**State-of-Science: Situation Awareness in individuals, teams and systems**

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**Abstract**: Our review addresses one of the most used, but debated, topics in Ergonomics: Situation Awareness (SA). We examine and elaborate upon key SA models. These models are divided into individual SA, team SA and systems SA categories. Despite, or perhaps because of, the debates surrounding SA it remains an enduring theme for research and practice in the domain of Ergonomics, now for over two decades. A contingent approach, which seeks to match different models of SA to different types of ergonomics problem, enables the differences between positions to be revealed and reconciled, and the practitioner guided towards optimum methodological solutions.

**Practitioner Summary:** Measuring situation awareness (SA) in individuals, teams and systems has become a key objective in Ergonomics. One single approach to SA does not fit all problems encountered. This review shows the importance of considering all three types of models and achieving a match between them and the problem at hand.

**Keywords**: Situation awareness, theory, models, team SA, distributed cognition

**THE State of the Science**

Situation awareness (SA) is one of the most keenly studied topics in Ergonomics (Wickens, 2008; Salmon and Stanton, 2013; Stanton et al, 2010). It is also one of the most hotly debated. SA is used to describe how people, and increasingly entire socio-technical systems, become and remain coupled to the dynamics of their operational environment (Moray, 2004). As a concept, SA provides researchers and practitioners with various models and methods to either describe what SA comprises, to determine how individuals, teams or systems develop SA, or to assess the quality of SA during task performance (Salmon and Stanton, 2013). Such accounts should also provide explanations for what happens when SA is ‘lost’, and how it affects performance when it is first gained or later regained (Stanton et al, 2015).

Unusually, for an Ergonomics concept, it has entered into wider society’s mainstream lexicon. SA is used in many settings and professions to refer interchangeably to information that resides in people’s heads and/or minds (Fracker 1991, Sarter and Woods 1991, Endsley 1995) or even brains (Endsley, 2015). It has more recently been viewed as something that exists in the world, in displays or other environmental features (e.g. Ackerman, 1998, 2005). It has also been expressed as an emergent property of people and their environment (Stanton et al. 2006, 2009a, 2010). SA has been explored in many operational contexts, including military settings (e.g. Endlsey 1993; Salmon et al, 2009; Stanton et al, 2006; Stanton, 2014; Stewart et al, 2008), transportation (e.g. Ma & Kaber, 2007; Golightly et al, 2010, 2015; Salmon et al, 2014, Walker et al, 2008, 2009) sport (Bourboussan et al, 2011; James & Patrick, 2004; Macquet & Stanton, 2014; Neville and Salmon, 2016), health care and medicine (Bleakley et al, 2013; Fioratou et al, 2010; Hazlehurst, McCullen & Gorman, 2007; Schulz, 2013), process control (Salmon et al, 2008; Sneddon et al, 2015; Stanton et al, 2009b) and emergency services (Seppanen et al, 2015; Blandford and Wong, 2004) to name a few. Experimental, theoretic and synthetic papers that deal with the concept of SA are among the most cited in the discipline (e.g. Lee, Cassano-Pinche´ & Vicente, 2005) and the term SA is one of Ergonomics’ most widely used (Patrick & Morgan, 2010). According to GoogleNgram (see Figure 1) the term ‘situation awareness’ was hardly used at all within the corpus of literature prior to Endsley’s (1988), Woods (1988) and other pioneering publications on SA in the late 80’s. The line graph shown in Figure 1 accelerates dramatically from that point in time forward. Despite its prevalent use in many areas, our understanding of SA remains in constant development, even flux (Flach, 1995; Dekker, 2015). Indeed, for such a fast moving and important part of our discipline, a state-of-the-science review is not simply timely, it is arguably well over-due.

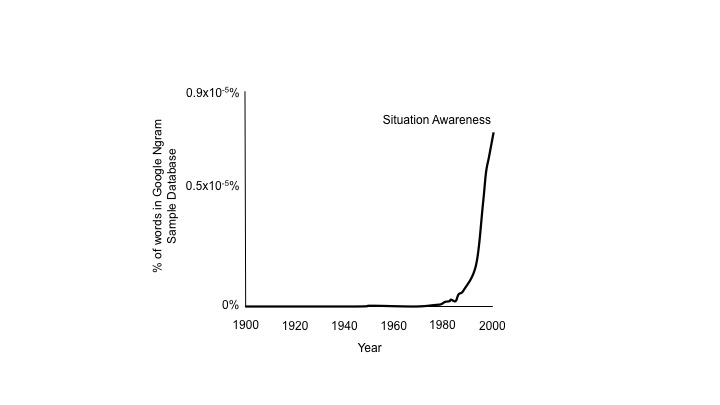


Figure 1 – Google Ngram plot showing how the use of the term Situation Awareness in the English language lexicon has accelerated dramatically since the 1980s

Like many comparable concepts, such as workload (Young et al, 2015), trust (Kauer et al, 2015), mental models (Revell and Stanton, 2012), and safety (Hignett et al, 2013) there is no universally accepted definition of situation awareness. There are definitions that have proven to be more popular than others, but there are clear differences in how researchers and practitioners understand and define the concept. This has been starkly illustrated in recent journal special issues on SA (e.g. Pritchett, 2015) wherein the topic has proven to be unusual for the degree of contention it generates (see Carsten and Vanderhaegen, 2015; Endsley, 2015; Salmon et al, 2015; Stanton, 2010, 2016; Stanton et al, 2015). Providing that positions do not become excessively entrenched and overly dogmatic, for the profession, this debate creates a rich and exciting constellation of ideas and contentions around SA (Stanton, 2016; Salmon and Stanton, 2013).

Taken at face value, the discipline already has a dominant theory of SA (the three level model promulgated by Endsley in a Special Issue of the *Human Factors* journal in 1995 being undoubtedly the most popular). There are also associated methods with which to convert this model into ergonomics practice (of which there are many examples, see Salmon et al, 2006). If the discipline were to be defined purely as a pragmatic endeavour, and success judged solely in terms of practical application, then a state of science review of SA might well prove exceedingly short and not at all contentious. Thankfully, for our science, this is not the case. Practical concerns are key, but their value derives from the state of the underlying science. What makes SA so captivating is how radically different the concept of SA looks when projected through different theoretical foundations and associated world-views. What is becoming increasingly evident is that the worldview through which early models of SA were projected is quite different from alternate world-views that are emerging today. When Endsley’s first paper on SA was published in the 1988 Proceedings of the Human Factors and Ergonomics Society Annual meeting, the paradigm of experimental and cognitive psychology was firmly established and even deeply entrenched in the discipline. This dominance is something that van Winsen and Dekker (2015) have referred to as the ‘first cognitive revolution’. Ideas around systems thinking, specifically distributed cognition (e.g. Hutchins, 1995a, b) and cognitive systems engineering (Rassmussen et al, 1994) were far from mainstream at that time. In many cases, they were in their infancy. Compare this with today. There is a much stronger and growing systems focus (Salmon et al, 2015; Dul, et al., 2012) and increased recognition of the importance of systems concepts like complexity (Walker et al., 2010), constraints (Vicente, 1999), dynamism (Dekker & Woods, 2000), multiplicity (Lee, 2001), fuzziness (Karwowski 2000, Lee et al. 2003), randomness (Hancock, et al. 2000) and a myriad of allied terms, like resilience (Hoffman and Hancock, 2016). These are used to describe the kinds of problems Ergonomists are called upon to resolve. Nearly three decades since the term situation awareness entered Human Factors the standard paradigm has shifted, with the second cognitive (systems) revolution now being upon us (van Winsen & Dekker, 2015). One question we look to address here is: how has SA shifted with these emerging paradigm shifts?

The goal of this state-of-the-science review, therefore, is to convey the richness of the current debate around SA. The purpose of this review is NOT to dissect the state of empirical science; rather it draws on the empirical findings is to assess the current status of SA theory and models. It will evaluate the SA concept through different world-views, highlight where the main debates originate, how they can be reconciled, and present practical implications for the benefactors of the services Ergonomists dispense. We argue it is insufficient to judge any important Ergonomics concept purely on the criterion of practical expediency. We have to understand and explain the philosophical foundations and assumptions upon which our science is founded. Consequently, to present the state-of-the-science in this review effectively, we need to go beyond current practice and return to our fundamental foundations.

**describing Situation Awareness**

At the most basic level, avoiding for the moment any strong links to a particular paradigm, situation awareness could be described simply as “knowing what is going on around you” or “having the big picture” (Jones, 2015, p. 98). To be more specific, situation awareness could be described as the ability of actors (usually humans, but not necessarily so) to become and remain coupled to the dynamics of their environment (e.g. Woods, 1988; Moray, 2004). This is on the assumption that being coupled to the dynamics of an environment is a desirable state of affairs for behaviours occurring within that environment (but again, this need not necessarily be so).

Knowing what is going on around you, as a high-level description of SA, imbues the concept with a strong ‘situation focus’, an objective ground-truth against which ‘awareness’ can be judged. There is an appealing cause (situation) and effect (awareness) logic in this ‘ground truth’ principle. It is only upon closer inspection that important subtleties are revealed. The notion of a ground-truth against which awareness of a situation can be judged tends to presume a *“mapping of the relevant information in the situation onto a mental representation of that information within the [individual]”* (Rousseau, Tremblay & Breton, 2004, p. 5). The term ‘mental representation’ reflects two further aspects of ‘awareness’. Firstly, that the ‘relevant information’ contained within a ‘mental representation’ is structured: SA is not merely about the presence or absence of discrete elements but also their contextual interconnections. Billings (1995) goes on to refer to an “abstraction within our minds” which reflects a second aspect of awareness: it is hypothetical in nature (Bryant et al., 2004). Awareness of a situation by an individual is not a canonical model with a direct one-to-one, homeomorphic, mapping to ‘reality’ (e.g. Banbury, Croft, Macken & Jones, 2004). Rather, it is *“a representation that mirrors, duplicates, imitates or in some way illustrates a pattern of relationships observed in data or in nature […]”, “a characterisation of a process […]”* (Reber, 1995, p.465) which may indeed contain isomorphic or polymorphic characteristics (but again, not necessarily so). It can be assumed that SA needs to provide individuals with “*explanations for all attendant facts”* (Reber, 1995; p. 793) in order for them to make better decisions and reap the benefit of improved performance.

A key issue is that explanations for attendant facts do not necessarily require either a particularly rich or detailed model of the situation. Indeed, it would be a highly inefficient form of representation if it did, and one not likely to have been supported by millennia of evolution. Rather, there is robust evidence that the better the mental representation (or awareness), the more parsimonious it is (e.g. Gobet, 1998; Chase & Simon, 1973). Information in ‘working memory’, upon which awareness is based (e.g. Bell & Lyon, 2000), can be forced to higher, more implicit levels of abstraction (Walker et al, 2009). The paradox is the better a person (or ‘agents’) ‘mental theory’ of their situation the less likely it is to have a direct one-to-one, isomorphic, mapping to the object or situation that is being perceived. In other words, ‘ground truth’ may have very little direct mapping with ‘awareness’. Furthermore, such awareness could conceivably represent one of many possible ‘ground truths’, each one individually capable of yielding optimal performance. It is well known that experts are able to chunk information (Chase and Simon, 1973) and that perception of the situation as a whole is greater than the sum of its parts (Duncan, 1979). In addition, there may be many paths to success, rather that just one right way (Vicente, 1999).

High-level definitions of SA also carry with them a linear or sequential flavour. This point is contentious (see Endsley, 2015; Stanton, Salmon & Walker, 2015) yet it is fair to say that many models of SA, including the most dominant (e.g. Endsley, 1995), assume that “humans typically operate in a closed-loop manner” (Endsley, 1995, p. 33). Whilst there can be little doubt that human performance does indeed rely on a chain of input-processing-output-feedback, there are contexts where this is not the case. Indeed, a larger proportion of behaviour than is often acknowledged is feed-forward (Plant & Stanton, 2013) where ‘processing’ and ‘outputs’ can conceivably occur without there being ‘input’ in the sense it is normally understood. Tasks such as driving, for example, which are routine and well learnt can often be performed on the basis of well-developed mental theories that require minimal input to guide effective behavior (Stanton et al, 2007; Walker et al., 2009c). Extreme examples of top-down, feed-forward behaviors are Driving Without Attention (May & Gale, 1998) and Mode Errors (Sarter and Woods, 1991), of which there are numerous examples, from rail (e.g. Stanton & Walker, 2009) to road (Stanton et al, 2011) to air (Griffin et al, 2010; Salmon et al, 2016). Situations like these result in part from top-down ‘knowledge in the head’ (awareness) overriding bottom-up ‘knowledge in the world’ (the actual situation: see Stanton & Walker, 2011). Expectations can play a major role in awareness of a situation and can be very misleading some of the time (Refferty et al, 2013). This is something mainstream models of SA readily acknowledge (see Endsley, 2015 for example) but in common usage around the wider discipline not always something that comes to the foreground. Instead, what tends to dominate the discourse (not exclusively, but commonly) is a focus on the presence or absence of specific features in a situation (e.g. Endsley, 1995; Fracker, 1991).

As well as linearity and sequentiality, high-level definitions of SA also carry a ‘normative’ flavour. The tacit assumption here being that the objective ‘ground-truth’ situation provides a relatively static and enduring reference point for judging the ‘goodness’ or ‘badness’ of SA (Endsley, 1988, p. 793). This is a generalization but one founded on a considerable body of visible work within the discipline. For example, see the reviews by Endsely (2015), Salmon et al (2006) and Wickens (2008). SA, however, is created for a purpose (Patrick & James, 2004) and that purpose, fundamentally, is to generate better situations – via improved performance - to subsequently be aware of. Smith and Hancock (1995) describe SA as *“a generative process of knowledge creation”* (p. 142) in which *“[…] the environment informs the agent, modifying its knowledge. Knowledge directs the agent’s activity in the environment. That activity samples and perhaps anticipates or alters the environment, which in turn informs the agent”* (Smith & Hancock, 1995, p. 142). Like many models of SA (e.g. Endsley, 1988) this process is cyclical in nature. Like all perception-action loops, the search for original ‘cause’ can be a diverting but often misleading one, something the Smith and Hancock (1995) model makes explicit by referring to SA as ‘constructive’ in its nature. The agent or actor is a part of the situation they find themselves and can influence its dynamics, indeed, are essential parts of its future. Thus, individuals are not always passive observers of a static normative situation, rather, they are agents in an interactive dynamic system, creating new ‘formative’ situations to become aware of (Stanton & Walker, 2011; Plant & Stanton, 2012). Clearly, SA is more complex then than the vernacular, everyday, use of the term suggests.

**defining situation awareness**

The definition of SA has changed and developed over the past three decades, reflecting an evolution in foci of the Ergonomics discipline as well as the understanding of SA itself. Early definitions of SA used the term ‘situational awareness’ and focused on the individual person, as defined by Endsley:

*“Situational awareness is the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and a projection of their status in the near future”* (Endsley, 1988).

As research interest in SA grew, so it expanded from the individual level to the team level; a step from the personal to the social. Definitions of SA came to reflect this expansion, thus:

*“the shared understanding of a situation among team members at one point in time”* (Salas et al., 1995, p. 131)

Contemporary research into systems ergonomics has led to an interest in applying SA to larger and more complex interacting systems of human and technical agents. Again this has led to an evolution in definition, such as:

*“activated knowledge for a specific task within a system….[and] the use of appropriate knowledge (held by individuals, captured by devices, etc.) which relates to the state of the environment and the changes as the situation develops”* (Stanton et al, 2006, p. 1291).

In aviation, for example, one might study the awareness of individual pilots in the cockpit, specifically the pilot flying. Or SA analysis could be expanded to include the aircrew, not just the pilot flying but the captain, engineer/navigator, cabin and/or cargo crew. Subsequent analysis could also embrace the flight deck instruments, flight deck computers, flight director, autopilot, air traffic management system, flight data recorders, and so on (Salmon et al, 2016; Stanton et al, 2010; Sorensen et al, 2011). An expanded, but still legitimate comprehension of system SA can be extended out to the wider aeronautical transport system to include en-route and terminal controllers as well as overall systemic traffic-flow planning (Stanton, 2016; Stanton et al, 2015). After all, these collective agents (i.e. both human and non-human entities) also have to track and/or represent the situation in complex (and not so complex) ways in order to function as they should, or at the very least, help human agents to achieve acceptable levels of performance. This perspective expands even further into an overarching evaluation of the ‘system-of-systems’ (Harris and Stanton, 2010), which opens up even higher-level concerns for the global environment (e.g., whether ‘good’ SA at the individual level translates into good performance at the collective level, e.g. Walker & Manson2014.).

The systems-of-systems view represents a significant departure from the appealing cause and effect logic of individualistic models of SA rooted in cognitive psychology. The notion that SA resides in human as well as non-human (technology) agents is particularly controversial (Endsely, 2015). Consideration of human and non-human agent awareness is, however, becoming increasingly important given technological advances such as artificial intelligence and advanced automation (e.g. Lee, 2001; Hancock, 2014; 2016 ), and so too is the notion of multiple ‘agents’ cooperating over time in order to remain coupled to the dynamics of their environment (Stanton, 2016; ). Issues like these lie at the heart of wider Socio-Technical Systems (STS) approaches to overall system performance (Walker et al, 2009). The practical utility of these systemic strategies stem from their ability to provide insights into particularly thorny Ergonomics problems. Automation is a case in point. Take the recent disaster involving Air France 447 as an example (Salmon et al, 2016). Here the automated aircraft and cockpit systems were unaware of the current airspeed due to icing of the three pitot tubes (which measure air speed independently). Following the autopilot’s disconnection in response to this informational shortfall, the aircrew were unaware of why the autopilot had defaulted to this condition, what control inputs were needed to create a stable situation and what the flight status of the aircraft was (i.e. stall and rapid descent). Added to this is that each flight phase represented a set of different ‘situations’ for the system as a whole to be ‘aware’ of. Within each of these phases, the situation was changing dynamically for each individual agent. There can be no question the concept of situation awareness has much to offer in diagnosing incidents such as these, and from a variety of perspectives. It is possible to define the ground truth situation and the subsequent individual awareness, but it is also possible to examine team SA, or the SA of the entire system. Combining these perspectives, contingent on the insights that need to be extracted, means the system has to be studied at an appropriate level of analysis, be it individual, team or entire system-level comprehension. In what follows, we use this idea of levels of analysis to frame and evaluate current SA theoretical models.

**Theoretical Models of SA**

Three distinct types of SA models have been identified: (i) individual, (ii) team and (iii) system. The theoretical bases for these models are now examined.

***Models accounting for situation awareness held by individuals***

Early models of SA focussed on individual operators and how they acquired SA cognitively during task performance (e.g. Adams, Tenney & Pew, 1995; Bedney & Miester, 1999; Endsley, 1995; Smith & Hancock, 1995). Heavily psychology-based, these models sought to explain the processes underpinning the awareness held in the minds of individual operators, that is, SA as experienced in the mind of the person (Stanton et al, 2010; Endsley, 2015). This focus incorporated the psychological processes involved (e.g. mental models, schema, perception, comprehension) and the nature of SA itself (e.g. the person’s SA comprising knowledge about x, y, and z). Such a focus explains why early discussion of SA so heavily featured the already well-rehearsed questions about the nature of human consciousness (James, 1890). Two of these models in particular stand out (Wickens, 2008): the three level model by Endsley (1995) and the perceptual cycle model by Smith and Hancock (1995). The former is by far the most popular, and has received increasing attention as individual models began to be integrated with wider and more comprehensive systems models (e.g. Stanton et al, 2009a, b). The latter represents a well-cited counterpoint founded on its own distinct theory-base. Both are shown, along with other relevant offerings, in Table 1.

Table 1 - Theories that account for Situation Awareness held by Individuals

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Definition** | **Author** | **Theoretical Underpinning** | **Origin** | **Google Scholar Citation** |
| Perception of elements, comprehension of meaning and projection of future status | Endsley (1988) | Three-level model | Started with aviation, later spread to other domains | 2253 |
| Situation awareness is based on the integration of knowledge resulting from recurrent situation assessments. | Sarter & Woods (1991) | Working memory, mental models, situation assessment awareness | Aviation | 273 |
| SA is the pre-requisite state of knowledge for making adaptive decisions in situations involving uncertainty, i.e. a veridical model of reality. | Taylor (1990) | Theories of attention and cognition | Military, air traffic control and nuclear power | 272 |
| Situation awareness is adaptive, externally-directed consciousness that has its products knowledge about a dynamic task environment and directed action within that environment. | Smith & Hancock (1995) | Perceptual cycle model | Air traffic control | 204 |
| The conscious dynamic reflection on the situation by an individual, providing dynamic orientation to the situation and an opportunity to reflect on the past, present and future and potential features of the situation. | Bedny and Meister (1999) | Theory of activity | Training, Information Systems and HCI | 159 |
| SA contributed to good performance, it is not synonymous with it. It is possible to have good SA but still not be a good pilot because of poor motor skills, coordination or attitude problems. Conversely, under automated flight conditions it is possible to have good performance with minimal SA. | Adams, Tenney & Pew (1995) | Perceptual cycle model,  working memory | Aviation | 33 |
| “…an abstraction that exists within our minds, describing phenomena that we observe in humans performing work in a rich and usually dynamic environment.” | Billings (1995) | Information processing theory | Aviation | 31 |
| Situation awareness is knowledge of current and near term disposition of both enemy and friendly forces within a volume of airspace. | Hamilton (1987) | Three-level model | Military airspace | 6 |

Endsley’s three-level model (1995a) has undoubtedly received the most attention with 2253 citations recorded for the original paper in the Scopus database (Scopus, accessed 15th February 2016). This citation frequency establishes it as the most cited paper on SA and indeed one of the most cited of all papers in Ergonomics. The information processing-based model describes SA as an internally held cognitive product comprising three levels: perception (level 1), comprehension (level 2) and projection (level 3), which feeds into decision-making and action execution. Level 1 SA involves perceiving the status, attributes and dynamics of task-related elements in the surrounding environment (Endsley, 1995). According to the model a range of factors influence what data are perceived, including the task being performed, the individual’s own personal goals, experience, expectations and also systemic factors such as interface design, level of complexity and automation. To achieve Level 2 SA, the individual interprets the level 1 data and comprehends its relevance to their task and goals. Level 3 SA involves forecasting future system states using a combination of level 1 and 2 SA-related knowledge, and experience in the form of mental models. By these means individuals can forecast likely future states and use this to effect action. In reality, such assertions recapitulate many earlier efforts to deal with the problems of consciousness in context (ct: Gibson & Crooks, 1938; Hancock & Diaz, 2001; James, 1890).

Endsley’s conception foregrounds cognitive models of information processing, and evidence of this can be seen in the loose parallels that can be drawn between more basic Input-Processing-Output (IPO) models of cognition (see Stanton et al, 2001). Endsley’s model is of course, to a degree, more complex and nuanced than this. Despite the use of the terms ‘Level 1, 2 and 3’, and the way in which the model has been previously described (e.g. Endsley, 2000), the model is not linear. This is a frequent misconception the original author has been keen to correct (Endsley, 2015), albeit one not aided by the aforementioned terms 1-2-3 or the way in which the model has frequently been deployed (e.g. Stanton, Salmon & Walker, 2015). With these important caveats in mind, it is fair to say the hereditary line between IPO models of cognition and early models of SA is apparent and entirely consistent with the zeitgeist of cognitive psychology at the theory’s inception in the 1980’s. It is for this reason that Smith and Hancock’s (1995) ecological approach to SA offers a useful contrast. It is based on schema theory (Plant & Stanton, 2013), in particular Neisser’s (1976) perceptual cycle model. Couched in these terms, Smith and Hancock describe SA as a:

*“generative process of knowledge creation and informed action taking”* (1995, p. 138).

Neisser’s original model describes the cyclical nature of perception and action, showing how our interaction with the world is directed by internally held schemata or mental templates. Then, in turn, how the outcome of these interactions serve to modify the initial schemata, which in turn directs further interactions and so on. It could be argued that Endsley’s three level model also represents a notion of cyclicity, but in a different way. Smith and Hancock (1995), for their part, argued that SA is a sub-set of working memory but, more importantly, that it neither resides exclusively in the world nor exclusively in the person, but instead emerges through the interaction of the person with the world. This is an important point of departure. Smith and Hancock (1995) thus described SA as *“externally, directed consciousness”* that is an *“invariant component in an adaptive cycle of knowledge, action and information”* (p. 138). They argued that the process of achieving and maintaining SA revolves around internally held schema, which contain information regarding certain situations. These schemata facilitate the anticipation of situational events, directing an individual’s attention to cues in the environment and guiding their eventual course of action. An individual then conducts checks to confirm that the evolving situation conforms to those expectations. Unexpected events serve as prompts for further search and explanation, which in turn modifies the operators existing model.

Models based on the notion that SA resides exclusively in the mind of the individual (e.g. Fracker 1991, Sarter and Woods 1991, Endsley 1995; 2015) provide satisfactory answers to many types of question. They also enable practical methods for SA of this type to be captured in an expedient way. However, such models provide less satisfactory answers for other types of SA. They often have difficulty explaining the formative aspects of SA and the contention that SA should help the actor create a better situation to be aware of; that knowledge in the head (or expectancy) can enable actors to create a rich awareness of their situation from very limited external stimuli; and that normative performance standards against which to judge the ‘rightness’ of SA do not exist in many tasks, and that such fixed and inflexible prescriptions may in fact be undesirable. These fundamental limitations to the individualistic/cognitive approach to SA can be crystalised into a set of tacit assumptions about SA itself; that:

1. it is a cognitive phenomenon residing in the heads of human operators;
2. there is a ground-truth available to be known; and
3. good SA can be derived from reference to expert or normative performance standards.

This is not to suggest models of SA referencing these tenets are not effective in certain practical situations. It is simply important to acknowledge that in applying individualistic models of SA certain assumptions are being made. It is fair to say that if the part of the socio-technical system under analysis can be usefully regarded as normative, closed loop and deterministic, then normative, closed loop and deterministic SA approaches are entirely appropriate. Many practical problems do indeed take this form (e.g. highly scripted tasks in which deviations from normative performance standards are not advisable, such as a pilot conducting pre-flight checks with checklists). Moreover, in an evolutionary sense, it is precisely these tasks that are the target of burgeoning automation (Hancock, 2014). Even when tasks do adhere to a form of quasi-deterministic logic there are multiple circumstances for which systems operation is defeated by the inherent complexity of context and the ambiguities of ambient uncertainty. From this evolving understanding has emerged a need to envisage SA through differing lenses and levels of analysis; such as whether to include operational teams as well as a complete systems approach. In the checklist example above, it is worth bearing in mind the check occurs within a sociotechnical system in which SA can also be viewed at the team (i.e. aircrew), organizational (i.e. flight provider) or system level (i.e. aircrew, aircraft, air traffic control, airport ground staff etc.).

***Models accounting for situation awareness held by teams***

The problem spaces in which ergonomics researchers and practitioners operate are frequently characterised by the presence of multiple member teams (Annett & Stanton, 2000). Teams are defined as *“a distinguishable set of two or more people who interact dynamically, interdependently and adaptively toward a common and valued goal, who have each been assigned specific roles or functions to perform and who have a limited life span of membership”* (Salas, Prince, Baker & Shrestha, 1995). Salas (2004) suggested that characteristics of teams include meaningful task interdependency, co-ordination among team members, specialised member roles and responsibilities, and intensive communication. We know from the team literature that effective teams engage in considerable mutual performance monitoring (Salas et al 2015). This is, in essence, a scanning of their mutual operational ‘situation’ and surroundings. It is not surprising then, that researchers quickly began to examine the application of SA models to team environments (Endsley, 1993; Salas et al, 1995; Shu & Furuta, 2005; Wellens, 1993; Table 2).

Table 2 - Definitions accounting for Situation Awareness held by Teams

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Theory** | **Domain of Origin** | **Applications** | **Authors** | **Theoretical Underpinning** | **Google Scholar Citation** |
| Team SA | Generic | None | Salas et al. (1995) | Three-level model, team work theory | 482 |
| Team SA | Military | Military | Wellens (1983) | Three-level model, distributed decision-making model | 144 |
| Inter- and intra-team SA | Military | Military | Endsley & Jones (2001) | Three-level model | 140 |
| Team SA | Aviation | Military aviation maintenance | Endsley & Robertson (2000) | Three-level model | 100 |
| Mutual Awareness Team SA model | Process control | Dual Reservoir System Simulation (DURESS) | Shu & Furuta (2005) | Three level model, Theory of shared cooperative activity | 77 |

Many early team SA applications involved scaling up Endsley’s model to the team level, and then incorporating the related concepts of team SA. This included the degree to which every team member possesses the SA required for his or her own individual responsibilities (Endsley, 1989). These elaborations were set alongside a requirement for shared SA, or the extent to which team members have the same SA on mutual operational requirements (Endsley & Jones, 1997). Using the three level model as its basis, this approach to team SA argued that that team members each have distinct portions of SA, but also overlapping or ‘shared’ portions of SA. Successful team performance requires that individual team members have sufficient SA on their specific elements and the equivalent SA for the necessarily shared elements (Endsley & Robertson, 2000).

While this approach provides satisfactory answers to some types of team SA questions it is again less satisfactory for a number of other critical dimensions (Stanton et al, 2001). As a result, two team SA models have received particular attention: Salas et al’s (1995) team SA model, and Shu and Furuta’s (2005) mutual awareness model. Salas et al. (1995) argued that team SA comprises individual SA together with various team processes. The critical component of team SA, according to Salas et al, is information exchange. They argued the perception of SA elements is influenced by the information exchange needed to accomplish mission objectives, determine individual tasks and roles, the team’s capability (i.e., expertise) alongside other team performance shaping factors (Salas, et al, 2005). Information exchange can be viewed, in a simplistic sense, as communication between actors. In detail, it involves more than merely verbal exchanges; it includes information in the form of task status, information displays, and the myriad of other cues that exist in complex team environments. Salas et al. (1995) go further and argue that schema limitations can be offset by this information exchange. The comprehension of this information is affected by the interpretations made by other team members, which in turn is affected by their own individual SA. Thus, it is evident that individual SA underwrites team SA, which subsequently modifies that person’s own SA in turn.

Thus a cyclical process of developing individual SA, sharing SA with other team members, and then modifying both team and individual SA based on other team members SA is apparent. This represents a direct extension of Smith and Hancock’s (1995) cyclic interpretation in which other team members represent salient parts of the ambient surroundings. Salas et al. (1995) conclude that team SA *“occurs as a consequence of an interaction of an individual’s pre-existing relevant knowledge and expectations; the information available from the environment; and cognitive processing skills that include attention allocation, perception, data extraction, comprehension and projection”* (Salas et al., p. 125). Like many such extensions, an emerging characteristic (i.e. team SA) results from the interaction of component elements (i.e. individual team member SA). It is possible to argue that what emerges is not of the same order of phenomenon as that of which it is composed. In recent years, other views of team cognition have emerged (see Fiore & Salas, 2004) that make the same point; specifically those relating to shared mental models, macrocognition, and team SA being more (or indeed less) than the sum of its individual SA parts (see Fiore at al, 2012).

Addressing this, Shu and Furuta (2005) expanded on team SA models by proposing the concept of mutual awareness. This idea is conceptually similar to Endsley’s shared SA model. Shu and Furuta (2005) argue that team SA comprises both individual SA and mutual awareness. That is, the mutual understanding of each other’s activities, beliefs and intentions. They further describe how team SA is a partly shared and partly distributed understanding of a situation among team members. For example, in the cockpit, mutual awareness would be achieved when both the pilot flying and the pilot not flying are able to understand each other’s behaviours and motives when dealing with an in-flight emergency (something that was notable by its relative absence in the aforementioned Air France 447 disaster – Salmon et al, 2016). Shu and Furuta (2005) therefore define team SA as, *“two or more individuals share the common environment, up- to-the-moment understanding of situation of the environment, and another person’s interaction with the cooperative task.”* (Shu & Furuta, 2005, p. 274).

Models based on the notion that team SA relies on a combination of individual and shared awareness also reveal some fundamental limitations in the cognitive/experimental psychology approach. In this conception, shared SA is equivalent to identical SA, at least on those parts of a situation that require shared SA. Whilst the notion of teams admits the possibility of greater degrees of change and dynamism, the normative nature of SA may still remain. As before, this is not to suggest that such models are not effective in certain practical situations, but it is again important to reiterate that in applying the most popular team-SA approaches certain assumptions are being made. Upon closer inspection they provide less than satisfactory answers to questions that are becoming increasingly relevant to ergonomists. For example, the case of highly interdependent but remote complex systems in which awareness resides in perhaps hundreds or even thousands of disparate human and machine entities, some in close proximity and others distributed across the globe (e.g., the air transportation system mentioned in the section on ‘Describing Situation Awareness’). It is important, therefore, to be careful distinguishing between inherent shortfalls in the concept of team SA and the necessary uncertainty that attends the operations of all complex human-machine systems. The challenge is both a practical one, in seeking to predict future operational states, as well as a theoretical one. On the latter point, the issue centres around specifying the concepts we presently use to conceive and capture such necessarily complex understanding.

***Models accounting for situation awareness held by sociotechnical systems***

For a concept that began in the world of cognitive psychology SA is no different from many other fundamental elements of the Ergonomics discipline. Our fundamental scientific paradigm is, however, shifting. The new strategic direction is attached firmly to an increasing extent of systems thinking (e.g. Carayon et al, 2015; Dul et al., 2014; Walker et al, 2010; Walker, 2016). A distinct part of the ‘ergonomics offer’ to stakeholders, therefore, is its greater role and contribution within wider systems. SA is naturally an important part of these developments.

Systems thinking presents distinct challenges for SA. The concept of Socio-Technical Systems (STS) can be used as a starting point for discussing these challenges. STS describes a combination of people (‘socio’) with technical elements that interact so as to support organisational activity. Teams and teamworking, broadly defined, are at the center of STS, but there is more to STS than merely teams. STS typically involves multiple stakeholders (with different goals) governed by distinct organisational policies, rules and culture. STS perspectives naturally include the technical/technological infrastructure into the unit of analysis, and see these as important constrainers and enablers of behavior. STS are affected by external constraints such as national laws and regulatory policies, and they too must remain coupled to the situation in which they find themselves, if they are to be effective. A cornerstone of the STS concept is that interacting combinations of people and systems behave in complex, non-deterministic, and often in non-linear and non-additive ways which need to be harnessed if the overriding goal of ‘joint optimisation’ is to be achieved (e.g. Walker et al., 2009). This complexity is already manifest in high-technology and safety-critical domains (i.e., aviation, aerospace, chemical and petroleum process industries, healthcare, defence and nuclear power). Indeed, it is the challenge to these safety-critical systems that have, in part, engendered the genesis of STS (Hollnagel, 2014) STS concepts are becoming increasingly domesticated as an ever expanding array of products and services becomes more networked and sophisticated (Walker et al., 2008). In all cases, close coupling and interactive complexity leads to unexpected ways for systems to succeed or fail (Stanton & Walker, 2011; Salmon et al, 2013; Perrow, 2001). Whilst it is self-evident that STS, comprising many agents, elements, subsystems and their interconnections are complex it is less obvious that such systems are non-reductive. In other words, it is no simple or straight-forward task to disaggregate such complex systems into smaller ‘explainable’ units as one could with more traditional linear systems (Walker et al, 2010). The reductionist approach has been the cornerstone of the Ergonomics’ discipline with its roots in experimental cognitive psychology. Naturally, early explanations of SA were centred around similarly reductionist modes of thought. Today, our challenge is for increasingly systemic ways of thinking (van Winsen & Dekker, 2015). A list of theories that try to account for a systemic view of SA is shown in Table 3.

Table 3 – Theories that account for Situation Awareness as a Systems Phenomenon

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Theory** | **Domain of Origin** | **Applications** | **Authors** | **Theoretical Underpinning** | **Google Scholar Citations** |
| Distributed SA model | Maritime | Military, maritime, energy distribution, aviation, air traffic control, emergency services, road and rail transport | Stanton et. al (2006) | Perceptual cycle (Neisser, 1976)  Distributed cognition theory (Hutchins, 1995)  Distributed SA theory (Artman & Garbis, 1995) | 239 |
| Distributed cognition approach | Tele-operation | Tele-operations | Artman & Garbis (1998) | Distributed cognition theory | 120 |
| Military awareness team SA model | Process control  Artificial intelligence | Process control | Shu & Furuta (2005) | Three level model , shared cooperative activity theory (Bratman, 1992) | 74 |

SA was first discussed at a systems level by Artman and Garbis (1998). They outlined the idea that the system (not an individual actor) could represent the unit of analysis, with a focus on the joint cognitive system as a whole. They argued that SA is distributed not only across team members, but also throughout the artefacts that teams use. Their model outlined SA as representing ‘the active construction of a model of a situation partly shared and partly distributed between two or more agents, from which one can anticipate important future states in the near future’ (Artman and Garbis 1998, p. 2). Accordingly, their model encourages a focus on interactions between team members and artefacts rather than individual team member cognition. An example of this may be seen in the bulk power generation industry, where individual companies and organisations must not only produce and manage their own power levels, but must stand ready to interact with other companies to ensure the continued stability of power production.

Other researchers have presented similar arguments without outlining a specific model (e.g. Masys, 2005). However, over the last decade Stanton and his colleagues have proposed and refined the Distributed Situation Awareness (DSA) model (Stanton et al, 2006; 2008; 2016; Salmon et al, 2008; 2016; Neville and Salmon, 2016). This model is arguably the closest the discipline currently possesses to a sufficiently developed and usable systemic view of SA. Not only in the number of citations but also the extent to which the ‘system view’ in question is most firmly couched in systems theory.

DSA is underpinned by three theoretical concepts: (i) schema theory (e.g. Bartlett, 1932), (ii) Neisser’s (1976) perceptual cycle model of cognition (cf., Smith and Hancock, 1995) and, of course, (iii) Hutchins’ (1995b) distributed cognition approach. In the DSA model, SA is viewed as an emergent property of collaborative systems, arising from the interactions between involved agents, both human and technological. The notion that SA is not confined to humans in systems often causes conceptual difficulty, but the idea has good pedigree in the distributed cognition approach (e.g. Hutchins, 1995b). Indeed, this perspective is gaining further acceptance as technologies become ever more advanced (Hancock, 2016).

According to Stanton et al (2006; 2009a, b) a system’s awareness comprises a network of information upon which different components of that system have distinct views and ownership. For example, a pilot flying will have one view of the situation, while the pilot not flying (the pilot monitoring) will have a slightly different view (due to the distinct tasks they each have to perform). The aircraft’s systems will have another view (based on what they are designed to monitor). Likewise, each will bring different information to the situation themselves. For instance, the pilot flying will communicate his or her planned actions, the pilot not flying will provide updates on certain flight parameters, and aircraft systems such as the pitot tubes will measure and utilise parameters such as airspeed to enact automated sequences of response and provide feedback to the pilots. The key to DSA is that these different views are connected such that the appropriate information is given to the right agent at the right time.

As previously described, the Air France 447 crash gives an appropriate illustration of the DSA view and how it differs from individual and team approaches. Here Salmon et al (2016) described how the awareness required to fly the plane safely was distributed across the aircrew, the autopilot, the cockpit and aeroplane systems (e.g. pitot tubes), and other coupled agents such as air traffic control. Whilst a conventional viewpoint would argue the crash was caused by the pilot flying’s ‘loss of SA’ and subsequent actions that put the plane into a stall, a DSA-based perspective would instead argue that the overall system lost SA due to various failures in the exchange of veridical information between human and non-human agents. Indeed, at a simplistic level the loss of SA was initiated when the aircraft’s pitot tubes (the external devices that measure airspeed) froze and began sending spurious data to the cockpit (an exchange between two non-human agents). This led to autopilot disconnection and a need for the human agents to take control of the aircraft without any clear indication or understanding as to why they needed to do so. In the ensuing confusion, and following inappropriate control inputs, the aircraft stalled and descended rapidly into the ocean. A key point we make here is that, although there was a network of information, key agents were using different and incompatible combinations of the available information and thus the systems awareness was degraded to a point that key agents were unable to fulfil their roles. In essence, our observations devolve to a levels-of-analysis argument. If one considers a Protagorean perspective in which ‘man is the measure of all things’, then the individual SA approach embraces Kantowitz and Sorkin’s (1987) observation that the human agent is the ‘subsystem of last resort’. It may well appeal to the inherent tendency that in looking to understand such incidents we are forever in search of some human agency on which to fix ‘blame’. Our distributed notion thus not only changes the level of emphasis but begins to recast the notion of simple causal chaining, and this single agent blaming, in ever more complex technologies.

An important feature of the DSA model is that it still acknowledges the periodic need to revert back to an individual lens. This brings Neisser’s perceptual cycle, as it was originally envisaged, into clearer focus. It shows where in the cycle individuals are and what is happening as they traverse it (Neisser, 1976; Smith & Hancock, 1995). For example, individuals go through a continual cyclical process of schema-driven perception and action in the world, and world driven updating and triggering of schema. In the Air France incident, one plausible explanation is that information provided by the aeroplane, environment, and cockpit triggered an ‘overspeed’ schema in the pilot flying leading him to initiate a series of actions designed to slow the aeroplane down (i.e. put the aircraft into a climb). Without well-developed schema for an autopilot disconnection scenario the pilot was unable to understand the unfolding situation.

These internally held schema are labelled genotype schema, whereas the task activated schema are labelled phenotype schema (Stanton et al, 2009). The former are built over time from exposure to different situations. The latter are triggered during activity by features that are generalizable across a broad class of situation. The pilot flying’s ‘overspeed’ schema may, therefore, have been activated by the presence of cues that normally indicate an overspeed situation (e.g. aerodynamic noise, buffeting, information presented in the Primary Flight Display; BEA, 2012).

It is through this task and schema driven process that the notion of shared SA (e.g. Endsley & Robertson, 2000) comes into question. This is because rather than possess shared SA (which suggests team members understand a situation or elements of a situation in the same manner) the DSA model instead suggests team members possess unique, but compatible, types of awareness. Team members experience a situation in different ways as defined by their own personal experience, goals, roles, tasks, training, skills, schema and so on. Compatible awareness is what holds distributed systems like these together (Stanton et al, 2006; 2009a, b; Stanton, 2014). Each team member has their own awareness related to the goals they are working toward. This is not the same as other team members, but is such that it enables them to work successfully together. In social collectives, such as stock markets, there may be thousands or even millions of actors each seeking to optimise their own local aspirations. Whether the output (and SA) of such systems necessarily becomes more indeterminate over time is an important theoretical and practical issue.

The compatible SA view does not discount sharing of information, nor does it discount the notion that different team members have access to the same information; this is where the concept of SA ‘transactions’ applies (Sorensen & Stanton, 2015). Transactive SA describes the notion that DSA is acquired and maintained through transactions in awareness that arise from sharing of information. A transaction, in this case, represents an exchange of SA between one agent and another (where agent refers to either humans and/or technological artefacts). It is important to note that transactions in this case represent more than just the communication of information; rather, they are the exchange of SA where one agent interacts with another and both modify their SA as a result of that process. As agents receive information, it is integrated and acted upon, and then passed on to other agents. The interpretation of that information is different across team members. For example, when Air Traffic Control provides instruction to an aircraft in a particular phase of flight, the resultant transaction in SA for each pilot is different, depending on their role (pilot flying or pilot monitoring). Each pilot is using the information to support their own ends and goals, integrated into their own schemata, and each reaching individual interpretations. This represents an exchange rather than a sharing of awareness per se. Transactive SA elements from one model of a situation can form an interacting part of another without any necessary requirement for parity of meaning or purpose; it is the systemic transformation of situational elements as they cross the system boundaries from one team member to another that bestows upon system SA an emergent property. In other words, it is difficult to discern this behaviour by looking at actors, agents or sub-systems in isolation: it only becomes manifest when the system as a whole is taken as the unit of analysis. Flowing from this theory are a set of tenets that serve as a lens through which future system SA concepts can be critiqued (Stanton et al, 2006; Stanton, 2016):

1. Situation awareness is an emergent property of a sociotechnical system. Accordingly, the system represents the unit of analysis, rather than the individual agents working within it;
2. Situation awareness is distributed across the human and non-human agents working within the system. Different agents have different views on the same scene. This draws on schema theory and the perceptual cycle model, suggesting that the role of past experience, memory, training and perspective. Animate technologies may be able to learn about their environment;
3. Systems have a dynamic network of information upon which different operators have each their own unique view, and contribution to. This being akin to a “hive mind” (Seeley et al, 2012). The compatibility between these views is critical to support safe and efficient performance, with incompatibilities creating threats to performance, safety and resilience;
4. Systemic SA is maintained via transactions in awareness between agents. These exchanges in awareness can be human-to-human, human-to-artefact, and/or artefact-to-artefact. Such interchanges serve to maintain, expand, or degrade the network underpinning the awareness within it. Transactions (in the form of communications and interactions) between agents may be verbal and non-verbal behaviour, customs, and practice. Technologies transact through sounds, signs, symbols and other aspects relating to their state;
5. Compatible SA is required for systems to function effectively: rather than have shared awareness, agents have their own unique view on the situation which connect together to form systemic SA;
6. Genotype and phenotype schema play a key role in both transactions and compatibility of SA;
7. DSA holds loosely coupled systems together. It is argued that without this coupling the systems performance may collapse. Dynamical changes in system coupling may lead to associated changes in DSA; and
8. One agent may compensate for degradation in SA in another agent. This represents an aspect of the emergent properties associated with complex systems.

Given the rise in prominence of systems thinking in Ergonomics, it is encouraging to see that SA is beginning to be examined in this manner. Indeed, the systems approach to SA has usefully shown some of the differences that emerge when SA is viewed through a lens wider than either individuals or teams (as summarised in the following section and Table 4). In representing a point of radical departure from some other approaches, emergent SA provides a good exemplar, especially of extensive thinking (Bourbousson et al, 2011; Fioratou et al, 2010; Golightly et al, 2010; Golightly et al, 2013; Haavik, 2011; Macquet and Stanton, 2014; Salmon et al, 2015; Schulz et al, 2013; Stanton et al, 2015).

**summary OF SA STATE-OF-SCIENCE**

What makes the state of science in SA at present so captivating is how radically different the concept of SA looks when evaluated from different world-views. The world-view through which early models of SA were projected is in some respects quite different from the world-view that exists today. From a practical and methodological point of view it is even more interesting to note that as SA theory has continued to develop, and in some respects become more complex, data collection needs still remain relatively straightforward and eminently practical. Even for the most sophisticated of systems SA concepts the information needed to drive such an analysis can be gathered from expedient methods such as communication logs, verbal transcripts, interviews as well as overt and covert bodily signals (De Winter et al, 2016). In this regard the value of a theory driven approach to Ergonomics becomes even more manifest. The theories presented in this state of science review represent lenses through which similar data can be projected, yet different insights revealed. The main points of theoretical similarity and difference are summarised in Table 4.

Table 4 – Comparison table showing main points of similarity and difference between different models of SA.

|  |  |  |  |
| --- | --- | --- | --- |
|  | Models of SA | | |
|  | Individual | Team | System |
| Defining (fundamental) features) | Single person | Two or more individuals | Human and non-human agents |
| Typical (but not necessary) features | Human constructed system | Human constructed system | Dynamic multi-agent systems view |
| Absent features | More than one person, non-human agents | System constraints and non-human agents | Internal information processing by individuals |
| Primary method | SAGAT probes | Information communication probes | EAST (Transactions) |
| Domain of origin | Aviation | Generic military | Maritime |
| Underpinning theory | Human information processing | Three-level model and team work theory | Perceptual cycle model, schema theory and distributed cognition |
| Definition | Perception of elements, comprehension of meaning and projection of future status | Shared understanding of a situation among team members at one point in time | Activated knowledge for a specific task within a system which relates to the state of the environments and the changes as the situation develops |
| Key citation | Endsley et al (1995) | Salas et al (1995) | Stanton et al (2006) |

Where does this leave the state of science in SA? We turn to Hutchins’ seminal papers on distributed cognition (1995a, b) that describes how STS really work in practice. By way of an example, Hutchins chose to examine an aircraft cockpit, focusing on the division of work between ‘agents’ in the cockpit on approach for landing. The term ‘agents’ had been chosen to represent both the aircrew and the cognitive artefacts. This example enables us to draw out the points of theoretical similarity and difference even more graphically.

The aircraft landing task presents an interesting SA case study because the speed of the aircraft and the flaps and slats in the wing require precise adjustments at set points on the descent. The changes in speed and the flaps/slats need to be undertaken in tandem to avoid undue stress being placed on the wings. These settings cannot simply be memorised by the aircrew, as they are highly dependent on the weight of the aircraft. In the example presented by Hutchins, four different speeds are required by different points on the approach and descent: starting at 245knots the airspeed has be reduced to 227knots, then 177knots, then 152knots and finally to 128 knots. Each reduction in speed is accompanied by a change in the wing’s configuration, either by moving the flaps and/or slats. To assist in the task the pilot relies heavily upon external representation of the speed settings. Devices called ‘speed bugs’ (black pointers that can be moved around the airspeed indicator dial – each with its own flap and slat setting name) are set by the pilot before the approach and descent. The pilot obtains the speed settings from aircraft’s speed card booklet after working out its weight. Then the speed bugs can be set ready for the approach, one bug assigned to each of the four speed settings. Clearly, the pilots are no longer required to remember the speed settings of the aircraft and, if asked via a probe recall SA method (e.g. SAGAT, SPAM, SACRI, etc), or indeed any other means, they would be unable to report the settings. Does this mean they have poor SA?

The individual psychology approach would attempt to elicit the content of the two pilots’ minds. At the point of descent the pilots would be unlikely to report the actual speed settings required, but would be able to report the flaps and slats settings as these are identical for all approaches. The use of an objective ‘ground truth’ and expert validation may go someway to achieving ecological validity, and the approach overall may be entirely appropriate given the specific research questions being asked. That said, it is not suitable for all types of research question.

The team view would report the overlap in content between the pilot flying and the pilot monitoring. Typically they are doing different work, one pilot is focused on flying the aircraft whereas the other is monitoring the aircraft systems and communicating with air traffic control (although both pilots are usually listening into the air traffic communications channels). Common tasks usually involve briefings, cross checks and checklist items. Again, this might be entirely appropriate for a given set of research questions; less so for others.

The systems view of SA would look at the interaction between the pilots and the artefacts to understand how the aircraft undertakes the descent tasks and what each of the ‘agents’ is aware of at any given point in time. This approach would show that the pilots hold information about changes in flaps and slats settings with a given point on approach and descent, whereas the speed bugs hold information about the required speed associated with that flaps and slats setting. It is only when the two sub-systems interact and transactions in awareness occur between them (the social sub-system in terms of the pilots and the technical sub-system in terms of the air speed indicator, speed bugs flaps and slats controls), that one can begin to understand how SA is maintained in the cockpit. Hutchins (1995a) points out that the cognitive processes are distributed amongst the agents in the system, some are human and others are not. The difference between the system view and individual and team views is that the system view holds that the socio-technical system is the unit of analysis, whereas the other views hold that the individual or human team is the unit of analysis (Stanton et al, 2010). As above, the research questions being asked will determine if this approach is appropriate or not.

One final but important question needs to be asked: is the concept of SA and indeed the whole corpus of literature useful? That is, does it result in improved performance? The assumption throughout this review is that yes, SA is useful. There is growing evidence from laboratory studies that using SA principles does result in improved performance (Sorensen and Stanton, 2013). Indeed, in a recent review of the field, Wickens (2008) presented a strong case for the value that SA has to offer. Salmon and Stanton (2013) have also argued that a contribution to safety has been made via the use of SA; however, they suggested that the impact could be strengthened by dispelling the theoretical and methodological confusion and by conducting longitudinal studies to examine the longer-term impact of SA-related interventions. Certainly, the number of citations and the use of the term in everyday language attest to its common acceptance. Further, SA resonates with many operational professionals. Interestingly, however, the precise relationship between SA and task performance was initially difficult to establish (Endsley, 1995). It is unquestionably the case that good task performance can occur despite poor SA and vice versa, so clearly the relationship is more complex than a simple one to one SA/task performance mapping. Current research is providing a much more nuanced but complete picture of the evidence and insights (Griffin et al, 2010; Sorensen and Stanton, 2013; Sorensen and Stanton, 2016; Rafferty et al., 2013; Walker et al, 2009).

One area in which emergent and systemic SA is, and will be playing and increasing role, is in the domain of automated vehicle operations (de Winter et al, 2014; Stanton et al, 2011). Clearly, drivers and semi-automated, automated and non-automated automobiles possess differing levels of understanding about ambient traffic situations (Banks and Stanton, 2015; 2016). In an analysis of automated driving systems, Banks et al (2014) showed how cognitive functions were distributed between drivers and automation. Human drivers understand much more about the motivations and potential actions of other drivers (Walker et al, 2015). Automated systems can possess much more accurate metrical information about kinematics such as range and rate change to other vehicles Young et al, 2007; Stanton and Salmon, 2011). Also, traffic streams will consist of highly sophisticated, automated, vehicles travelling alongside dumb, manually driven, cars (Stanton, 2015). No one element will have anything other than partial awareness and yet we will continue to need to organize this on-road flow in real-time in order to support safe and effective road travel (Salmon et al, 2012). The notion of emergent SA can, and will, have a profound impact on these critical infrastructure developments (Walker et al, 2015). In turn, there is no doubt that the body of SA research that accompanies these developments in automated driving systems will lead to further theoretical and methodological extensions.

Recent scientific debates around SA have tended to be adversarial in nature, with the perceived merits of one approach being frequently and, on occasion, pejoratively, juxtaposed with the perceived demerits of another (Endsley 2015; Dekker, 2015; Salmon et al, 2015; Stanton et al, 2015). Polemicism can serve to subject theories and concepts to the heat of analysis through which veridical insights are distilled. Beyond such partisan contentions, however, must evolve a more measured picture. Indeed, the issues discussed in this review go to the heart of wider methodological issues in Ergonomics (Hancock et al, 2005). Simply put, there is no ubiquitously best theory. Rather, it depends on the fundamental nature of the problem to which different SA approaches are being applied (Stanton et al, 2010). All have a role to play. If the practical SA issue being examined can be reasonably characterized as stable, relying on deviations from accepted normative practices, and focusing on individual personnel, then there are SA theories that match appropriately to this situation and will deliver the insights needed. If, on the other hand, the problem space involves a sociotechnical system in which SA is neither normative nor stable, and resides as a systems level phenomenon rather than individual one, then likewise, other SA approaches, matched to these features, will deliver the necessary perspective. We have endeavoured to illustrate this diagrammatically in Figure 2. The key issue is that an overly doctrinaire and rigid approach, unresponsive to the nature of the problems being tackled, will: first fail to deliver the required insights and/or second do so with excessive analytical effort compared to alternatives and/or third, in the worst case, will mask or even prevent understanding. The result of such dogmatic adherence to a singular perspective will be a diminution of the reputation of our discipline.

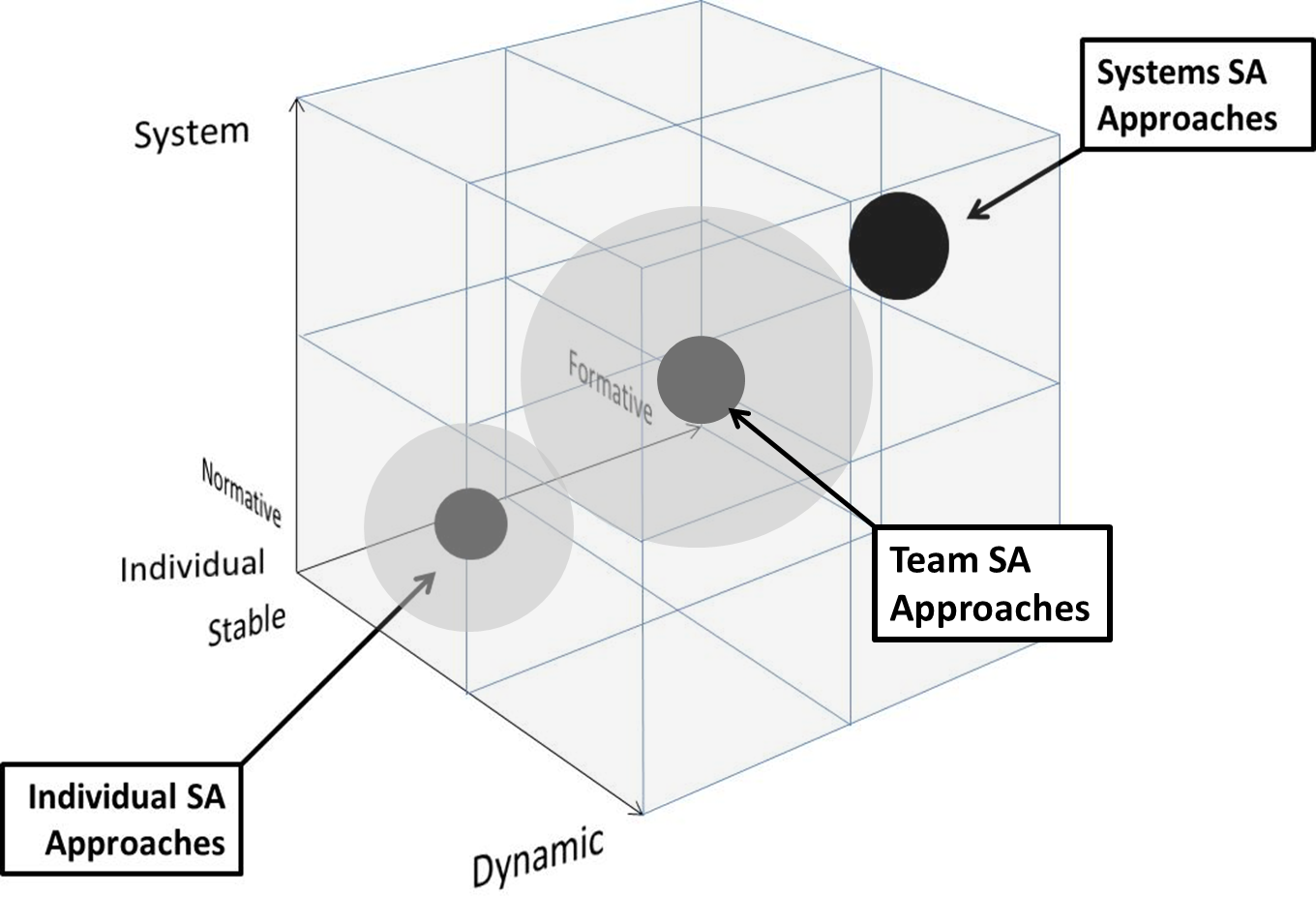


Figure 2 – Different approaches to SA match to different features of Ergonomic problems. By its nature, the more systemic the SA model, the more of the problem space it can operate within, although other approaches may prove more practically expedient. The real challenge going forward is to become better at this matching rather than compete one approach with another.

**Prospects for the Future of SA**

From what we have observed, the future appears bright for SA research and practice (Salmon & Stanton, 2013). Beyond the immediate issues that require resolution, systems are becoming even more complex and connected; technologies more advanced, and the role of technology is both increasing and changing dramatically (see Hancock, 2016). There are also new, emerging constructs from other disciplines that can enrich the science of SA. These include embodied cognition, advances in the brain sciences, as well as ethnographic and prescriptive ontologies. Systems continue to become more complex and technology-driven, which in turn raises important questions around awareness and how best to support it across individuals, teams, organisations, and entire systems. Critical new SA research questions continue to reveal themselves, such as how human operators can exchange awareness with agents of artificial intelligence, how we can study SA in teams comprised entirely of non-human actors, and how to design advanced automation systems where awareness is distributed (e.g. vehicle-to-vehicle and vehicle-to-infrastructure). The concept’s popularity is such that it continues to be applied in new domains and there is no doubt new questions will arise, with new areas to be explored. The challenges and opportunities for SA are strong and encouraging but the driver of the future’s SA will indubitably be different to those of today (Stanton et al, 2011). Future pilots will be required to exchange awareness with a co-pilot located on the ground (Stanton et al, 2015). Robot surgeon’s will be aware of changes in their patient’s condition and will have to share this knowledge with human surgeons and nurses. Pushing the envelope further still, the ‘Internet of Things’ will herald a form of ‘hyper’ awareness as ever more ‘things’ are made contextually aware, and profound questions about collective and individual awareness start to emerge. In either case, the nature of SA is changing quickly. SA research thus has a key role to play, both in the design and operation of modern day systems, and in understanding safety compromising problems, as well as helping to prescribe the systems of tomorrow.

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