for ATCos to make good decisions, and it is not surprising that SA has been linked to ATCo performance (Durso, Hackworth, Truitt, Crutchfield, & Manning, 1998; Endsley & Smolensky, 1998; Rodgers & Nye, 1993). For example, Durso, Bleckley, and Dattel (2006) found that measures of SA were able to predict performance on an ATC task even after controlling for other cognitive variables.

Maintaining SA requires detecting many features of the operational environment, and integrating this information with information stored in long-term memory so that its relevance to current operational goals can be determined (Chiappe, Strybel, & Vu, 2015; Endsley, 2015; Stanton, Salmon, Walker, & Jenkins, 2010). It also requires that attention be allocated to relevant features in the environment, whereas irrelevant information is ignored so that an operator's limited cognitive resources are not depleted (Pew, 2000). It is useful to characterize SA as consisting of three levels that Endsley (1995a; 2015; Endsley & Smolensky, 1998) refers to as *perception*, *comprehension*, and *projection*. Level 1, *Perception* involves determining the "status, attributes, and dynamics of relevant elements in the environment" (Endsley & Jones, 2012, p. 14). For example, an ATCo needs to perceive, among other things, the relative location, speed, and direction of flight of the AC in a sector. Level 2, *Comprehension* involves integrating perceived information with background knowledge and information about current operational goals to determine the relevance of the information. For example, an ATCo needs to infer, given the relative position of two AC, whether or not they are in danger of losing separation. Comprehension is also involved in prioritization, determining which potential problems need to be dealt with first. Level 3, *Projection* involves predicting future states of the elements, and in ATC activities it is used to determine whether a particular course of action will resolve the conflict, and whether or not other ancillary conflicts would be created. According to Endsley (2015), the three levels of SA are not strict stages that must be carried out sequentially; they can often occur concurrently.

SITUATION AWARENESS THEORY AND MEASUREMENT IN AIR TRAFFIC CONTROL CONTEXTS

To determine whether displays, tools, operational concepts, and training regimens for ATCo activities enhance SA, we need to have valid, reliable, diagnostic, and sensitive metrics of the construct; we cannot simply rely on the intuitive judgments of designers. Although there is broad agreement in human factors regarding the importance of SA, there is little consensus on exactly how to measure it, even in the specific domain of ATC operations (Salmon, Stanton, Walker, and Green, 2006). Moreover, the tools that have been used to measure SA in ATC contexts are not theory-neutral; they presuppose specific theories about the nature of SA, making it difficult to achieve consensus on which to use (Vu & Chiappe, 2015; Chiappe, Vu, & Strybel, 2012; Stanton et al., 2010). The theories differ in many ways, including whether or not they claim that the product of SA can be separated from the processes by which that knowledge is acquired. The products of SA refer to consciously held knowledge about the task environment (Endsley, 2015; Wickens, 2008). The processes of SA refer to the epistemic actions operators carry out to acquire knowledge, including for example, how they scan an ATC display or engage in communication (Durso, et al., 2007). Theories also differ in terms of whether they hold SA is a purely internal, conscious state of an individual, or whether it resides in the interactions between operators and their task environment, such that operators often offload information and access it only when needed (Chiappe et al., 2012; 2015; Stanton et al., 2010).

These different theoretical commitments can be seen in probe techniques, which are the most popular metrics used to assess SA in ATC contexts (Durso et al., 1998, 2006; Endsley & Smolensky, 1998; Endsley, Sollenberger, & Stein, 2000; O'Brien & O'Hare, 2007; Vu et al., 2009). Probe techniques involve asking ATCos questions about task-relevant information, such as "will AAL124 and SWA673 be in conflict within the next two minutes if no further action is taken?" or "which AC is going to be the next one to enter your sector from the east?" Depending on the specific probe technique, SA is reflected in either the accuracy of the responses, or the time that it takes operators to answer. Two of the main probe techniques are Endsley's (1995b) Situation Awareness Global Assessment Technique (SAGAT) and Durso and Dattel's (2004) Situation Present Assessment Method (SPAM).

These two methods have a lot in common, including the fact that probe questions are derived from task analyses and discussions with subject matter experts, so that the questions pertain to information that an operator should know. Questions are also asked periodically during a task and often require yes/no or multiple-choice response formats. Nonetheless, there are important differences between these techniques. SAGAT typically asks multiple questions at a time, whereas SPAM asks only one. SAGAT assesses SA using accuracy, whereas SPAM uses accuracy and reaction time. SPAM also makes use of a ready prompt, such that operators are alerted when there is a question in the cue, and only once they indicate that they are ready to receive it is the question presented. Time to respond to the ready prompt is taken as a measure of workload because operators are only supposed to indicate they are ready to receive a question when their workload permits. The key difference, however, is that SAGAT involves freezing scenarios and blanking ATCo displays, whereas SPAM involves asking questions while scenarios are running and displays are visible.

This difference in whether or not scenarios are paused and whether or not displays remain visible reflects the theoretical commitments presupposed by each approach (Chiappe et al., 2015). In particular, SAGAT assumes SA is a product. It is made up of only internal, consciously held knowledge; that is, a detailed situation model held in internal memory, based on information derived from perception, comprehension, and projection (Endsley, 2012, 2015). As SA is viewed as a product, SAGAT measures the knowledge that operators possess, but does not directly assess how operators acquire this information, which Endsley refers to as *situation assessment*. Endsley (1995a; 2015) does discuss processing issues, claiming that situation assessment is carried out by various systems that include perceptual processes and attention mechanisms, as well as mental models and other related long-term memory structures. Mental models offer a means for rapid categorization based on cues, which also speeds up the decision-making process. An ATCo, for example, will have a mental model pertaining to sector characteristics, including conflict hotspots, and he or she can use this knowledge to judge the consequences of sending an AC in a particular direction.

In contrast, by leaving ATC displays visible and scenarios running, SPAM assumes that although ATCos store some information internally, other information is offloaded, with SA often involving knowing where to access it in the external world, an approach we have termed *Situated SA* (Chiappe et al., 2012, 2015). As Durso et al. (1998, p. 3) state "SA may sometimes involve simply knowing where in the environment to find a particular piece of information, rather than remembering what the piece of information is." To this end, an ATCo may not store an AC call sign but may remember where to locate this information on the display (Durso et al., 2007). According to SPAM, reaction time (RT) to answer probes reflect whether information is stored internally, or whether it has to be accessed externally. Specifically, Durso and Dattel (2004) state that the RTs to answer questions will be fastest when the information is stored in memory. They will be slower if the information is offloaded onto an external display, but the operator knows where to find it. RTs will be the longest when the information is externally represented, but the operator has to search to find it on a display.

The Situated SA approach claims that operators create partial internal representations and leave as much information in the external environment as they can (Chiappe et al., 2015; Clark, 2008). They let the world serve as its own representation, and they retrieve information from it on an as-needed basis. Action is therefore central to cognition, and not a mere peripheral process. Due to the fact that much of the world is predictable, people can exploit its structure by relying on highly strategic eye fixations rather than trying to retain a detailed, stable, internal picture of the surrounding environment. Indeed, change blindness research shows that although they may not perceive everything that is going on, people's eye fixations are tightly coupled to the actions they are carrying out, allowing them to access limited information from the environment at any given point in time (Simons & Rensink, 2005). According to Rensink (2000), people store internally general *scene schemata* that contain information about what objects are likely present in a scene and where these are located. People can use these schemata to direct their gaze to particular parts of the visual field when they need to get more specific information about objects. In short, situated approaches stress a tight coupling of perception and action rather than relying on intensive internal processing. Process and product are intimately linked and inseparable.

In terms of ATC operations, controllers will often offload crucial information about flights by annotating flight progress strips (Roske-Hofstrand & Murphy, 1998). These are also stored in a strip bay in an offset manner so that ATCos can rely on perception rather than internal memory to determine which flights require further actions. The Situated SA approach also makes precise claims about what information is likely to be held internally and what information is likely to be offloaded (Chiappe et al., 2012, 2015). For example, among other things, it holds that information generality and priority are important variables that are likely to affect offloading behavior. General information, which is likely to be stored internally, pertains to information regarding many or all AC in the sector, whereas specific information pertains to information regarding a particular AC in the sector. General representations, such as Rensink's (2000) scene schemata, would help operators know where in the display to access specific information. Information priority reflects the likelihood that an ATCo needs to act on certain information quickly. Operators may store high priority information internally (e.g., potential conflicts between AC in the next minute), whereas low priority information is stored externally (e.g., whether any AC are 30 nautical miles from the sector boundary). Having high-priority information stored internally would ensure it is promptly acted upon, without having to spend time accessing information on the display. Storing low-priority information externally but knowing where to access it, on the other hand, would limit the amount of information that needs to be held in internal memory.

Recently, Chiappe et al. (2016 Sturre, Chiappe, Vu, & Strybel, 2015) tested these claims. Participants were student ATCos who controlled air traffic in a simulation environment. They were presented with probe questions that varied in generality and priority, creating four question categories (i.e., general/high priority, general/low priority, specific/high priority, specific/low priority). The SPAM technique was used to ask probe questions. These were presented on a probe display that was located adjacent to (and at an angle from) the ATCo radar scope. A camera mounted onto the probe display was used to record where participants looked while answering probe questions. The results revealed that ATCos were more likely to turn to look at their radar display while answering specific questions and low-priority questions, suggesting that this information was offloaded. In contrast, they were less likely to turn to look at the radar display following high priority and general information questions, suggesting that the information to answer them was stored internally.

In short, Situated SA holds that ATCos often offload information onto their displays, and as a result, when measuring SA we should not remove operators from their task environment if we want to capture this behavior. SPAM is therefore an appropriate method to use if one takes this approach, because it allows operators to refer to their displays while answering probe questions. By comparing RTs to answer questions, or by examining eye gazes, one can examine whether ATCos are answering on the basis of what they have stored internally or whether they have offloaded the information. In contrast, SAGAT, by blanking displays and freezing scenarios, does not allow us to study the situated ATCo but does allow us to examine what information operators consciously store in internal memory.

Vu and Chiappe (2015; see also Chiappe et al., 2015; Stanton et al., 2010) view SPAM and SAGAT as examining SA from a different unit of analysis, both of which are legitimate, depending on one's research goals. The unit of analysis implicit in SAGAT is the individual operator's conscious mind. This would be appropriate, for instance, if a researcher was interested in examining what an ATCo knows about the sector when there is a malfunction of their radar scope and displays go dark. In contrast, the unit of analysis of SPAM is the individual operator in interaction with his or her displays, and it allows us to study how ATCos offload key information. Neither of these is correct or incorrect, but we need to be clear on what we are studying and we need to use the right tool given the particular research goals (Stanton et al., 2010). Indeed, SPAM and SAGAT each have advantages and disadvantages that need to be kept in mind when deciding which metric to use. In what follows, we summarize the pros and cons of each.

Situation Awareness Global Assessment Technique

There are many desirable features of SAGAT (Endsley, 1995b; 2015; Salmon et al., 2006; Vu & Chiappe, 2015). First, it marks an improvement over subjective techniques such as the Situation Awareness Rating Technique (SART; Taylor, 1990) because it objectively measures what the operator does and does not know, comparing their answers with what was actually taking place. Subjective techniques are better seen as measures of meta-SA, what a person thinks their SA is at any given time, rather than what it actually is (Durso et al., 2007). Second, SAGAT can be scored very easily, which allows one to make quantitative comparisons. One could compare the relative merits of two ATCo displays, for example, by determining which led to the higher percent of probe questions answered correctly. Third, it has good psychometric properties, as many studies have validated it, including in the ATC domain (e.g., Endsley et al., 2000; Kaber & Endsley, 2004). Kaber and Endsley (2004), for example, used SAGAT to examine the consequences of different levels of automation on SA of ATCos. Fourth, by asking a broad range of questions at all three levels of SA, it can provide a fine-grained analysis of how some tool or concept of operation affects SA. This allows designers to assess whether improvements in one aspect of SA come at the expense of SA for other information. By drawing from a large list of questions during query presentation, it also makes it unlikely that operators can come to pay attention to information they would not normally attend to (Salmon et al., 2006).

Nonetheless, SAGAT also has some important limitations that need to be kept in mind. First, it cannot be effectively used to study the processes of situation assessment because it only measures the conscious knowledge operators possess. One cannot simply infer processes from the products, as the same product can be achieved in many different ways (Durso & Sethumadhavan, 2008). Second, pausing scenarios and removing displays interrupts the activities of operators (Salmon et al., 2006). This makes it difficult to apply SAGAT in real world. So, it can only be applied in the context of a simulation. Third, SAGAT measures what operators can recall about the situation, making it heavily dependent on memory (Durso & Sethumadhavan, 2008). An operator, however, can have good SA at a particular point in time but not be able to recall that information at the time that the queries are presented.

Situation Present Assessment Method

SPAM also has many desirable properties. First, it has also received much validation in the context of ATC operations (Durso et al., 1998, 2006; Vu et al., 2009). Vu et al. (2009), for example, showed that SPAM is able to capture differences in SA that stem from different roles and responsibilities for separation assurance. Likewise, the ability of SPAM to separate workload from SA by using the *ready* prompt to assess the former and probe RT to assess the latter, has also received validation (e.g., Vu et al., 2012b). Second, similar to SAGAT, SPAM can be scored relatively easily by comparing operator responses with what was actually taking place in the system being controlled. By making use of RT in addition to accuracy, however, SPAM also provides a more fine-grained measure of SA (Durso & Dattel, 2004). Third, by presenting questions one at a time and recording RT, SPAM can be used to study the processes of SA and not just the product. For example, it can be used to examine whether operators are storing information internally or offloading it onto a display (Durso et al., 2007). Fourth, SPAM can be applied in the field and is not limited to simulation studies. The reason is that it does not remove operators from their task environment. Durso and Dattel (2004) cite examples, including applications of SPAM to real world driving.

Despite its virtues, SPAM also has important limitations. First, it can be intrusive to an operator's primary task. Although it employs the ready prompt to prevent this, performing a second task while managing a sector can still be intrusive on ATCo activities. For example, Pierce (2012) found that SPAM negatively affected ATCo performance and increased workload ratings to a level comparable with other conditions in which participants had to manage traffic while carrying out cognitively demanding secondary tasks. Likewise, Strybel et al. (2008) found that although both probe techniques predicted performance on a piloting task, SPAM interfered with performance compared with SAGAT, as evidenced by greater variability in air speeds in SPAM scenarios. Given the potential for interference, it is not ideal to apply the SPAM technique when task demands are very high. Second, it can be difficult to interpret the latencies to answer probe questions. Although advocates for SPAM claim that RT differences reflect where operators are storing information (in the world or in the head), they could reflect other factors as well, such as question difficulty. Thus, it is desirable to supplement the SPAM method with a technique for measuring eye gaze while questions are being answered (e.g., Sturre et al., 2015; Chiappe et al., 2016).

To summarize, we have reviewed two probe methods that are frequently used to measure SA in ATC contexts. These differ in important respects, including the theories on which they are based. Importantly, they differ in the unit of analysis for which they are most suited (Stanton et al., 2010; Vu & Chiappe, 2015). SAGAT is most suited for studying the SA possessed by the conscious mind of the individual operator. SPAM is most suited for a unit of analysis that includes the individual operator and his or her interactions with the immediate task environment, assessing for example how information is offloaded and accessed on an as-needed basis.

PRINCIPLES FOR DESIGNING TO SUPPORT SA

Although there are theoretical disagreements as to what constitutes SA and how best to measure it, most researchers agree that ATC displays should be designed with the goal of enhancing SA. This can be achieved by keeping in mind various principles that reflect a user-centered approach, ones that transcend specific theoretical approaches. Indeed, Endsley and Jones (2012) provide a list of eight principles that serve to enhance SA that can readily be applied in the domain of ATC operations (Table 13.1).

1. *Organize information around goals*: Information should be organized around the tasks and goals that ATCos have to perform. Doing so makes it more likely that the goals will be achieved accurately and efficiently. If an ATCo needs information *X* and *Y* to carry out a task, then *X* and *Y* should be presented together on a display. The operator should not have

TABLE 13.1
SA-Enhancing Design Principles

No.	Design Principle
1	Organize information around goals
2	Present information to support comprehension directly
3	Provide assistance for projections
4	Support global SA and resist cognitive tunneling
5	Support tradeoffs between goal-driven and data-driven processing
6	Make critical cues for schema activation salient
7	Take advantage of parallel processing capabilities
8	Use information filtering carefully

Source: Endsley, M.R., and Jones, D.G., *Designing for Situation Awareness: An Approach to Human-Centered Design*, CRC Press, New York, 2012.

to look in multiple locations to access needed information. For example, if an ATCo needs to consider an AC's altitude and bearing to infer whether the AC presents a threat to another AC, both of these pieces of information should be presented together on the display.

2. *Present information to support comprehension directly*: Displays should present information that has been integrated and processed with respect to the ATCo's comprehension requirements. For example, an ATCo display could indicate whether two AC are in conflicting trajectories rather than having controllers infer this on the basis of the relative position, direction, and speed. In this way, the meaning of the displayed information would be more easily understood by controllers, and they would be able to direct their efforts to resolving the conflict as opposed to figuring out whether a conflict actually exists.
3. *Provide assistance for projections*: As projection of future system states is often quite cognitively demanding, system designs should support this level of understanding by providing such information on the displays whenever possible. For instance, an ATC display could directly represent whether any secondary conflicts would be created by selecting a particular maneuver for an AC instead of having the ATCo compute this information by integrating the information about each of the AC along the path. It could also portray what the closest point of approach would be.
4. *Support global SA*: Global SA refers to a *big picture* understanding, an overview of the situation taking into account all of an ATCo's goals. It is important for a display not to encourage cognitive tunneling by allowing an operator to focus only on one goal at the exclusion of all other important goals (Wickens, 2005). Interfaces that have an excessive number of menus, for example, can exacerbate this problem. Likewise, although it may be desirable to be able to adjust the zoom on an ATC display, this must not impede an ATCo's ability to know what is going on in adjacent sectors, as this can be strategically costly because controllers may not be able to plan ahead.
5. *Support tradeoffs between data-driven and goal-driven processing*: In goal-driven processing, goals guide an ATCo to seek out certain information on the display in a top-down manner. For example, an ATCo may look for altitude information about a specific AC on their display because of a concern about its position relative to another AC. In data-driven processing, an ATCo's attention is captured by salient cues present on a display. It is particularly important for nonroutine situations. If an AC suddenly deviates from its flight plan, for example, it would be useful to have an ATCo's attention drawn to this fact. Both of these types of processing are important. Without goal-driven processing, ATCos would simply be reacting to an unfolding situation, which would be an ineffective strategy. Data-driven processing is important too, however, because controllers cannot always know what is going to be the most important information to process at any given point in time.
6. *Make critical cues for schema activation salient*: Experts make decisions by using their perceptual mechanisms to detect the presence of specific cues. Once detected, these cues cause the activation of schemata stored in long term memory (LTM), which tell the operator how to respond to this particular situation (Klein, 2008). Making those cues salient is therefore an effective way to enhance performance. For example, using an easily perceivable cue (such as AC icons turning red from amber) to identify coaltitude AC on converging trajectories would be helpful, as it would trigger a *conflict* schema in the mind of controllers. Doing so would also activate knowledge on how to resolve those conflicts.
7. *Take advantage of parallel processing abilities*: Although people are limited in the amount of information that they can process in any single sensory modality, their ability to process multiple pieces of information at the same time is better when it involves different sensory modalities (Wickens, 2008). In the case of ATC operations and aviation in general, there tends to be an excessive reliance on a visual presentation of information. As a result, relying on other modalities such as hearing is encouraged. This is especially the case for alarms and alerts.

8. *Use information filtering carefully*: Information filtering is when a system is designed to provide ATCos with only the information that the system judges to be needed by the operator at any given point in time. Filtering is usually done so as to not overload an operator. For example, key information about a flight may be contained in a data block, and this information could be hidden, and only pop up when the AC is in conflict with another AC. The problem is that systems are rarely able to accurately determine what information a user needs. As a result, the user can be deprived of key information when they need it. Furthermore, because the information is not always there, the ATCo may be deprived of trend information. Thus, without this information, he or she would be unable to look ahead to see if any other potential problems are developing. It would put them in a position of being forced to react to situations rather than being proactive in their handling of unfolding situations.

Summary

SA, knowing what is going on in a dynamic system, is a crucial concern for ATC operations, as it drives ATCo decision-making and ultimately performance. It can be studied, however, from different perspectives, or different units of analysis, including from a perspective that focuses solely on the conscious contents of the mind of controllers, or from one that examines how they offload crucial information onto the environment. These different perspectives warrant different measurement techniques. Furthermore, there are valuable principles that need to be kept in mind when designing tools and technology for supporting ATC operations, ones that enhance SA.

RESEARCH ON IMPACT OF POTENTIAL NEXTGEN TOOLS AND CONCEPTS OF OPERATIONS

The concern for operator workload and SA in NextGen, as noted earlier, stems primarily from the projected increase in air traffic over the next several decades. ATCos will not be able to handle this amount of traffic using the existing tools and procedures (Prevot, Homola, & Mercer, 2008). The technological upgrades in the NAS envisioned under NextGen will require that ATCos interact with automated components of the ATM system. Many NextGen concepts of operation for the task of separation assurance have been proposed (e.g. Dwyer & Landry, 2009) on the basis of different function allocations to human operators or automation. Separation assurance algorithms for an autoresolver tool have also been developed (e.g., Erzberger, 2009; Erzberger & Heere, 2008; Farley & Erzberger, 2007) and shown to be effective when implemented in an interactive teaming environment with ATCos or autonomously (e.g., Prevot et al., 2012). Many of the studies examining NextGen ATCo tools and concepts of operation (e.g., Homola et al., 2010; Prevot et al., 2012; Pop, Stearman, Kazi, & Durso, 2012), however, do not focus on the topic of SA, despite the fact that it is a known determinant of operational errors in ATC (Endsley & Smolensky, 1998). In this section, we provide examples of a few human-in-the-loop simulation studies that we have conducted that were designed specifically to examine the impact of potential NextGen tools and concepts of operation on ATCo SA with experienced and novice operators.

In all these studies, a variant of the SPAM method was employed as an online measure of workload and SA. This variant included a visual and auditory *ready* prompt presented on a secondary display. Upon acceptance of the ready prompt, the question was visually displayed along with response alternatives in multiple-choice format. Strybel et al. (2009) found this multiple-choice format to be an effective in reducing the intrusiveness of a secondary task associated with this online probe procedure. Moreover, Bacon et al. (2011) found that latencies resulting from this probe technique were valid indicators of SA, and sensitive enough to discriminate between student and expert ATCo performance in mixed equipage environments (i.e., environments in which there were both, NextGen tool equipped AC and nonequipped AC). In addition, Bacon et al. found that the results obtained with this probe technique were consistent with expert ATCo over-the-shoulder ratings of the participants' overall performance, performance in maintaining separation, attention, and SA.

EFFECTS OF NEXTGEN CONCEPTS ON SA OF EXPERIENCED AIR TRAFFIC CONTROLLERS

Research has shown that an automated conflict resolution tool can reduce ATCo workload and have a positive impact on the ATM system, including increasing its safety and efficiency (Homola et al., 2010; Prevot et al., 2012). Yet, for the automated separation assurance tool to be effective, it should not decrease ATCo SA. Moreover, the separation assurance tool should work well with other NextGen tools designed to reduce workload, such as merging and spacing, and allow the ATCos to interact with other operators in the NAS (e.g., pilots). In this section, we will summarize a study conducted by Strybel et al. (2016) that measured ATCo SA and workload as a function of whether the task of separation assurance and merging and spacing were assigned to the human operator or to automation. The impact of these NextGen tools and concepts on operator SA will be discussed.

NextGen Scenario and Concepts of Operation

The current study involved a multiparticipant distributed, human-in-the loop simulation. It was run using the Multi Aircraft Control System (MACS), Aeronautical Datalink and Radar Simulator, developed by the Airspace Operations Laboratory at NASA Ames Research Center (e.g., Prevot et al., 2012). ATCos used MACS configured as a DSR display with integrated Data Comm (text-based communication) and conflict alerting. At the start of the scenarios, AC were populated in two adjacent sectors (named 90 and 91, respectively) and flown by trained pseudopilots (experimental confederates who controlled all AC in the sector). Each sector was managed by an ATCo, and the pair of ATCos had to work collaboratively to handoff AC from one sector to the other.

The traffic in the scenarios included arrivals, departures, and *en route* AC. In addition, there was a stream of United Parcel Service (UPS) AC in the sector that were engaging in company spacing. That is, these AC were assigned a lead AC to follow and were expected to merge in a sequence at a particular waypoint to achieve a continuous descent approach. In addition to the separation assurance and spacing tasks (which could be assigned to a human operator or to automation depending on the concept of operation being tested), the two controllers had different responsibilities based on the characteristic of their sector. In particular, the sector 90 ATCo was responsible for weather deviations (weather was only present in that sector); the AC's top of descent also occurred in this sector. The sector 91 ATCo was responsible for finalizing the merging of the UPS AC; after the merge, the ACs started a continuous descent arrival approach to the airport. If requested by the UPS pilots, both sector ATCos were required to provide clearances for resequencing and spacing to the airport. The ATCos were provided with conflict alerting, a trial planner with route assessment for potential conflicts, and an autoresolver tool, which provides the ATCos suggested resolutions to traffic conflicts at their request. The autoresolver was engaged autonomously when separation assurance was assigned to automation.

As noted earlier, the responsibility of separation assurance was assigned to the human (i.e., the pilot or ATCo) or automation. Similarly, the merging and spacing task was assigned to the human or automation. The various function allocation strategies resulted in three potential NextGen Concepts of Operation:

- Concept 1: *Pilot Primary*: Pilots flying NextGen equipped AC were given the primary responsibility for separation assurance between ownship and all other AC. The ATCos were only responsible for resolving conflicts between NextGen unequipped AC and all conflicts with experimental AC on their continuous descent arrival. The ground-based autoresolver agent had no responsibility.

- Concept 2: *ATCo Primary*: The ATCos were given the primary responsibility for separation assurance. ATCos had responsibility for NextGen equipped–unequipped and unequipped–unequipped conflicts only, and for conflicts between any AC on a continuous descent arrival. The autoresolver agent was responsible for NextGen equipped–equipped conflicts.
- Concept 3: *Autoresolver Primary*: In Concept 3, the autoresolver agent was responsible for resolving most conflicts. The autoresolver agent was responsible for conflicts between NextGen equipped–equipped and equipped–unequipped AC. ATCo was responsible for resolving conflicts between unequipped AC only.

SA Probe Questions

The SA probe questions, which were developed and evaluated by a retired ATCo, were categorized on the basis of the type of information queried (e.g., questions relating to conflicts, spacing status, and traffic/weather) and whether the information was relevant to the ATCo's own sector or the sector of the adjacent ATCo (for more details, see Strybel et al., 2012). Conflict questions asked about potential conflicts (e.g., "In the next three minutes, will there be any conflicts between ...."), and recent conflict resolution, (e.g., "What was the resolution to the last conflict?"). Spacing-status questions asked about the arrival AC and their status regarding spacing (e.g., "Will any AC need re-sequencing in your sector?"). Traffic/weather questions asked about current status of AC in a sector, such as the number of equipped versus unequipped AC, altitudes and headings of specific ACs, or about weather (e.g., "How close is [call sign] to the nearest weather cell?").

IMPACT OF CONCEPT ON AIR TRAFFIC CONTROLLER WORKLOAD AND SITUATION AWARENESS

As the focus of the current chapter is on ATC, we only summarize the main findings relating to ATC in terms of workload and SA (see Vu et al., 2012b, for the role of the concepts on pilot SA, and Strybel et al., 2016, for more details). In terms of performance, conflict resolution times and the number of ATCo-responsible losses of separation were higher when the ATCo was primarily responsible for separation assurance (i.e., Concept 2). This finding was not surprising as this was the condition in which the ATCo workload was the highest. However, Strybel et al. (2016) found that automating separation assurance produced the greatest reductions in workload, and automating the merging and spacing task lowered workload further, so that the lowest levels of workload occurred when both functions were automated (Concept 3). This finding was not surprising given that the ATCos had less to do when both functions were automated. The reductions in workload, however, were in some cases accompanied by changes in controller SA, depending on sector characteristics and weather location. In the sector where the AC started its descent (sector 90), SA of conflicts was higher when the ATCo was responsible for separation assurance, especially when spacing task was automated. Automating spacing task also produced higher awareness of traffic and weather information. However, in the adjacent sector (sector 91), where all the arrival AC merged, SA of conflicts was highest when both functions were either automated or manually controlled by ATCos. These differences regarding the effects on SA, point out the need for evaluating automation concepts across different types of sectors in future investigations. Moreover, future studies need to examine the impact that failures of NextGen specific tools can have on ATCo workload and SA. For example, Kraut et al. (2011) found that failure of one NextGen tool, specifically Data Comm, resulted in increased ATCo workload and decreased SA. The changes in workload and SA made the ATCo prioritize the task of maintaining AC separation, but this was done at a major cost to the efficiency with which they managed their sector. Kraut et al. (2011) only examined one type of failure, but it is likely that different NextGen tools can fail or be temporarily unavailable and their combined impact on ATCo workload and SA need to be examined.

Summary

The current study illustrates the importance of examining the effects of NextGen tools and concepts of operations across sectors having different characteristics and measuring their effects not only on ATCo performance, but also on SA and workload, as the latter are important harbingers of future performance problems. Most studies examining the feasibility of NextGen tools and technologies have not focused on operator SA. However, we found that ATCo functions such as separation assurance and interval spacing interact with each other in determining ATCo performance, workload, and SA. Thus, to determine an optimal function allocation strategy under NextGen, one cannot simply focus on a single factor such as reducing ATCo workload. The optimal solution for NextGen will require many iterative simulations that account for the various contexts in which the human–automation teaming will be functioning.

TRAINING AIR TRAFFIC CONTROLLERS WITH POTENTIAL NEXTGEN TOOLS

Once NextGen tools and concepts of operations for ATC have been selected for implementation, ATCos will need to be trained on their use so that they can properly form the *picture* and perform their task safely and efficiently. It is important to keep in mind, however, that NextGen will be implemented gradually, and that at least early on, the airspace will feature mixed equipage, that is, some of the AC will be equipped with NextGen tools and technology, whereas others will feature traditional tools. As a result, ATCos in the near term will have to be trained to use both sets of tools and will have to be able to fluidly transition between them. Thus, research is required on how best to train controllers to use both sets of tools.

Kiken et al. (2011) trained experienced ATCos, that is, ones with many years of experience using the manual, voice-based tools, to manage a simulated sector that they were unfamiliar with. The sector consisted of either NextGen equipped or NextGen unequipped (current-day) AC. They recorded the number of session required for the ATCo to master the sector. Kiken et al. found that the ATCos took twice as long to master the sector with equipped AC compared with unequipped AC, indicating that their ATM skills do not directly transfer. Future ATCos, though, will likely develop the skills for managing NextGen equipped AC as part of their initial training. Thus, training techniques that can assist students in acquiring advanced ATM concepts early in training, and help them acquire and maintain SA, may improve their overall skill acquisition and success as ATCos. In this section, we will review a series of training studies that examine how to best introduce NextGen tools to student ATCos, and the impact of these training techniques on the student ATCo's SA.

Training Approach

The participants in this study were students from Mount San Antonio College who were enrolled in different semesters of an internship course at the Center for Human Factors in Advanced Aviation Technologies at California State University, Long Beach. All students were pursuing careers in ATC. Every session of the internship course was taught by the same retired ATCo over one semester during a four-year period. The course focused on *en route* ATC operations and consisted of a lecture period and two lab periods over 14–16 weeks. Students were assigned to different lab sections of the course and experienced different hands-on training techniques for managing traffic on a radar screen (see Vu et al., 2013; Kiken et al., 2012). By comparing the performance of students using the different instructional methods, we could infer the beneficial components of different types of training techniques. This approach to examining differences in classroom training has been shown to be effective (e.g., Kiboss, Ndirangu, & Wekesa, 2004) and representative of real-world training programs.

All students attended the lecture portion of the course together. The lectures focused on training students ATCo skills and thought processes that were exercised in the lab portion. The most critical skill taught to the students was how to be able to project AC locations and protect them from losing minimum separation (i.e., prevent AC from having a loss of separation or LOS). Students were given exercises that allow them to estimate the point of contact for two AC on conflicting trajectories, as well as to identify where the LOS would occur and strategies for resolving the conflict prior to the LOS. A LOS was defined as AC coming within 5-nautical miles lateral or 1,000-feet vertical of each other. Students were taught how to resolve conflicts by vectoring AC (i.e., issue a series of heading changes), changing their altitude or speed, or through more strategic techniques (e.g., setting up a structure for their airspaces that would prevent LOS from occurring if the structure is maintained). The students were also taught pilot–controller communication and strategies for handling off-nominal situations and general expectations of the ATC career based on the instructor's personal experience.

To determine the effectiveness of different types of training regimens, in the lab sections, students experienced different types of training approaches, depending on which semester of the course they were enrolled in. Common to all lab sections was the general software training. All students spent the first week familiarizing themselves with the interface of the MACS software (Prevot, 2002) that was used to run the radar simulation for the course and for the testing sessions. All students were exposed to the DSR mode of MACS and Indianapolis Center (ZID) Sector 91, which was the sector that the students were trained to manage in all of these studies. Students were taught characteristics of the airspace, including the main waypoints in the sector, arrival/departure paths, general traffic flows, and altitude conventions. The students were also trained to take and make handoffs and to adjust components of the display, such as switching datablocks from a full to limited view, or vice versa.

For the NextGen tools, students were trained with potential tools for NextGen equipped AC. The first set of tool relates to CD&R. NextGen equipped AC had conflict detection that was paired with a trail planner that allowed the controller to display the AC's current trajectory and make route modifications visually by clicking and dragging the route or by inserting new waypoints and adjusting the AC trajectory. The CD&R tool also determined whether the route change would produce secondary conflicts in a six to eight-minute window. The students were also trained on a Data Comm system that allowed them to issue commands and clearances via a text-based medium that was intended to reduce workload by reducing the amount of voice communication needed. Data Comm was also integrated with the trial planner tool, so route modifications were made possible via a single command.

ATCo SA was measured using a variant of the SPAM technique described earlier. The student ATCos were provided with a visual *ready* prompt presented on a secondary display, accompanied by an audio alert presented through their ATCo headset. Upon acceptance of the ready prompt, the question was visually displayed along with response alternatives in multiple-choice format. The SA probe queries asked about conflicts and the status of AC or ATC operations in the scenario.

TRAINING MANIPULATIONS AND FINDINGS

Research on training techniques has resulted in a large number of methods for assisting operators to acquire and maintain complex skills. Common training techniques include part-task training (i.e., training component tasks prior to whole-task performance; Paas & van Gog, 2009; van Merriënboer & Kester, 2008), increasing the difficulty of training (e.g., Healy & Bourne, 2013; Young, Healy, Gonzalez, Dutt, & Bourne, 2010), interactive and simulation training (e.g., Wieland, 2010; Vu, Kiken, Chiappe, Strybel, & Battiste, 2013), and use of supplemental instructions (e.g., Rabitoy, Hoffman, & Person, 2015). All these techniques have achieved varying levels of success. The effectiveness of any one of them, however, is dependent on a variety of contextual factors (see, e.g., Wickens, Hutchins, Carolan, & Cumming, 2013).

Given that ATC is a complex task, we mainly employed different variants of the part-task training paradigm, in which students were trained to manage traffic using one skill at a time (i.e., first manage traffic through changing headings, then through issuing altitude changes, and finally through imposing strategic sector structures). As we were interested in the introduction of NextGen tools and concepts, we introduced those tools to students at different points in time, depending on the semester in which they were enrolled. We consider whole-task performance as being able to manage a mixed-equipage sector of NextGen equipped and current-day equipped AC.

Billinghurst et al. (2011) examined whether the order of training (i.e., training current-day manual skills first or NextGen skills first) made a difference in student ATCo's subsequent performance and SA managing a mixed-equipage sector. Training current-day, manual skills may be beneficial because it is the more difficult skill (includes less automated tools to aid the controller). Training the NextGen skills first, however, may allow the students to acquire global ATC skills given that they are not devoting much of their resources learning to perform manual tasks. Both groups were tested in mixed-equipage scenarios. Billinghurst et al. (2011) found that the students' air traffic performance was better when tested immediately after manual training than after NextGen tools training regardless of when the skills were introduced. There was no effect of training order on the student ATCo's SA.

Kiken et al. (2012; see also Vu et al. 2013) more directly compared part-whole (training on one type of equipage on its own first before combining it with the other type of equipage) and whole-task (training both types of equipages concurrently) procedures. The part-whole lab was trained only on the traditional, manual skills during the first half of the semester and then with the mixed-equipage environment during the second half of the semester. In contrast, the whole-task group learned both the manual and NextGen tools concurrently in mixed-equipage scenarios for the entire semester. Kiken et al. (2012) found that training did overall improve the student ATCo's performance, but the type of training mattered only for certain students. In particular, students with higher aptitude were not affected by when the NextGen tools were introduced in training, but the students with lower aptitude benefited from initial training with the traditional, manual skills before being introduced to the NextGen tools (Vu et al., 2013). Consistent with the finding that student aptitude was a larger factor than type of training, Vu et al. (2013) found that students with higher aptitude showed higher levels of SA in general. For students with lower aptitude, those with whole-task training showed lower SA compared with the students with part-whole training. As the part-whole training reduces the cognitive load imposed on the low-aptitude students, they likely had the extra capacity needed to acquire good SA.

Vu et al. (2012a) trained students from both lab groups to manage their sector with both NextGen equipped and unequipped AC but varied the proportion of the NextGen equipped AC so that students would have more (sector with 75% equipped AC) or less (sector with 25% equipped AC) experience with NextGen tools and procedures. Vu et al. (2012a) found a benefit for training with NextGen tools. Specifically, the student controllers performed better and reported reduced levels of workload when the sector consisted of more NextGen equipped AC. The students showed similar levels of SA regardless of training technique. However, when they were tested in a scenario with all NextGen equipped AC, students showed lower SA than when they were tested in scenarios with some or no NextGen equipped AC. This finding indicates that student ATCos do become complacent when they expect that all conflicts in their sector will be alerted. In general, there was little effect of order of training under nominal situations. That is, students trained to rely more on manual skills early in training performed just as well as students who were trained to rely more on NextGen tools early in training.

The order of training did, however, have an impact on ATCo performance when NextGen tools failed. When a Data Comm failure was introduced in the very last test session, the group that was trained to rely more on manual skills early in training showed fewer detrimental effects in terms of LOS and sector efficiency. However, training order did not differentially impact the student ATCo's workload or SA during the Data Comm failure. All training groups showed lower SA and higher workload levels during the failure scenario compared with the nominal one.

Summary

Our course has been successfully delivered to over 80 students over a four-year period. By using this course structure and a variety of manipulations, we have shown that students benefit more from recent training of traditional manual skills compared with NextGen skills (Billinghurst et al., 2011). Moreover, students who were trained to rely more on traditional, manual skills early in training performed better than the group trained to rely more on NextGen tools early in training when NextGen tools failed (Vu et al., 2012a). Students with higher aptitude were not affected by when the NextGen tools were introduced in training, but the students with lower aptitude benefited from a training schedule that introduced the NextGen tools after the traditional, manual skills were practiced (Vu et al., 2013). Training order and type had less impact on the student ATCo's SA, with the exception that students with lower aptitude benefited more from part-whole than whole-task training, because the task simplification allowed them the extra capacity needed to acquire good SA.

To conclude, this chapter illustrates why the topic of SA is important to the design and evaluation of NextGen tools, technologies, concepts of operation, and training procedures for ATC. SA drives ATCo decision-making abilities and impacts ATCo performance in terms of maintaining safety of flight and efficiency of air traffic flows. Research evaluating components of NextGen need to include comprehensive measures of SA, because observed changes in workload may come at a cost to SA.

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