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Toward a Theory of Situation Awareness in Dynamic Systems

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This paper presents a theoretical model of situation awareness based on its role in dynamic human decision making in a variety of domains. Situation awareness is presented as a predominant concern in system operation, based on a descriptive view of decision making. The relationship between situation awareness and numerous individual and environmental factors is explored. Among these factors, attention and working memory are presented as critical factors limiting operators from acquiring and interpreting information from the environment to form situation awareness, and mental models and goal-directed behavior are hypothesized as important mechanisms for overcoming these limits. The impact of design features, workload, stress, system complexity, and automation on operator situation awareness is addressed, and a taxonomy of errors in situation awareness is introduced, based on the model presented. The model is used to generate design implications for enhancing operator situation awareness and future directions for situation awareness research.

INTRODUCTION

The range of problems confronting human factors practitioners has continued to grow over the past 50 years. Practitioners must deal with human performance in tasks that are primarily physical or perceptual, as well as consider human behavior involving highly complex cognitive tasks with increasing frequency. As technology has evolved, many complex, dynamic systems have been created that tax the abilities of humans to act as effective, timely decision makers when operating these systems. The operator's situation awareness (SA) will be presented as a crucial construct on which decision making and performance in such systems hinge.

In this paper I strive to show (a) the importance of SA in decision making in dynamic environments and the utility of using a model of decision making that takes SA into account, and (b) a theory of SA that expands on prior work in this area (Endsley, 1988a, 1990c, 1993b). True SA, it will be shown, involves far more than merely being aware of numerous pieces of data. It also requires a much more advanced level of situation understanding and a projection of future system states in light of the operator's pertinent goals. As such, SA presents a level of focus that goes beyond traditional information-processing approaches in attempting to explain human behavior in operating complex systems.

SA can be shown to be important in a variety of contexts that confront human factors practitioners.

Aircraft. In the area with perhaps the longest history, SA was recognized as a crucial commodity for crews of military aircraft as far back as World War I (Press, 1986). SA has grown in importance as a major design goal for civil,

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commercial, and military aircraft, receiving particular emphasis in recent years (Federal Aviation Administration, 1990; U.S. Air Force 57th Fighter Wing, 1986). In the flight environment, the safe operation of the aircraft in a manner consistent with the pilot's goals is highly dependent on a current assessment of the changing situation, including details of the aircraft's operational parameters, external conditions, navigational information, other aircraft, and hostile factors. Without this awareness (which needs to be both accurate and complete), the aircrew will be unable to effectively perform their functions. Indeed, as will be discussed further, even small lapses in SA can have catastrophic repercussions.

Air traffic control. In a related environment, air traffic controllers are called on to sort out and project the paths of ever-increasing numbers of aircraft in order to ensure goals of minimum separation and safe, efficient landing and takeoff operations. This taxing job relies on the SA of controllers who must maintain up-to-date assessments of the rapidly changing locations of aircraft (in three-dimensional space) and their projected locations relative to each other, along with other pertinent aircraft parameters (destination, speed, communications, etc.).

Large-systems operations. The operators of large, complex systems such as flexible manufacturing systems, refineries, and nuclear power plants must also rely on up-to-date knowledge of situation parameters to manage effectively. In their tasks, operators must observe the state of numerous system parameters and any patterns among them that might reveal clues as to the functioning of the system and future process state changes (Wirstad, 1988). Without this understanding and prediction, human control could not be effective.

Tactical and strategic systems. Similarly, firefighters, certain police units, and military command personnel rely on SA to make their decisions. They must ascertain the critical features in widely varying situations to determine the best course of action. Inaccurate or incomplete SA in these environments can lead to devastating loss of life, such as in the case of the U.S.S. *Vincennes*. Incorrect SA concerning an incoming aircraft (from confusing identification signals and a lack of direct information on changes in altitude) led to the downing of a commercial airliner and subsequent loss of all aboard. From reports of the accident (Klein, 1989a), it appears that the decision makers' SA was in error (perceived hostility of the incoming aircraft), not the decision as to what to do (if hostile, warn off and then shoot down if not heeded). This is an important distinction that highlights the criticality of SA in dynamic decision making.

Other. Many other everyday activities call for a dynamic update of the situation to function effectively. Walking, driving in heavy traffic, or operating heavy machinery surely call for SA. Roschelle and Greeno (1987) reported that experts in solving physics problems rely on the development of a situational classification. Gaba, Howard, and Small (1995, this issue) describe the role of SA in medical decision making. As humans typically operate in a closed-loop manner, input from the environment is almost always necessary.

The need for SA applies in a wide variety of environments. Acquiring and maintaining SA becomes increasingly difficult, however, as the complexity and dynamics of the environment increase. In dynamic environments, many decisions are required across a fairly narrow space of time, and tasks are dependent on an ongoing, up-to-date analysis of the environment. Because the state of the environment is constantly changing, often in complex ways, a major portion of the operator's job becomes that of obtaining and maintaining good SA. This task ranges from trivial to one of the major factors determining operator performance. In analyzing the decision making of tactical commanders, Kaempf, Wolf, and Miller (1993, p. 1110) reported that "recognizing the situation provided the challenge to the decision maker," confirming SA's criticality.

In each of the domains discussed, operators must do more than simply perceive the state of their environment. They must understand the integrated meaning of what they are perceiving in light of their goals. Situation awareness, as such, incorporates an operator's understanding of the situation as a whole, forming a basis for decision making. Researchers in many areas have found that expert decision makers will act first to classify and understand a situation, immediately proceeding to action selection (Klein, 1989b; Klein, Calderwood, and Clinton-Cirocco, 1986; Lipshitz, 1987; Noble, Boehm-Davis, and Grosz, 1987; Sweller, 1988).

There is evidence that an integrated picture of the current situation may be matched to prototypical situations in memory, each prototypical situation corresponding to a "correct" action or decision. Dreyfus (1981) presented a treatise that emphasized the role of situational understanding in real-world, expert decision making, building on the extensive works of deGroot (1965) in chess, Mintzburg (1973) in managerial decision making, and Kuhn (1970) in science. In each of these areas the experts studied used pattern-matching mechanisms to draw on long-term memory structures that allowed them to quickly understand a given situation. They then adopted the course of action corresponding to that type of situation. Hinsley, Hayes, and Simon (1977) have found that this situation classification can occur almost immediately, or, as Klein (1989b) has pointed out, it can involve some effort to achieve.

In his studies of fire ground commanders, Klein (1989b) found that a conscious deliberation of solution alternatives was rare. Rather, the majority of the time, experts focused on classifying the situation in order to immediately yield the appropriate solution from memory. Kaempf et al. (1993) reported that of 183 decisions by tactical commanders, 95% used this type of recognition decision strategy, involving either feature matching to situation prototypes (87%) or story building (13%). Although much of this work emphasizes the decision processes of experts, novices must also focus a considerable amount of their effort on assessing the state of the environment in order to make decisions. Cohen (1993) pointed out that metacognitive strategies may become more important in these cases as forming an assessment of the situation becomes more challenging.

Given that SA plays such a critical role in decision making, particularly in complex and dynamic environments, there is a need to more explicitly incorporate the concept into human factors design efforts. A theory of SA that clearly defines the construct and its relation to human decision making and performance is needed to fulfill this mission.

A MODEL OF SITUATION AWARENESS

Because direct research on SA itself is limited and has been conducted only in recent years, a thorough and rigorously defined theory may not yet be possible. The present objective is to define a common ground for discussion using the information that is available in order to provide a starting point for future work on SA.

This information will be presented in a framework model—a model that is descriptive of the SA phenomenon and that synthesizes information from a variety of areas. It will explicitly address certain attributes of the construct. Specifically, Klein (1989b) stated that a desired theory of situation awareness should explain dynamic goal selection, attention to appropriate critical cues, expectancies regarding future states of the situation, and the tie between situation awareness and typical actions. Within this context, it is the goal of this effort to delineate what SA is and what it is not, to provide an understanding of the mechanisms that underlie the construct, and to discuss the factors that may influence it. The implications of the model for design, error investigation, and future research will be discussed. (This discussion will be illustrated by examples of SA from the aircraft domain; however, it applies equally to other contexts presented earlier.)

A Model

Figure 1 provides a basis for discussing SA in terms of its role in the overall decision-making process. According to this model, a person's perception of the relevant elements in the

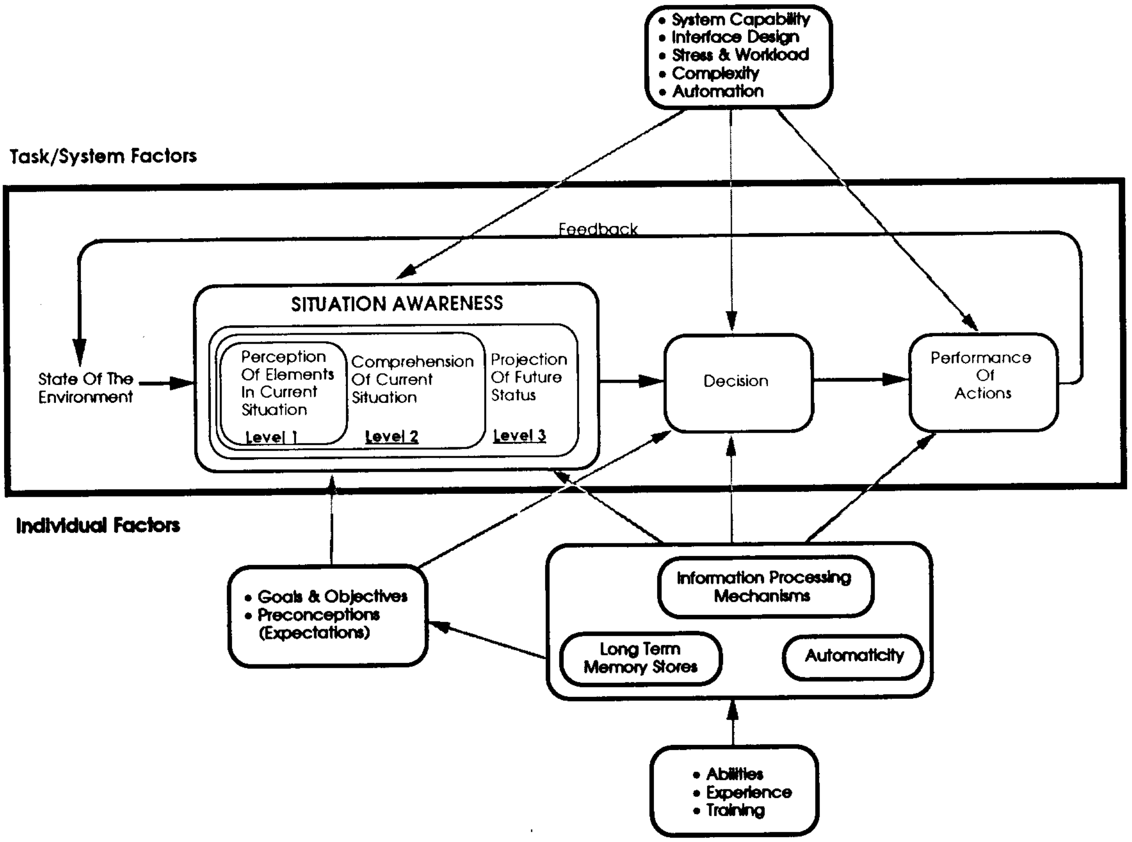

Figure 1. *Model of situation awareness in dynamic decision making.*

environment, as determined from system displays or directly by the senses, forms the basis for his or her SA. Action selection and performance are shown as separate stages that will proceed directly from SA.

Several major factors are shown to influence this process. First, individuals vary in their ability to acquire SA, given the same data input. This is hypothesized to be a function of an individual's information-processing mechanisms, influenced by innate abilities, experience, and training. In addition, the individual may possess certain preconceptions and objectives that can act to filter and interpret the environment in forming SA.

SA will also be a function of the system design in terms of the degree to which the system provides the needed information and the form in which it provides it. All system designs are not equal in their ability to convey needed information or in the degree to which they are compatible with basic human information-processing abilities. Other features of the task environment, including workload, stress, and complexity, may also affect SA. The role of each of these individual and system factors in relation to SA will be addressed.

Definitions and Terminology

Contrary to Sarter and Woods (1995, this issue), who believe that developing a definition of SA is futile and not constructive, I believe it is first necessary to clearly define SA. The term has lately become the victim of rather loose usage, with different individuals redefining it at whim, leading to the recent criticism that SA is the "buzzword of the '90s" (Wiener, 1993, p. 4). Unless researchers stick to a clear, consistent meaning for the term, the problem will present a significant handicap to progress.

In conjunction with the model, therefore, a few issues will be stated explicitly to clarify the present formulation of SA. As a matter of consistent terminology, it is first necessary to distinguish the term *situation awareness*, as a state of knowledge, from the processes used to achieve that state. These processes, which may vary widely among individuals and contexts, will be referred to as *situation assessment* or as the process of achieving, acquiring, or maintaining SA. (This differs from recent efforts by Sarter and Woods [1995, this issue], who view SA as "a variety of cognitive processing activities," in contrast to most past definitions of SA, which have focused on SA as a state of knowledge. I am in full agreement with Adams, Tenney, and Pew [1995, this issue] that there is great benefit in examining the interdependence of the processes and the resultant state of knowledge; however, in order to clarify discourse on SA, it is important to keep the terminology straight.)

Furthermore, SA as defined here does not encompass all of a person's knowledge. It refers to only that portion pertaining to the state of a dynamic environment. Established doctrine, rules, procedures, checklists, and the like—though important and relevant to the decision-making process—are fairly static knowledge sources that fall outside the boundaries of the term.

In addition, SA is explicitly recognized as a construct separate from decision making and performance. Even the best-trained decision makers will make the wrong decisions if they have inaccurate or incomplete SA. Conversely, a person who has perfect SA may still make the wrong decision (from a lack of training on proper procedures, poor tactics, etc.) or show poor performance (from an inability to carry out the necessary actions). SA, decision making, and performance are different stages with different factors influencing them and with wholly different approaches for dealing with each of them; thus it is important to treat these constructs separately. (This stance also differs from that taken by the U.S. Air Force [Judge, 1992], which has adopted a definition of SA that includes action and decision making, in contrast to most prior research on SA.)

Similarly, SA is presented as a construct separate from others that may influence it. Attention, working memory, workload, and stress are all related constructs that can affect SA but that can also be seen as separate from it. Subsuming any of these constructs within the term *situation awareness* loses sight of the independent and interactive nature of these factors. SA and workload, for instance, have been shown to vary independently across a wide range of these variables (Endsley, 1993a), although workload may have a negative effect on SA in certain situations. These factors will be addressed more explicitly in a later section.

Although numerous definitions of SA have been proposed (Endsley, 1988a; Fracker, 1988), most are not applicable across different task domains. For the most part, however, they all point to "knowing what is going on." Referring to Figure 1, I will use the following general definition of SA (Endsley, 1987b, 1988b):

> Situation awareness is the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future.

Each of the three hierarchical phases and primary components of this definition will be described in more detail.

Level 1 SA: Perception of the Elements in the Environment

The first step in achieving SA is to perceive the status, attributes, and dynamics of relevant elements in the environment. A pilot would perceive elements such as aircraft, mountains, or warning lights along with their relevant characteristics (e.g., color, size, speed, location). A tactical commander needs accurate data on the location, type, number, capabilities, and dynamics of all enemy and friendly forces in a given area and their relationship to other points of reference. A flexible manufacturing system operator needs data on the status of machines, parts, flows, and backlogs. An automobile driver needs to know where other vehicles and obstacles are, their dynamics, and the status and dynamics of one's own vehicle.

Level 2 SA: Comprehension of the Current Situation

Comprehension of the situation is based on a synthesis of disjointed Level 1 elements. Level 2 SA goes beyond simply being aware of the elements that are present to include an understanding of the significance of those elements in light of pertinent operator goals. Based on knowledge of Level 1 elements, particularly when put together to form patterns with the other elements (gestalt), the decision maker forms a holistic picture of the environment, comprehending the significance of objects and events. For example, a military pilot or tactical commander must comprehend that the appearance of three enemy aircraft within a certain proximity of one another and in a certain geographical location indicates certain things about their objectives. The operator of a power plant needs to put together disparate bits of data on individual system variables to determine how well different system components are functioning, deviations from expected values, and the specific locus of any deviant readings. In these environments a novice operator might be capable of achieving the same Level 1 SA as more experienced decision makers but may fall far short of also being able to integrate various data elements along with pertinent goals in order to comprehend the situation.

Level 3 SA: Projection of Future Status

The ability to project the future actions of the elements in the environment—at least in the very near term—forms the third and highest level of SA. This is achieved through knowledge of the status and dynamics of the elements and comprehension of the situation (both Level 1 and Level 2 SA). For example, knowing that a threat aircraft is currently offensive and is in a certain location allows a fighter pilot or military commander to project that the aircraft is likely to attack in a given manner. This provides the knowledge (and time) necessary to decide on the most favorable course of action to meet one's objectives. Similarly, an air traffic controller needs to put together information on various traffic patterns to determine which runways will be free and where there is a potential for collisions. An automobile driver also needs to detect possible future collisions in order to act effectively, and a flexible manufacturing system operator needs to predict future bottlenecks and unused machines for effective scheduling.

SA, therefore, is based on far more than simply perceiving information about the environment. It includes comprehending the meaning of that information in an integrated form, comparing it with operator goals, and providing projected future states of the environment that are valuable for decision making. In this aspect, SA is a broad construct that is applicable across a wide variety of application areas, with many underlying cognitive processes in common.

Elements

From a design standpoint, a clear understanding of SA in a given environment rests on a clear elucidation of the elements in the definition—that is, identifying which things the operator needs to perceive and understand. These are specific to individual systems and contexts, and as such are the one part of SA that cannot be described in any valid way across arenas. Although the pilot and power plant operator each relies on SA, it simply is not realistic or appropriate to expect the same elements to be relevant to both. Nonetheless, these elements can be, and should be, specifically determined for various classes of systems.

Endsley (1993c) presented a methodology for accomplishing this and described such a delineation for air-to-air fighter aircraft. Examples of elements in this arena include

a. Level 1: location, altitude, and heading of ownship and other aircraft; current target;

detections; system status; location of ground threats and obstacles

b. Level 2: mission timing and status; impact of system degrades; time and distance available on fuel; tactical status of threat aircraft (offensive/defensive/neutral)

c. Level 3: projected aircraft tactics and maneuvers, firing position and timing.

One may also talk about awareness of certain subcategories of SA (usually system specific), which include requirements across all three levels of SA. For instance, spatial awareness or geographical awareness is frequently of concern in aircraft. Mode awareness, as discussed by Sarter and Woods (1995, this issue), is another example of a subset of SA that may be of concern in certain systems, across all three levels (e.g., "What is it doing, why is it doing that, what will it do next?").

Time

Several other aspects of SA should be mentioned at this point. First, although SA has been discussed as a person's knowledge of the environment at a given point in time, it is highly temporal in nature. That is, SA is not necessarily acquired instantaneously but is built up over time. Thus it takes into account the dynamics of the situation that are acquirable only over time and that are used to project the state of the environment in the near future. So although SA consists of an operator's knowledge of the state of the environment at any point in time, this knowledge includes temporal aspects of that environment, relating to both the past and the future.

Space

It has been observed that SA is highly spatial in many contexts. Pilots and air traffic controllers, for instance, are concerned with the spatial relationships among multiple aircraft, and this information also yields important temporal cues. Many other fields may also be concerned with the spatial as well as functional relationships among system components. In addition to its aspect as a frequent "element" of SA, spatial information is highly useful for determining exactly which aspects of the environment are important for SA.

An operator's SA needs to incorporate information on that subset of the environment that is relevant to tasks and goals. Within this boundary, the elements may be further subdivided into levels of importance for SA or may assume a relevance continuum, depending on the problem context. In a piloting context, for example, the relevance of different aircraft will depend on their location and speed relative to ownship and the pilot's goals (e.g., response to an immediate threat, tactics determination, or long-term mission replanning); a different amount of relevance may be indicated for different goals. In other contexts, such as manufacturing or power plant environments, relevance of elements may be determined by the spatial, temporal, or functional relationships of elements to goals.

In this way, elements may vary in their relevance across time, although they do not generally fall out of consideration completely. At least some SA on all elements has been found to be needed, even if this conveys merely that the element is not very important at the moment. For instance, while in close combat, many pilots report that they are interested only in where their opponent is. Too frequently, however, though they are successful in avoiding enemy missiles, they end up flying into the ground with lethal results (Kuipers, Kappers, van Holten, van Bergen, and Oosterveld, 1989; McCarthy, 1988). In order to know that they can afford to pay less attention to altitude than to enemy aircraft, pilots need to know that they are at least above a certain level at all times. A certain amount of SA on other elements is required at all times in a similar manner.

Team SA

It is possible to talk about SA in terms of teams as well as individuals. In many situations several individuals may work together as a team to make decisions and carry out actions. In this case one can conceive of overall team SA, whereby each team member has a specific set of

SA elements about which he or she is concerned, as determined by each member's responsibilities within the team.

SA for a team can be represented as shown in Figure 2. Some overlap between each team member's SA requirements will be present. It is this subset of information that constitutes much of team coordination. That coordination may occur as a verbal exchange, as a duplication of displayed information, or by some other means. As such, the quality of team members' SA of shared elements (as a state of knowledge) may serve as an index of team coordination or human-machine interface effectiveness.

Overall team SA can be conceived as the degree to which every team member possesses the SA required for his or her responsibilities. This is independent of any overlaps in SA requirements that may be present. If each of two team members needs to know a piece of information, it is not sufficient that one knows perfectly but the other not at all. *Every* team member must have SA for all of his or her own requirements or become the proverbial chain's weakest link.

For instance, in an aircraft cockpit, both the pilot and copilot may need to know certain pieces of information. If the copilot has this information but the pilot in charge does not, the

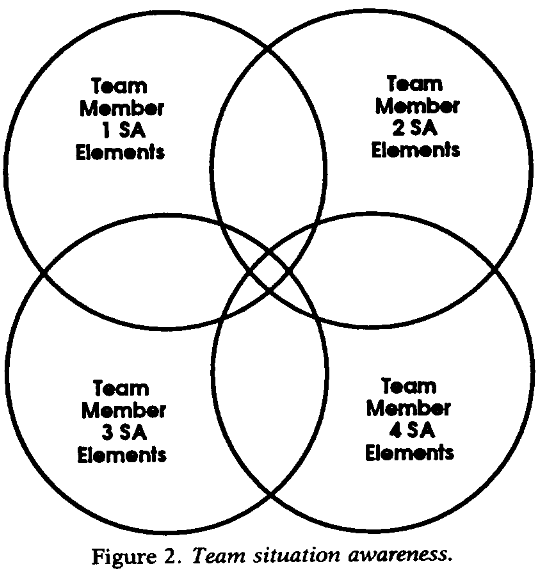

Figure 2. *Team situation awareness.*

SA of the team has suffered and performance may suffer as well unless the discrepancy is corrected. How that information transmission occurs—the process of achieving SA—can vary. It may constitute a verbal exchange or separate, direct viewing of displays, with each individual independently acquiring information on the status of the aircraft. Higher levels of SA that may not be directly presented on displays may be communicated verbally, or, if the team members possess a shared mental model (Salas, Prince, Baker, and Shrestha, 1995, this issue), each team member may achieve the same higher-level SA without necessitating extra verbal communication. Mosier and Chidester (1991), for example, found that better-performing teams actually communicated less than did poorer-performing teams. In this case, the degree to which each team member has accurate SA on shared items could serve as an index of the quality of team communications (i.e., each member's ability to achieve the goal of communication as efficiently as possible).

Link to Decision Making

In addition to forming the basis for decision making as a major input, SA may also impact the process of decision making itself. There is considerable evidence that a person's manner of characterizing a situation will determine the decision process chosen to solve a problem. Manktelow and Jones (1987) reviewed the literature concerning deductive problem solving and showed, through numerous studies, that the situation parameters or context of a problem largely determines the ability of individuals to adopt an effective problem-solving strategy. It is the situation specifics that determine the adoption of an appropriate mental model, leading to the selection of problem-solving strategies. In the absence of an appropriate model, people will often fail to solve a new problem, even though they would have to apply the same logic as that used for a familiar problem.

Other evidence suggests that even the way a given problem is presented (or framed) can determine how the problem is solved (Bettman and Kakkar, 1977; Herstein, 1981; Sundstrom, 1987; Tversky and Kahneman, 1981). The simplest explanation for this is that different problem framings can induce different information integration (situation comprehension), and this determines the selection of a mental model to use for solving the problem. Thus it is not only the detailed situational information (Level 1 SA) but also the way the pieces are put together (Level 2 SA) that direct decision strategy selection.

Link to Performance

The relationship between SA and performance, though not always direct, can also be predicted. In general, it is expected that poor performance will occur when SA is incomplete or inaccurate, when the correct action for the identified situation is not known or calculated, or when time or some other factor limits a person's ability to carry out the correct action. For instance, in an air-to-air combat mission, Endsley (1990b) found that SA was significantly related to performance only for those subjects who had the technical and operational capabilities to take advantage of such knowledge. The same study found that poor SA would not necessarily lead to poor performance if subjects realized their lack of SA and were able to modify their behavior to reduce the possibility of poor performance. Venturino, Hamilton, and Dvorchak (1989) also found that performance was predicted by a combination of SA and decision making (fire-point selection) in combat pilots. Good SA can therefore be viewed as a factor that will increase the probability of good performance but cannot necessarily guarantee it.

HUMAN PROPERTIES AFFECTING AND UNDERLYING SA

Within this basic model of SA, I will discuss the factors underlying and influencing the SA process. This discussion will first focus on characteristics of the individual, including relevant information-processing mechanisms and constructs that play a role in achieving SA. It will proceed to factors related to the system and task environment as they affect the operator's ability to achieve SA.

Although some researchers have continued to argue that relatively little is known about SA (Sarter and Woods, 1991), this belies the vast amount of highly pertinent work that has been done—specifically, research devoted to more general aspects of human cognition. Although members of the psychology community continue to debate the exact structure and nature of information-processing mechanisms, a detailed discussion of various theories regarding each lies beyond the scope of this paper. Thus, the relationship between SA and these mechanisms, as generally understood, will be explored.

In combination, the mechanisms of short-term sensory memory, perception, working memory, and long-term memory form the basic structures on which SA is based. Figure 3 shows a schematic description of the role of each of these structures in the SA process.

Preattentive Processing

According to most research on information processing (for a review see Norman, 1976, or Wickens, 1992a), environmental features are initially processed in parallel through preattentive sensory stores in which certain properties are detected, such as spatial proximity, color, simple properties of shapes, or movement (Neisser, 1967; Treisman and Paterson, 1984), providing cues for further focalized attention. Those objects that are most salient, based on preattentively registered characteristics, will be further processed using focalized attention to achieve perception. Cue salience, therefore, will have a large impact on which portions of the environment are initially attended to, and these elements will form the basis for the first level of SA.

Attention

The deployment of attention in the perception process acts to present certain constraints on a person's ability to accurately perceive multiple items in parallel and, as such, is a major limit on SA. Direct attention is needed for not only perceiving and processing the cues attended to but

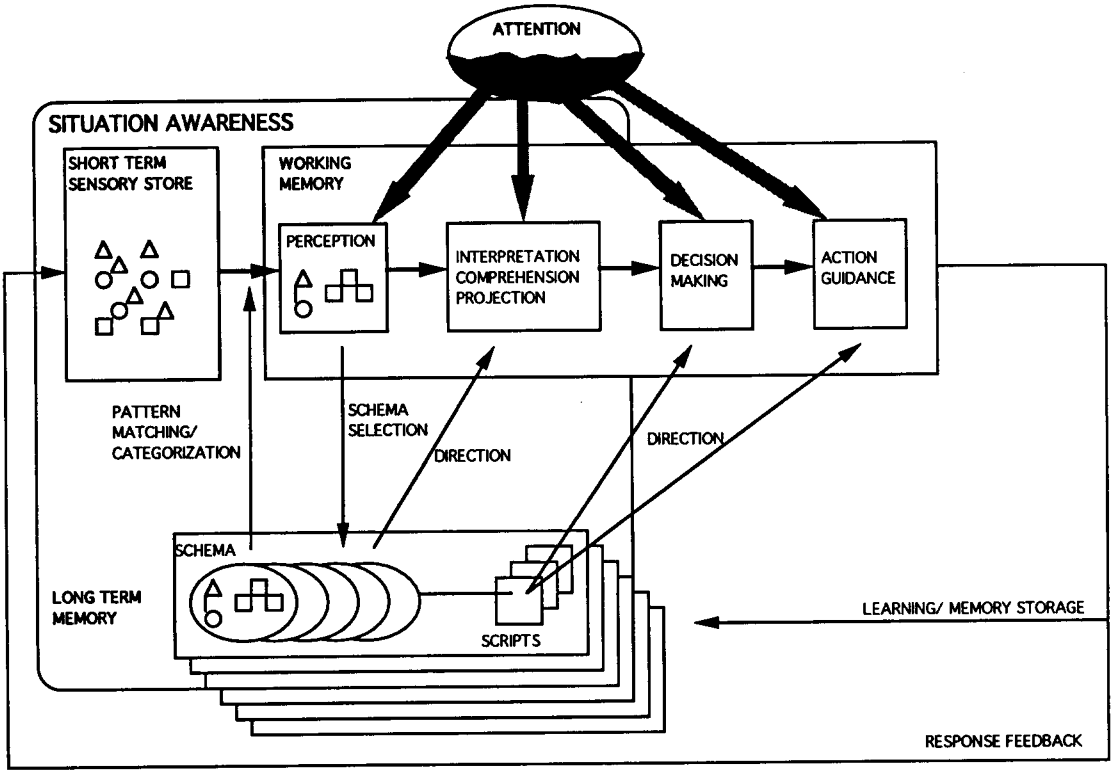

Figure 3. *Mechanisms of situation awareness (reprinted from Endsley, 1988a).*

also the later stages of decision making and response execution. In complex and dynamic environments, attention demands resulting from information overload, complex decision making, and multiple tasks can quickly exceed a person's limited attention capacity.

Operators of complex systems frequently employ a process of information sampling to circumvent this limit. They attend to information in rapid sequence following a pattern dictated by the portion of long-term memory concerning relative priorities and the frequency with which information changes (Wickens, 1992a). Working memory also plays an important role, allowing one to modify attention deployment on the basis of other information perceived or active goals (Braune and Trollip, 1982). For example, perception of a strange noise may prompt a pilot to look at the engine status indicator. When involved in the goal of shooting at an enemy aircraft, attention may be directed primarily at that target. In addition to highly salient cues catching one's attention, therefore, people are active participants in determining which elements of the environment will become a part of their (Level 1) SA by directing their attention based on goals and objectives and on the basis of long-term and working memory (each of which will be discussed in more detail).

In a study of pilot SA, Fracker (1989) showed that a limited supply of attention was allocated to environmental elements based on their ability to contribute to task success. Because the supply of attention is limited, more attention to some elements (resulting in improved SA on these elements), however, may mean a loss of SA on other elements once the limit is reached, which can occur rather quickly in complex environments. In an investigation of factors leading to fighter aircraft accidents involving controlled descent into the terrain, Kuipers et al. (1989) cited lack of attention to primary flight instruments (56%) and too much attention to target planes during combat (28%) as major causes. Focusing on only certain elements led to a lack of SA and fatal consequences.

In addition to information sampling, it may be possible to work around attention limits in other ways to some degree. Kahneman (1973) stated that attentional resources can be increased somewhat by physiological arousal mechanisms. Further relief to attention limitations can be provided through people's ability to divide their attention under certain circumstances. Wickens's multiple resource theory (1992a) provides a model for determining which types of information can be most easily attended to in parallel. Damos and Wickens (1980) also found that attention sharing is a skill that can be learned and that some people excel at it over others. In addition, limitations of attention may be circumvented to some degree through the development of automaticity.

Perception

In addition to affecting the selection of elements for perception, the way in which information is perceived is directed by the contents of both working memory and long-term memory. Advanced knowledge of the characteristics, form, and location of information, for instance, can significantly facilitate the perception of information (Barber and Folkard, 1972; Biederman, Mezzanotte, Rabinowitz, Francolin, and Plude, 1981; Davis, Kramer, and Graham, 1983; Humphreys, 1981; Palmer, 1975; Posner, Nissen, and Ogden, 1978). That is, one's preconceptions or expectations about information will affect the speed and accuracy of the perception of that information (Jones, 1977, pp. 38–39).

Repeated experience in an environment allows one to develop expectations about future events. In the aircraft environment, premission briefings typically build up preconceptions about what will be encountered during the mission. An air traffic controller's report of traffic at a particular altitude or a bill of lading that accompanies a shipment in a manufacturing environment each develops in recipients a certain expectation about what they will encounter that predisposes them to perceive the information accordingly. They will process the information faster if it is in agreement with those expectations and will be more likely to make an error if it is not (Jones, 1977).

Long-term memory stores also play a significant role in classifying perceived information into known categories or mental representations as an almost immediate act in the perception process (Hinsley et al., 1977). Categorization is based on integrated information and typically occurs in a deterministic, nearly optimal manner (Ashby and Gott, 1988). The classification of information into understood representations forms Level 1 SA and provides the basic building blocks for the higher levels of SA.

With well-developed memory stores, very fine categorizations may be possible. For instance, an experienced pilot will be able to classify observed aircraft into exact models (e.g., F-18c vs. F-18d). This highly detailed classification provides the pilot with access to detailed knowledge about the capabilities of the aircraft (from long-term memory). A novice may not be able to make this level of classification and would consequently have less information from the same data input.

The cues used to achieve these classifications are important to SA. With higher levels of expertise, people appear to develop knowledge of critical cues in the environment that allow them to make very fine classifications. The development of memory structures for this process will be discussed more fully subsequently. At this juncture it is important to note that the classification made in the perception stage (right or wrong, detailed or gross) is a function of the knowledge available for making such classifications and will produce the elements of Level 1 SA.

Working Memory

Once perceived, information is stored in working memory. In the absence of other mechanisms (such as relevant long-term memory stores), most of a person's active processing of information must occur in working memory. New information must be combined with existing knowledge and a composite picture of the situation developed (Level 2 SA). Projections of future status (Level 3 SA) and subsequent decisions as to appropriate courses of action must occur in working memory as well. In this circumstance, a heavy load is imposed on working memory, as it is taxed with simultaneously achieving the higher levels of SA (Levels 2 and 3), formulating and selecting responses, and carrying out subsequent actions.

Wickens (1984, p. 201) has stated that prediction of future states (the culmination of good SA) imposes a heavy load on working memory by requiring the maintenance of present conditions, future conditions, rules used to generate the latter from the former, and actions that are appropriate to the future conditions. Fracker (1987) hypothesized that working memory constitutes the main bottleneck for SA. This is most likely the case for novices or those dealing with novel situations.

Long-Term Memory

In practice long-term memory structures can be used to circumvent the limitations of working memory. The exact organization of knowledge in long-term memory has received diversified characterization, including episodic memory, semantic networks, schemata, and mental models. This discussion will focus on schemata and mental models that have been discussed as important for effective decision making in a number of environments (Braune and Trollip, 1982; Rasmussen and Rouse, 1981) and that are hypothesized to play an important role in SA.

Schemata provide coherent frameworks for understanding information, encompassing highly complex system components, states, and functioning (Bartlett, 1932; Mayer, 1983). Much of the details of situations are lost when information is coded in this manner, but the information becomes more coherent and organized for storage, retrieval, and further processing. A single schema may serve to organize several sets of information and as such will have variables that can be filled in with the particulars for the case being considered. A script—a special type of schema—provides sequences of appropriate actions for different types of task performance (Schank and Abelson, 1977). Ties between schemata and scripts can greatly facilitate the cognitive process because an individual does not have to actively decide on appropriate actions at every turn but will automatically know the actions to take for a given situation based on its associated script.

A related concept is the *mental model*. Rouse and Morris (1985) defined mental models as "mechanisms whereby humans are able to generate descriptions of system purpose and form, explanations of system functioning and observed system states, and predictions of future states" (p. 7). They stated that experts will develop mental models in a shift from representational to abstract codes. From this definition, mental models can be described as complex schemata that are used to model the behavior of systems. Therefore, a mental model can be viewed as a schema for a certain system.

Related to this is the *situational model* (or situation model), a term used by VanDijk and Kintsch (1983) and by Roschelle and Greeno (1987), which will be defined as a schema depicting the current state of the system model (and often developed in light of the system model). Rasmussen (1986) also used the term *internal dynamic world model* with the same general meaning. The terms *situation model* and *situation awareness* will be defined here as equivalent.

A situation model (i.e., SA) can be matched to schemata in memory that depict prototypical situations or states of the system model. These prototypical classifications may be linked to associated goals or scripts that dictate decision making and action performance. This provides a mechanism for the single-step, "recognition-primed" decision making described earlier. This process is hypothesized to be a key mechanism whereby people are able to efficiently process a large amount of environmental information to achieve SA. A well-developed mental model provides (a) knowledge of the relevant elements of the system that can be used in directing attention and classifying information in the perception process, (b) a means of integrating the elements to form an understanding of their meaning (Level 2 SA), and (c) a mechanism for projecting future states of the system based on its current state and an understanding of its dynamics (Level 3 SA).

For example, a pilot may perceive several aircraft (considered to be important elements per the mental model) recognized as enemy fighter jets (based on critical cues) that are approaching in a particular spatial arrangement (forming Level 1 SA). By pattern-matching to prototypes in memory, these separate pieces of information may be classified as a particular recognized aircraft formation (Level 2 SA). According to an internally held mental model, the pilot is able to generate probable attack scenarios for this type of formation when in relation to an aircraft with the location and flight vector of his or her ownship (Level 3 SA). Based on this high-level SA, the pilot is then able to select prescribed tactics (a script) that dictate exactly what evasive maneuvers should be taken.

The key to using these models to achieve SA rests on the ability of the individual to recognize key features in the environment—critical cues—that will map to key features in the model. The model can then provide for much of the higher levels of SA (comprehension and projection) without loading working memory. In cases in which scripts have been developed for given prototypical situation conditions, the load on working memory for generating alternative behaviors and selecting among them is even further diminished.

A major advantage of this mechanism is that the current situation need not be exactly like one encountered before. This is a result of categorization mapping (a best fit between the characteristics of the situation and the characteristics of known categories or prototypes). Of prime importance is that this process can be almost instantaneous because of the superior abilities of human pattern-matching mechanisms. When an individual has a well-developed mental model for the behavior of particular systems or domains, the model will provide (a) for the dynamic direction of attention to critical cues, (b) expectations regarding future states of the environment (including what to expect as well as what not to expect) based on the projection mechanisms of the model, and (c) a direct, single-step link between recognized situation classifications and typical actions.

Development. Schemata and mental models are developed as a function of training and experience in a given environment. A novice in an area may have only a vague idea of important system components and sketchy rules or heuristics for determining the behavior he or she should employ with the system. With experience, recurrent situational components will be noticed along with recurrent associations and causal relationships. This forms the basis for early schema or model development.

Holland, Holyoak, Nisbett, and Thagard (1986) provided a thorough description of the development of mental models. According to their description, an individual will learn (a) categorization functions that allow people to map from objects in the real world to a representative category in their mental model, and (b) model transition functions that describe how objects in the model will change over time. By repeatedly comparing the predictions of their internal model with the actual states of the system, individuals will progressively refine their models to develop more specific and numerous categorization functions which allow for more-accurate predictions based on detailed object characteristics and better transition functions for these specialized categorizations. This process enables people to progressively refine their classification of a perceived object from an aircraft to fighter aircraft to F-18 to F-18c and gives them a more refined idea of the behavior and capabilities of the aircraft (in order to provide predictions). Their explanation also provides for two more features that are important to recognized attributes of situation awareness: default information and confidence levels.

Default information. Holland et al.'s (1986) explanation includes a "Q-morphism" in which default information for the system is provided in a higher layer of the model (i.e., a more general level of classification). These default values may be used by individuals to predict system performance unless some specific exception is triggered, in which case the appropriate transition function for that more detailed classification will be used. For example, a pilot will make decisions based on general knowledge of how fighter aircraft maneuver if the specific model of aircraft is not known. This feature allows people to operate effectively on the basis of often limited information.

In addition, default values for certain features of a system can be used if exact current values are not known. Fighter pilots, for example, usually get only limited information about other aircraft. They therefore must operate on default information (e.g., it is probably a MIG-29 and therefore likely traveling at certain approximate speed). When more details become available, their SA becomes more accurate (e.g., knowledge of the exact airspeed), possibly leading to better decisions, but they are still able to make reasonable decisions without perfect information. This provision of mental models allows experts to have access to reasonable defaults that provide more effective decisions than those of novices who simply have missing information (or poorer defaults). In many cases, experts may incorporate this type of default information in forming SA.

Confidence level. A second important aspect of situation awareness concerns a person's confidence level regarding that SA. People may have a certain confidence level regarding the accuracy of information they have received based on its reliability or source. The confidence level associated with information can influence the decisions that are made using that information (Norman, 1983). An important aspect of SA, therefore, is the person's confidence concerning that SA, a feature that has been cited by both pilots and air traffic controllers (Endsley, 1993c; Endsley and Rodgers, 1994).

Holland et al. (1986) hypothesized that there is a degree of uncertainty associated with the mental model's transition function that will provide confidence levels associated with predictions from the model. Similarly, one could hypothesize a degree of uncertainty associated with the validity of features used to make the mapping from the real world to categories in the model. For example, if three sources of information indicate a certain object is an apple but one source indicates it is an orange, the object may be characterized in the internal model as an apple but with an uncertainty factor attached to it.

VanDijk and Kintsch (1983), in work on speech understanding, have conceptualized a context model that allows uncertainties to be linked to information from various sources and taken into account in the decision process as well as the stated facts. Borrowing this concept, any given situation model may include a context feature representing the degree of uncertainty regarding the mapping of world information to the internal model and the projections based on the model. This feature allows people to make decisions effectively, despite numerous uncertainties, yet small shifts in factors underlying the uncertainties can dramatically change resultant conclusions (Norman, 1983).

Automaticity

In addition to developing mental models with experience, a form of automaticity can be acquired. Automatic processing tends to be fast, autonomous, effortless, and unavailable to conscious awareness in that it can occur without attention (Logan, 1988). Thus automaticity of certain tasks can significantly benefit SA by providing a mechanism for overcoming limited attention capacity.

In relation to SA, automaticity poses an important question, however. To what degree do people who are functioning automatically have SA? SA, by definition, involves one's level of awareness, which implies consciousness of that information. With automaticity, however, certain features of cognitive processing occur below conscious awareness.

Logan (1988) provided a detailed discussion of automaticity in cognitive processing that he maintained occurs through a direct-access, single-step retrieval of actions to be performed from memory. This description of automaticity is consistent with the previous discussion on the use of schemata and mental models for matching recognized classes of situations to scripts for actions. In this process, "attention to an object is sufficient to cause retrieval of whatever information has been associated with it in the past" (Logan, 1988, p. 587)—that is, to activate the schema or mental model.

When processing in this way, an individual appears to be conscious of the situational elements that triggered the automatic retrieval of information from memory (SA), but he or she probably will not be conscious of the mechanisms used in arriving at the resultant action selection. That is, a person will know the Level 1 elements (e.g., there is an engine problem), even though he or she may not be aware of or be able to articulate the critical cues that led to that knowledge (e.g., a slight change in engine pitch; Nisbett and Wilson, 1977) and may not be able to identify the process used to arrive at a decision because it was directly retrieved from memory as the appropriate script for that situation (Bowers, 1991; Manktelow and Jones, 1987). As expressed by Dreyfus (1981), the individual knows the what but not the how. If asked to explain why a particular decision was made, an individual will usually have to construct some rationale using logical processes to provide an explanation of the action he or she actually chose in an automatic, nonanalytic manner (through the direct link of prototypical situations to scripts). The state of the situation itself (SA), however, can still be verbalized as it is in awareness. (This process has direct implications for the measurement of SA, which is addressed in the following article in this issue.)

This account is consistent with Nisbett and Wilson's (1977) review of people's awareness of and ability to report on mental events. In all of the cases presented by Nisbett and Wilson, it would appear that the how becomes occluded through the use of automatic processes but the what is still available to awareness. The one exception to this statement is the possibility of processing based on subliminal stimuli, which have been shown to modify affective processes. Evidence for the role of subliminal stimuli on typical dynamic decision making, as opposed to affective processes, however, is less apparent.

In addition, the degree to which automatic processing occurs without any attention or awareness has been questioned. Reason (1984) argued that a minimum level of attention is required for all activity—even automatic processes—in order to bring appropriate schemata into play at the right times and to restrain unwanted schemata from interfering. At this very low level of attention, there would be no awareness (equated with consciousness) of the detailed procedures. Once a plan has been put into motion, it serves to execute scripts and process schema as instructed.

An example of the possibility of decision making without conscious SA is that of a person driving home from work who follows the same predetermined path, stops at stoplights, responds to brake lights, and goes with the flow of traffic, yet can report almost no recollection of the trip. Did this person truly operate with no conscious awareness? Or, is it that only a low level of attention was allocated to this routine task, keying on critical environmental features that automatically evoked appropriate actions? The low level of consciousness simply did not provide sufficient salience to allow that particular drive home to be retrieved from memory as distinguishable from a hundred other such trips. I would argue, in agreement with Reason (1984), that this latter alternative is far more likely. Several authors in support of this view have found that when effortful processing is not used, information can be retained in long-term memory and can affect subject responses (Jacoby and Dallas, 1981; Kellog, 1980; Tulving, 1985).

The major implications of the use of automatic processes are (a) good performance with minimal attention allocation, (b) significant difficulty in accurately reporting on the internal models used for such processing and possibly on reporting which key environmental features were related, and (c) unreliability and inaccuracy of reporting on processes after the fact. Based on this discussion, automaticity is theorized to provide an important mechanism for overcoming human information-processing limitations in achieving SA and making decisions in complex, dynamic environments.

The primary hazard created by automatic cognitive processing is an increased risk of being less responsive to new stimuli, as automatic processes operate with limited use of feedback. A lower level of SA could result in atypical situations, decreasing decision timeliness and effectiveness. For example, when a new stop sign is suddenly erected on a familiar route, many people will initially proceed through the intersection without stopping, as the sign is not part of their automatic process and is not heeded.

Goals

SA is not generally thought of as a construct that exists solely for its own sake. SA is important as needed for decision making regarding some system or task. As such, it is integrally linked with both the context and the decisions for which the SA is being sought; it is fundamentally linked with a person's goals. Goals form the basis for most decision making in dynamic environments. Furthermore, more than one goal may be operating simultaneously, and these goals may sometimes conflict (e.g., "stay alive" and "kill enemies"). In most systems, people are not helpless recipients of data from the environment but are active seekers of data in light of their goals.

In what Casson (1983) has termed a *top-down decision process*, a person's goals and plans direct which aspects of the environment are attended to in the development of SA. That information is then integrated and interpreted in light of these goals to form Level 2 SA. The observation of each of three parameters of a system is not in itself meaningful. When integrated and viewed in the context of what they indicate about the goal of operating the system in a given manner, however, they become meaningful. The decision maker then selects activities that will bring the perceived environment into line with his or her plans and goals based on that understanding.

Simultaneously with this top-down process, *bottom-up processing* will occur. Patterns in the environment may be recognized that will indicate that new plans are necessary to meet active goals or that different goals should be activated. In this way a person's current goals and plans may change to be responsive to events in the environment. The alternating of top-down and bottom-up processing allows a person to process effectively in a dynamic environment.

This process also relates to the role of mental models and schemata. The model in Figure 4 can be used to visualize the relationship. Mental models of systems can be seen to exist as set (although slowly evolving) memory structures. Independently, individuals form a set of goals that relate to some system. These goals can be thought of as ideal states of the system that they wish to achieve. The same set of goals may exist frequently for a given system or may change often. Conversely, a set of goals may relate to more than one system model. A person's current goal(s), selected as the most important among competing goals, will act to direct the selection of a mental model. The selected goals will also determine the frame (Casson, 1983), or focus, on the model that is adopted.

Plans are then devised for reaching the goal using the projection capabilities of the model. A plan will be selected whose projected state best matches the goal state. When scripts are available for executing the selected plan, they will be employed (Schank and Abelson, 1977). When scripts are not available, actions will have to be devised to allow for plan completion. Again, the projection capabilities of the system model will be used to accomplish this.

As an ongoing process, an individual observes the current state of the environment, with his or her attention directed to environmental features by the goal-activated model and interpreted in light of it. The model that is active provides a future projection of the status of key

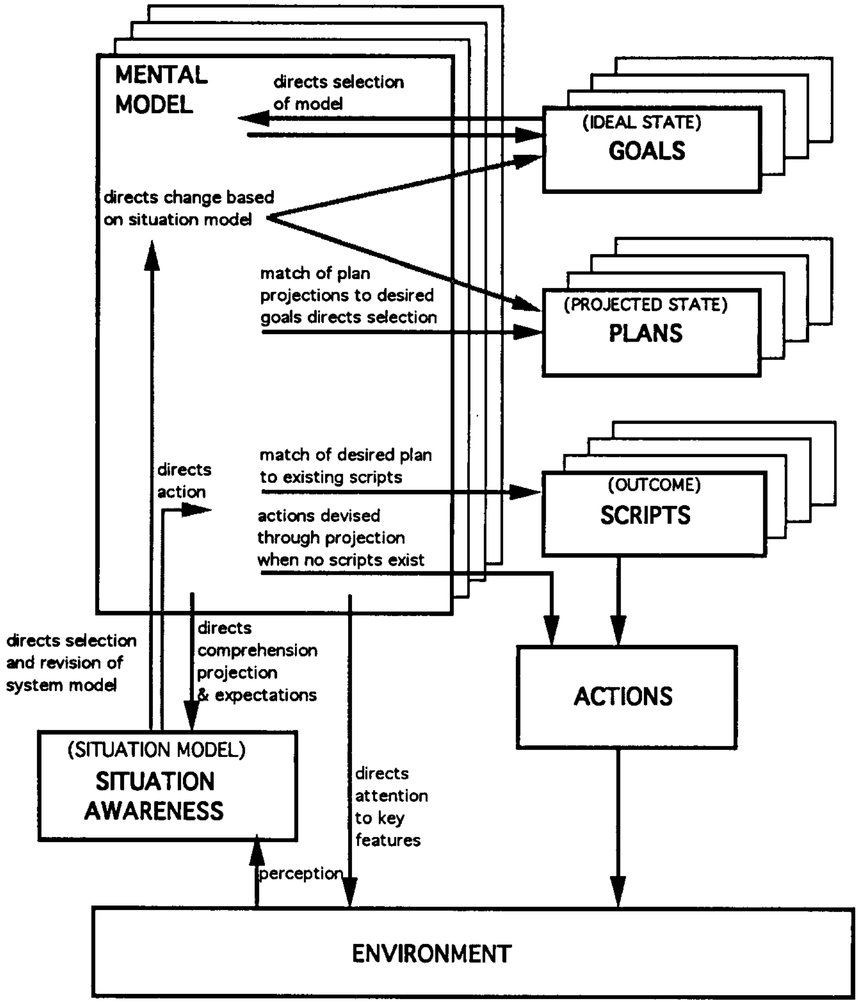

Figure 4. *Relationship of goals and mental models to situation awareness.*

environmental features and expectations concerning future events. When these expectations match that which is observed, all is well. When they do not match because values of some parameter are different or an event occurs that should not, or an event does not occur that should, this signals to the individual that something is amiss and indicates a need to change goals or plans because of a shift in situation classes, a revision of the model, or selection of a new model.

This process can also act to change current goal selection by altering the relative importance of goals, as each goal can have antecedent rules governing situation classes in which each needs to be invoked over the others. When multiple goals are compatible with each other, several may be active at once. When goals are incompatible, their associated priority level for the identified situation class determines which shall be invoked. Similarly, plans may be altered or new plans selected if the feedback provided indicates that the plan is not achieving results in accordance with its projections, or when new goals require new plans. Through learning, these processes can also serve to create better models, allowing for better projections in the future.

To give a detailed example of this process in a military aircraft environment, a pilot may have various goals, such as stay alive, kill enemy aircraft, and bomb a given target. These general goals may have more specific subgoals, such as navigate to the target, avoid detection, avoid missiles, and employ missiles. The pilot would choose between goals (and subgoals) based on their relative importance and the existing situation classification. Staying alive is a priority goal, for example, which usually is active (except in extreme kamikaze circumstances). A pilot may alternate between the goals of bombing a target and killing an enemy aircraft based on the predetermined criticality of each goal's success to the current mission and the specifics of the situation (which would convey the likelihood of each goal's success).

The current goal would indicate the model and frame to be active. A model for the goal of missile employment might direct attention toward key environmental features, such as dynamic relative positions of own and threat aircraft (location, altitude, airspeed, heading, flight path), and current weapon selection, including weapon envelope and capabilities, current probability of kill, and rate of change of probability of kill. If this model was active, the pilot would be inclined to seek out and process those key elements of the environment. Use of the resultant situation model (SA), in conjunction with the missile employment model, would allow the pilot to determine how best to employ the aircraft relative to the enemy aircraft and missile launch timing (plans and actions).

While carrying out this goal, the pilot will also be alert to critical features that might indicate that a new model should be activated. If the pilot detected a new threat, for example, the activated goals might change so that the pilot would cease to operate on the missile employment model, and a threat assessment model would be activated consistent with that goal. The model selected, if detailed enough, would be used to direct situation comprehension, future projection, and decision making. A threat assessment model might include information as to what patterns of threats and threat movements constitute offensive versus defensive activities, for example. Future threat movements might be predictable from the model based on current threat movements and known tactics. Appropriate tactics for countering given threat actions might also be resident in the form of scripts, simplifying decision making.

Summary

To summarize the key features of SA in this model, a person's SA is restricted by limited attention and working memory capacity. Where they have been developed, long-term memory stores, most likely in the form of schemata and mental models, can largely circumvent these limits by providing for the integration and comprehension of information and the projection of future events (the higher levels of SA), even on the basis of incomplete information and under uncertainty. The use of these models depends on pattern matching between critical cues in the environment and elements in the model. Schemata of prototypical situations may also be associated with scripts to produce single-step retrieval of actions from memory. SA is largely affected by a person's goals and expectations which will influence how attention is directed, how information is perceived, and how it is interpreted. This top-down processing will operate in tandem with bottom-up processing in which salient cues will activate appropriate goals and models. In addition, automaticity may be useful in overcoming attention limits; however, it may leave the individual susceptible to missing novel stimuli that can negatively affect SA.

TASK AND SYSTEM FACTORS

A number of task and system factors can also be postulated to influence an individual's ability to achieve SA. Although a full list of these factors has yet to be determined, a few major issues would seem apparent.

System Design

Figure 5 shows the sequence by which a person gains access to information from the environment (Endsley, 1990a). Some information may be acquired directly. In many domains of interest, however, an intervening system senses information and presents it to a human operator. In this process, transmission error, defined as a loss of information, can occur at each transition.

First of all, the system may not acquire all of the needed information (e_1). Most aircraft systems, for example, even those with the latest radar, do not provide complete tracks on all aircraft. Nor do they provide everything the pilot would like to know about those aircraft that are detected. Similarly, most systems will acquire only certain information, based on the designer's understanding of what is required and technological limitations.

Of the information acquired by the system, not all of it may be displayed to the operator (e_2). This may be because the interface is either not set up to display certain information or only subsets can be displayed at any one time. Frequently, the operator can determine to a certain degree which subset of data is displayed (and also in some systems in which data are acquired). Finally, of the information displayed by the system and that directly acquirable from the environment, there may be incomplete or inaccurate transmission to the human operator (e_3 and e_4) because of perceptual, attention, and working memory constraints, as discussed earlier.

The first external issue influencing SA, therefore, is the degree to which the system acquires the needed information from the environment. The second major issue involves the display interface for providing that information to the operator.

Interface Design

The way in which information is presented via the operator interface will largely influence SA by determining how much information can be acquired, how accurately it can be acquired, and to what degree it is compatible with the operator's SA needs. Hence, SA has become a topic of great concern in many human factors design efforts. In general, one seeks designs that will transmit needed information to the operator without undue cognitive effort. In this light, mental workload has been a consideration in design efforts for some time. At the same time, the level of SA provided (the outcome of that process) needs to be considered.

Determining specific design guidelines for improving operator SA through the interface is the challenge fueling many current research efforts. Several general interface features can be hypothesized to be important for SA, based on the model presented here.

1. As attention and working memory are limited, the degree to which displays provide information that is processed and integrated in terms of Level 2 and 3 SA requirements will positively affect SA. For instance, directly portraying the amount of time and distance available on the fuel remaining in an aircraft would be preferable to requiring the pilot to calculate this information based on lower-level data (e.g., fuel, speed, altitude, etc.).
2. The degree to which information is presented in terms of the operator's major goals will positively affect SA. Many systems provide information that is technology oriented—based on physical system parameters and measurements (e.g., oil pressure

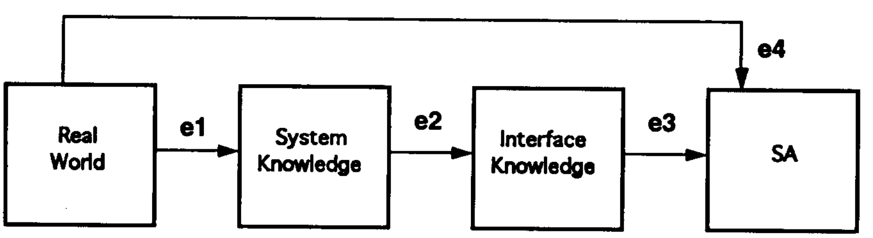

Figure 5. *Situation awareness inputs (adapted from Endsley, 1990a).*

or temperature). To improve SA, this information needs to be SA oriented. That is, it should be organized so that the information needed for a particular goal is colocated and directly answers the major decisions associated with the goal. For example, for the goal of weapons employment, factors such as opening/closing velocity, weapon selected and firing envelope, probability of kill, target selected, and time to employment would be relevant elements that should be presented in an integrated form for this goal.

3. Considering that mental models and schemata are hypothesized to be key tools for achieving the higher levels of SA in complex systems, the critical cues used for activating these mechanisms need to be determined and made salient in the interface design. In particular those cues that will indicate the presence of prototypical situations will be of prime importance. Kaplan and Simon (1990) found decision making is facilitated if the critical attributes are perceptually salient.
4. Designs need to take into consideration both top-down and bottom-up processing. In this light, environmental cues with highly salient features will tend to capture attention away from current goal-directed processing. Salient design features, such as those indicated by Treisman and Paterson (1984), should be reserved for critical cues that indicate the need for activating other goals and should be avoided for noncritical events.
5. A major problem for SA occurs when attention is directed to a subset of information and other important elements are not attended to, either intentionally or unintentionally (Endsley and Bolstad, 1993). It is hypothesized that designs that restrict access to SA elements (via information filtering, for instance) will contribute to this problem. A preferred design will provide *global SA*—an overview of the situation across operator goals—at all times, while providing the operator with detailed information related to his or her immediate goals, as required. Global SA is hypothesized to be important for determining current goals and for enabling projection of future events.
6. Although filtering out information on relevant SA elements is hypothesized to be detrimental, the problem of information overload in many systems must still be considered. The filtering of extraneous information (not related to SA needs) and reduction of data (by processing and integrating low-level data to arrive at SA requirements) should be beneficial to SA.
7. One of the most difficult and taxing parts of SA is the projection of future states of the system. This is hypothesized to require a fairly well developed mental model. System-generated support for projecting future events and states of the system should directly benefit Level 3 SA, particularly for less-experienced operators.
8. The ability to share attention between multiple tasks and sources of information will be very important in any complex system. System designs that support parallel processing of information should directly benefit SA. For example, the addition of voice synthesis or three-dimensional audio cues to the visually overloaded cockpit is predicted to be beneficial on this basis.

These recommendations may not appear that radically different from those that have been espoused, at least singularly, elsewhere. This is because the SA theory described here rests on various information-processing constructs that have been discussed for some years. The value added by the SA concept is as a means of integrating these constructs in terms of the operator's overall goals and decision behavior. As such, this provides several advantages in the design process.

1. The integrated focus of SA provides a means of designing for dynamic, goal-oriented behavior, with its constant shifting of goals. Traditional design approaches (Meister, 1971) have focused on task analysis, which works fairly well for fixed, sequential tasks but does not provide the mechanisms or flexibility necessary for dealing with dynamic tasks and fluctuating goals. By focusing at the level of operator goals, the degree to which multiple goals may be operating simultaneously can be considered and the precursors to goal activation represented. Thus a more compatible representation of operator behavior can be generated for creating "user-centered" designs.
2. It provides a means of moving from a focus on providing operators with data to providing operators with information. When focusing on data, all of the integration, comprehension, and projection is still up to the operator. When focusing on information, the design focus is on presenting what the operator really needs to know in the format it is needed in, thus allowing the operator to achieve more SA at a given level of workload. By presenting the Level 1, 2, and 3 SA requirements associated with each goal or subgoal, this can be accomplished.
3. It provides a means of incorporating into the design a consideration of the interplay of elements, wherein more attention to some elements may come at the expense of others. Many design guidelines are at the level of the specific component (e.g., a dial or audio signal's characteristics). Yet the real challenge in designing systems arises when the components must be integrated. The SA provided to the operator as a result of the combination of system components becomes the goal of the integration process.
4. Perhaps most important, this integrated level of focus provides a means for assessing the efficacy of a particular design concept that an examination of underlying constructs (attention, working

memory, etc.) does not provide. As an integrated system, the degree to which a particular design provides SA (as a resultant state) can be determined after all these other factors, with their associated trade-offs and interactions, have come into play.

The number of possible display formats, technologies, and design concepts that have been or may be contemplated for improving SA are too numerous to mention. A few major design issues, however, pose a serious enough challenge to SA across numerous systems to warrant special consideration: stress, workload, complexity, and automation.

Stress

Several types of stress factors exist that may act to influence SA, including (a) physical stressors—noise, vibration, heat/cold, lighting, atmospheric conditions, drugs, boredom or fatigue, and cyclical changes; and (b) social psychological stressors—fear or anxiety, uncertainty, importance or consequences of events, aspects of task affecting monetary gain, self-esteem, prestige, job advancement or loss, mental load, and time pressure (Hockey, 1986; Sharit and Salvendy, 1982).

Mandler (1982) stated that these stressors "are effective to the extent that they are perceived as dangerous or threatening" (p. 91). That is, they are stressors only if the person perceives them as being stressing. A large interpretive component exists in the process. A certain amount of stress may actually improve performance by increasing attention to important aspects of the situation. A higher amount of stress can have extremely negative consequences, however, as accompanying increases in autonomic functioning and aspects of the stressors can act to demand a portion of a person's limited attentional capacity (Hockey, 1986).

Stressors can affect SA in a number of different ways. The first, and probably most widespread, finding is that under various forms of stress, people tend to narrow their field of attention to include only a limited number of central aspects (Bacon, 1974; Baddeley, 1972; Bartlett, 1943; Callaway and Dembo, 1958; Davis, 1948; Eysenck, 1982; Hockey, 1970). Under perceived danger, a decrease in attention has been observed for peripheral information (i.e., those aspects that attract less attentional focus; Bacon, 1974; Weltman, Smith, and Egstrom, 1971). Broadbent (1971) found that there was an increased tendency to sample dominant or probable sources of information under stress. Sheridan (1981) has termed this effect *cognitive tunnel vision.*

This is a critical problem for SA, leading to the neglect of certain elements in favor of others. In many cases, such as in emergency conditions, it is those factors outside the operator's perceived central task that prove to be lethal. A United Airlines DC-8 crashed in Portland, Oregon, in 1978 when it ran out of fuel. It was reported that the captain, preoccupied with a landing gear problem, neglected to keep track of fuel usage (National Transportation Safety Board, 1979). Many similar incidents of attentional narrowing can be found.

Premature closure, arriving at a decision without exploring all information available, has also been found to be more likely under stress (Janis, 1982; Keinan, 1987; Keinan and Friedland, 1987). This includes considering less information (Janis, 1982; Wright, 1974) and attending more to negative information (Wright, 1974). Several authors have found that scanning of stimuli under stress is scattered and poorly organized (Keinan, 1987; Keinan and Friedland, 1987; Wachtel, 1967).

Complex tasks with multiple input sources appear to be particularly sensitive to the effects of stressors (Broadbent, 1954; Jerison, 1957, 1959). Woodhead (1964) found that performance decrements that occurred during intermittent noise stress took place during the information input stage. It would seem, then, that stress significantly affects the early stage of the decision-making process that is involved in the assessment of the situation. It is expected that stress will significantly influence SA on this basis, beginning with the initial perception of environmental elements (Level 1).

A second way in which stress may affect SA is through decrements in working memory capacity and retrieval (Hockey, 1986). Wickens, Stokes, Barnett, and Hyman (1988) found that optimality of performance was negatively affected by stress only on decision tasks with a high spatial component, however, and not on those with purely a high working memory or long-term memory component.

The degree to which working memory decrements will affect SA depends on the resources available to the individual operator. In tasks in which achieving SA involves a high working memory load, a significant impact on SA Levels 2 and 3 would also be expected. In the *Vincennes* incident, the systems operators had to rely on working memory to calculate whether an incoming aircraft was ascending or descending. Their error in believing the incoming aircraft was descending could have been associated with reduced working memory capacity in a stressful combat environment. If long-term memory stores are available to support SA, less effect will be expected.

Workload

In many dynamic systems, high mental workload is a stressor of particular importance, so much so that at least one major approach to SA measurement combines workload features (supply and demand of operator resources) with information features (Taylor, 1989). Endsley (1993a), however, demonstrated independence between these two constructs across a wide range of values. That is, the following may exist:

(1) Low SA with low workload: The operator may have little idea of what is going on and is not actively working to find out because of inattentiveness, vigilance problems, or low motivation.
(2) Low SA with high workload: If the volume of information and number of tasks are too great, SA may suffer because the operator can attend to only a subset of information or may be actively working to achieve SA, yet has erroneous or incomplete perception and integration of information.
(3) High SA with low workload: The required information can be presented in a manner that is easy to process (an ideal state).
(4) High SA with high workload: The operator is working hard but is successful in achieving an accurate and complete picture of the situation.

Thus SA and workload are hypothesized to diverge because of characteristics of the system design, tasks, and the individual operator. If the operator is exerting effort at attaining SA and if the demands associated with this task and others exceed the operator's limited capacity, only then will a decrement in SA be expected.

Complexity

A major factor creating a challenge for operator SA is the increasing complexity of many systems. System complexity is hypothesized to negatively affect both operator workload and SA through factors such as an increase in the number of system components, the degree of interaction between these components, and the dynamics or rate of change of the components. In addition, the complexity of the operator's tasks may increase through the number of goals, tasks, and decisions to be made in regard to the system.

Each of these factors will increase the amount of mental workload required to achieve a given level of SA. When that demand exceeds human capabilities, SA will suffer. This complexity may be somewhat moderated by the degree to which the operator has a well-developed internal representation of the system to aid in directing attention, integrating data, and developing the higher levels of SA, as these mechanisms may be effective for coping with complexity.

Automation

A lack of SA has been hypothesized to underlie the out-of-the-loop performance decrement that can accompany automation (Carmody and Gluckman, 1993; Endsley, 1987a; Wickens, 1992b). System operators working with automation have been found to have a diminished ability to detect system errors and subsequently perform tasks manually in the face of automation failures as compared with manual performance on the same tasks (Billings, 1991; Moray, 1986; Wickens, 1992a; Wiener and Curry, 1980). Although some of this problem may result from a loss of manual skills under automation, SA is also a critical component.

Operators who have lost SA may be slower to detect problems and also will require extra time to reorient themselves to relevant system parameters in order to proceed with problem diagnosis and assumption of manual performance when automation fails. This has been hypothesized to occur for a number of reasons: (a) a loss of vigilance and increase in complacency associated with the assumption of a monitoring role under automation, (b) the difference between being an active processor of information in manual processing and a passive recipient of information under automation, and (c) a loss of or change in the type of feedback provided to operators concerning the state of the system under automation (Endsley and Kiris, in press). In their study, Endsley and Kiris found evidence for an SA decrement accompanying automation of a cognitive task that was greater under full automation than it was under various levels of partial automation. Lower SA in the automated conditions corresponded to a demonstrated out-of-the-loop performance decrement, supporting the hypothesized relationship between SA and automation.

SA may not suffer under all forms of automation, however. Wiener (1993) and Billings (1991) have stated that SA may be improved by systems that provide integrated information through automation. In commercial cockpits, Hansman et al. (1992) found that automated flight management system input was superior to manual data entry, producing better error detection on clearance updates. Automation that reduces unnecessary manual work and data integration required to achieve SA may provide benefits to both workload and SA. The exact conditions under which SA will be positively or negatively affected by automation need to be determined.

ERRORS IN SA

From an operational point of view, there is major concern about situations in which the operator has poor SA, thus increasing the probability of undesirable performance. Errors in SA can be discussed in terms of the presented model. It is not the intention here to discuss all types of human error, for which several taxonomies exist (Norman, 1983; Rasmussen, 1986; Reason, 1987) but, rather, to investigate the factors that can lead to breakdowns in the SA portion of the decision-making process. These breakdowns can occur from either incomplete SA—knowledge of only some of the elements—or inaccurate SA—erroneous knowledge concerning the value of some elements. The discussion will be separated into those factors affecting SA at each of its three levels.

Level 1 SA. At the very lowest level, a person may simply fail to perceive certain information that is important for SA in the assigned task (incomplete SA). In the simplest case, this may result from a lack of detectability or discriminability of the physical characteristics of the signal in question, from some physical obstruction preventing perception (visual barrier, auditory masking, etc.), or from a failure of the system design to make the information available to the operator. Accurate, reliable weather information for aircrew is frequently lacking, for instance. The crew of a Northwest Airlines DC-9 attempted to take off from Detroit unaware that the aircraft flaps were retracted, leading to the death of 154 people (National Transportation Safety Board, 1988). A partial reason cited for this lack of knowledge was the failure of a takeoff warning system to alert the crew to the problem with the flaps. (In addition, the crew failed to fully execute a checklist, thus they did not directly check the flaps themselves.)

In extreme cases, the only cue a person will have regarding the presence of certain information will coincide with the occurrence of an error. Rasmussen (1986) gave the example of a person not realizing that it is icy until he or she slips. In this case, the condition could be discerned only in conjunction with the error and not sufficiently in advance to allow for behavior modification to prevent the error. In other cases, because of luck, no error may result from the lack of SA; however, the potential for error would rise significantly.

In many cases in which SA is incomplete, the relevant signals or cues are readily discernible but not properly perceived by the subject. The failure of the Northwest Airlines crew to manually check flap status would fall into this category. There can be several underlying causes for not perceiving available information. Many complex environments present an overabundance of information. Data sampling should maintain a fair degree of accuracy on each of the relevant variables (Wickens, 1992a), in which case errors in SA would be small (determined by the amount of change in each variable between successive samples) and distributed across the various variables of concern. Failures in information sampling are commonplace, however, and may result from the lack of an adequate strategy or internal model for directing sampling. Wickens (1992a) has also noted that humans have several general failings in sampling, including misperception of the statistical properties of elements in the environment and limitations of human memory (forgetting what has already been sampled). The phenomenon of visual dominance can act as a further limit; auditory information is less likely to be processed in some situations (Posner, Nissen, and Klein, 1976).

Furthermore, some people appear to be better than others at dividing their attention across different tasks (Damos and Wickens, 1980). Martin and Jones (1984) have found cognitive errors to be significantly correlated with capabilities in distributing attention across tasks. So, although environmental sampling can be an effective means of coping with excessive SA demands, human limitations in sampling, attention, and attention sharing can lead to significant Level 1 SA errors.

This problem is compounded by the addition of stress, which can affect the information input stage through premature closure, changes in factors attended to, and deterioration of the scanning process. The narrowing of attention brought on by stress or heavy workload can lead to a lack of SA on all but the factor at hand. In 1972 an L-1011 commercial airliner went down in the Florida Everglades because all of the crew members were so focused on a problem with the nose gear indicator that they failed to notice that the aircraft was descending. Ninety-nine lives were lost (National Transportation Safety Board, 1973). A major problem with attentional narrowing is that often a person will be sure he or she is attending to the most important information, but there is no way to know whether or not that assumption is valid without having some idea of the value of the other elements. In other cases, the normal sampling strategy has merely been interrupted and not reactivated in a timely manner. In either case, attentional narrowing can lead to serious errors in SA.

Inaccurate SA—the belief that the value of some variable is different from what it actually is—can also occur. In relation to Level 1 SA, this would occur through the misperception of a signal—for instance, seeing a blue light as green because of ambient lighting or seeing a 3 as an 8 on a dial. Exemplifying this problem is the instance in which a Boeing 737 hit power lines near Kansas City, Missouri, because the pilot misidentified lights north of the runway as the runway approach lights (National Transportation Safety Board, 1990). Erroneous expectations can be a major contributor to these misperceptions.

Level 2 SA. SA errors are most often the result of an inability to properly integrate or comprehend the meaning of perceived data in light of operator goals. Orasanu, Dismukes, and Fischer (1993) described five National Transportation Safety Board (NTSB) aircraft accident reports. In all five cases, sufficient environmental cues were present, but the aircrew did not determine their relevance to important goals.

This misreading of cues can occur for several reasons. A novice will not have the mental models necessary for properly comprehending and integrating all of the incoming data or for determining which cues are actually relevant to established goals. Fischer, Orasanu, and Montalvo (1993) found that less-effective crews lacked sensitivity to contextual factors, indicating a failure to recognize prototypical situations. In the absence of a good internal model, one must accept low SA and thus be compromised in decision making, develop a new model, or adapt an existing model to the task at hand. SA errors will exist in the form of inaccurate or incomplete Level 2 SA when the adapted or newly developed model fails to match the new environment.

In other cases, a person may incorrectly select the wrong model from memory, based on a subset of situational cues, and use this model to interpret all perceived data. Mosier and Chidester (1991) found evidence that aircrews made "recognitional, almost reflexive judgments, based upon a few, critical items of information; and then spent additional time and effort verifying its correctness through continued situational investigation." This strategy can be effective. Mosier and Chidester found that the best-performing crews obtained a substantial portion of their information after making a decision.

However, if the wrong mental model is initially selected, based on a subset of cues, a representational error may occur. These errors can be particularly troublesome, as pointed out by Carmino, Idee, Larchier Boulanger, and Morlat (1988). They noted that realizing that the wrong model is active can be very difficult because new data are interpreted in light of the model. Difficulties in recognizing the error may also be compounded by confirmation bias (Fracker, 1988). Thus data that should indicate one thing are taken to mean something quite different based on the incorrect model.

Klein (1993) reported on errors in medical decision making in which successive symptoms continued to be interpreted into an existing diagnosis even though they clearly pointed to a different diagnosis. Fracker also pointed out that an incorrect model may be selected initially because of representativeness and availability biases.

Even when a person has selected the correct model with which to interpret and integrate environmental stimuli, errors can occur. Certain pieces of data may be mismatched with the model or not matched at all, resulting in a failure to recognize a prototypical situation (Klein, 1989b; Manktelow and Jones, 1987). The NTSB (1981) noted that several aircraft conflicts were related to the fact that air traffic controllers received the same aural signal for both conflict alerts and low-altitude warnings. In this case, inadequate perceptual salience of the signals probably prevented an immediate correct match of cue to model.

In addition, SA errors could occur from overrelying on the default values embedded in a model (Manktelow and Jones, 1987). In general, when new situations are encountered in which the known default values are not appropriate, the model is modified to include the new class of situations. Before this occurs, or if cues received have not flagged the specific situation type, significant SA errors can occur by incorrectly assuming defaults for some variables. The newly developed French Airbus 320 crashed during a low flyover demonstration in 1988. The inquiry noted that the pilot may not have been adequately aware of effects on handling performance when flying near the angle-of-attack limits of the aircraft and may have been relying on the much-advertised envelope protection designed into the new aircraft (Ministry of Planning, Housing, Transport and Maritime Affairs, 1989). In terms of this paper, a refined model for the specific aircraft capabilities had not yet been developed, and the pilot had to rely on a general understanding of envelope protection.

When no model exists at all, Level 2 SA must be developed in working memory. An inability to perform this integration in an accurate, timely manner—resulting from insufficient knowledge or working memory limitations, particularly under stress—can also lead to inaccurate or incomplete SA.

Level 3 SA. Finally, Level 3 SA may be lacking or incorrect. Even if a situation is clearly understood, it may be difficult to accurately project future dynamics without a highly developed mental model. Klein (1989b) has noted that some people simply are not good at mental simulation. Lack of a good model and attention and memory limitations would account for this. Simmel and Shelton (1987) described the problems pilots have in determining potential consequences of assessed situations. Amalberti and Deblon (1992) and MacMillian, Entin, and Serfaty (1993) noted, however, that experts frequently determine possible future occurrences in order to plan ahead.

General factors. A few general underlying factors may also lead to SA errors at all three levels. Martin and Jones (1984) pointed out that people who have trouble with distributed attention may be having trouble in maintaining multiple goals. This could lead to considerable SA problems in complex systems, in which the ability to juggle goals on the basis of incoming information is a necessity. An inability to keep multiple goals in mind could seriously degrade an operator's receptivity to highly pertinent data related to the neglected goal, leading to significant errors.

A second major type of error affecting SA relates to the role of habitual schemata (or automaticity). In the normal course of events, habitual schemata will be automatically activated based on the presence of environmental cues. While the schema is active, environmental cues will be processed in a predetermined manner. When a change needs to be made, however, problems can occur. A person leaving work and getting into the car may automatically embark on the "drive home" schema. If on a particular day the person wishes to stop at the store, he or she must change or interrupt the schema. Often, however, the person arrives home to realize the desired detour was completely forgotten.

Although this has been termed a *slip of action* (Reason, 1984), it can also be shown to be related to SA. Under normal circumstances, environmental cues (the store sign) will be processed in light of current goals (stop at the store). While habitual schemata are operating, however, the new, nonhabitual goal is suppressed, and seeing the store sign does not conjure the associated goal of stopping. While the habitual schema is operating, the person either is not receptive to the nonhabitual cues or does not generate the appropriate higher-level SA from the perception of the cues because the appropriate schema is suppressed.

Detection of SA errors. A real issue concerns how people know when their SA is in error. Very often they may be completely unaware of how much they do not know or of the inaccuracy of their internal representation of the situation. The main clue to erroneous SA will occur when a person perceives some new piece of data that does not fit with expectations based on his or her internal model. When a person's expectations do not match with what is perceived, this conflict can be resolved by adopting a new model, revising the existing model, or changing one's goals and plans to accommodate the new situation classification (Manktelow and Jones, 1987). The inappropriate choice could easily sabotage SA efforts for some time.

If the new data can be incorporated into the model, this may merely indicate that a new prototypical situation (state of the model) is present that calls up different goals and plans accordingly. If the new data cannot easily fit into the existing model, the model may be revised. A common problem is whether to continue to revise the existing model to account for the new data or choose an alternate model that is more appropriate. For the latter to occur, something about the data must flag that a different situation is present. Without this flag, the person may persist in a representational error whereby the data continue to be misinterpreted in light of the wrong model. Of course, if the inadequacy of the existing model is recognized but no appropriate new model exists, significant errors may still occur while a new model is being developed.

CONCLUSIONS

This paper presents a model of SA, including various mechanisms and factors hypothesized to be important for its generation. Based on this model, a taxonomy of SA errors was generated. The model also presents a means of conducting future research on SA.

Theoretical Hypotheses

Several characteristics of individuals and systems have been presented that are believed to affect a person's ability to acquire and maintain SA. In terms of information-processing mechanisms available to individuals, the following key features affecting SA are hypothesized:

1. The way in which attention is directed across available information is critical to achieving SA (particularly in dynamic and complex systems in which attention is overloaded).
2. In the absence of long-term memory structures, SA will be constrained by the limitations of attention and working memory.
3. Schemata and mental models are presented as mechanisms for (a) directing attention in the perception process, (b) providing a means of integrating and comprehending perceived information, and (c) projecting the future states of the environment. These mechanisms allow decision makers to develop SA when they have only limited information from the environment.
4. A person's expectations or preconceptions about future events and environmental features, as generated from mental models, instructions, and communications, will influence the perception process and the interpretation of what is perceived.
5. SA is viewed as being generated from a combination of goal-directed (top-down) and data-directed (bottom-up) processing. As such, it will be affected by both the operator's current goals and the presence of salient environmental cues.
6. The operator's current goals will act to direct the selection of a mental model and the focus (or frame) taken on the model.
7. Knowledge of critical cues in the environment is highly important for (a) directing the selection of active goals from among possible operator goals (and thus mental model selection) and (b) pattern matching with schemata of prototypical situations according to the current model.
8. Automaticity is presented as an additional mechanism for overcoming attention and working memory limitations. When operating with automaticity, it is expected that operators will have reduced awareness of environmental factors (lower SA), particularly for those elements outside the automated sequence, and thus will be more likely to make errors under novel circumstances.

In addition, several characteristics of systems and tasks are hypothesized to influence an individual's ability to achieve SA.

1. The degree to which relevant features of the environment are available to the operator either directly or through the system's displays fundamentally affects a person's ability to achieve SA.
2. The way in which information is presented via the operator interface will affect a person's ability to achieve SA. Specific features hypothesized to positively impact SA include: integrated and goal-oriented information presentation, salience of critical cues, support for parallel processing of information, elimination of unneeded information and reduction in salience of noncritical information, presentation of global information across goals and detailed information on current goals, and system support for projection of future events and states.
3. Although small amounts of stress may improve SA through an increase in arousal and attention, excess stress will negatively affect SA through disruptions in acquiring information and, in some cases, through reductions in working memory capacity.
4. SA and workload are hypothesized to be essentially independent across a wide range of these constructs. Only under high levels of perceived workload will decrements in SA be expected.
5. Increases in perceived system complexity are expected to negatively affect both workload and SA unless moderated by the presence of a mental model for dealing with that complexity.
6. Automation of human decision making and active system control is hypothesized to negatively affect operator SA, leading to out-of-the-loop performance problems. Automation of peripheral tasks (e.g., data integration) is expected to positively affect SA by reducing the load on limited working memory.

Directions for Future Research

The model presented provides an integrated framework for conceptualizing the SA construct, thus providing a common ground for moving forward. As such, it provides several capabilities.

SA requirements. The model can be used to generate a means of determining SA requirements (elements) for individual domains of interest. The criticality of operator goals in the SA process dictates that SA requirements (at all levels) are dependent on the operator's goals in relation to the system. Thus a goal-directed task analysis methodology is indicated in which the requirements for system data, the comprehension and integration of that data, and the projection of future states are determined for each of the operator's major goals and subgoals.

A methodology for conducting this type of analysis has been developed and applied to air-to-air fighter aircraft (Endsley, 1993c), advanced bombers (Endsley, 1989a), and air traffic control (Endsley and Rodgers, 1994). In many domains, designers are working with only simple information requirements, without determining how the information needs to be integrated to support operator goals. This methodology can be applied to these domains to determine the SA requirements for systems.

Individual abilities. Endsley and Bolstad (1994) found evidence of fairly stable differences between individuals in their ability to achieve SA given the same system. Based on the present model, variations in SA abilities were hypothesized to arise from individual differences in (a) spatial abilities; (b) attention sharing; (c) memory, including working memory capacity and long-term memory stores; (d) perceptual skills, including perceptual speed, encoding speed, vigilance, and pattern-matching skills; and (e) higher-order cognitive skills, including analytic skills, cognitive complexity, field independence, and locus of control. Testing these hypotheses on a group of experienced fighter pilots, Endsley and Bolstad found strong evidence for the importance of spatial skills and perceptual skills and partial support for the importance of attention-sharing and pattern-matching skills.

More studies are needed to expand these findings to a larger, broader population. In addition, the degree to which such capabilities generalize across different domains, indicating a general SA skill or ability, needs to be determined. The identification of basic human abilities that are important for SA may be useful for improving operator SA through either selection or training.

Training. Programs directed at improving operator training by making it "SA oriented" can also be generated from the model. (See Endsley, 1989b, for a detailed discussion.) They can be developed to instruct operators to identify the important characteristics of mental models in specific domains, such as the components, dynamics and functioning of the components and projection of future actions based on these dynamics. SA-oriented training would focus on training operators to identify prototypical situations of concern associated with these models by recognizing critical cues and what they mean in terms of relevant goals.

As SA is not a passive process, the skills required for achieving and maintaining good SA need to be identified and formally taught in training programs. Factors such as how to employ a system to best achieve SA (when and where to look for what), appropriate scan patterns, or techniques for making the most of limited information need to be determined and explicitly taught in the training process. This type of focus greatly supplements traditional technology-oriented training that concentrates mainly on the mechanics of how a system operates.

In addition, the role of feedback in the learning process may be exploited. It may be possible to provide feedback on the accuracy and completeness of operator SA as a part of training programs. This would allow operators to understand their mistakes and better assess and interpret the environment, leading to the development of more effective sampling strategies and better schemata for integrating information. Training techniques such as these need to be explored and tested to determine methods for improving SA with existing systems.

Design. Several general hypotheses and recommendations concerning how to design systems to enhance SA were generated by the model. More research is needed to apply, test, and expand on these recommendations in relation to the design of specific systems in various domains. Several factors need to be determined, including ways to determine and effectively deliver critical cues; ways to ensure accurate expectations; methods for assisting operators in deploying attention effectively; methods for preventing the disruption of attention, particularly under stress and heavy workload; and ways to develop systems that are compatible with operator goals.

Research is being conducted to investigate a host of new technologies and designs being considered for future systems, including three-dimensional visual and auditory displays, voice control, expert systems, helmet-mounted displays, and virtual reality. This model should be useful for generating hypotheses concerning the effect of new technologies on SA in the context of a particular domain and system interface. Through controlled testing and an objective determination of the impact of these concepts on SA, specific design guidelines for their implementation, alone and in conjunction with one another, can be established.

SA construct. Future research on the SA construct is greatly needed. Several major hypotheses have been formulated concerning underlying information-processing mechanisms. The role of each of the major components needs to be formally tested and explored. In addition, empirical data are needed on SA as a whole in order to better understand and validate the hypothesized interactions and integration of individual factors. SA has been presented as a three-level concept. The relative importance of these levels needs to be established. How critical of a role does projection play, for instance? How is higher-level SA generated from lower-level data? Mental models and goals are hypothesized here as critical mechanisms, but they need further exploration.

Research is also needed to better understand the processes operators use to achieve SA. The way in which information is acquired by individuals and teams needs to be determined to identify successful techniques for coping with complex, dynamic systems. Useful critical cues that may be vital to achieving good SA (or cues that lead to poor SA via the representational error) need to be determined. The degree and nature of individual differences in such processes are not widely known at this point, except anecdotally.

In addition, the concept of SA may be useful in researching other constructs. For instance, situation models (or SA), which are a virtual reflection of system models, may shed some light on the concept of a mental model. Problems with the nebulous use of the term and the need for more precise specification of mental models have been expounded by Wilson and Rutherford (1989). If mental models are truly "mechanisms whereby humans are able to generate descriptions of system purpose and form, explanations of system functioning and observed system states, and predictions of future systems states," as described by Rouse and Morris (1985, p. 7), then three of the four criteria (system functioning, states, and predictions) can be determined by examining situation models (SA) across various contexts or states of the model. This type of effort may help create a better understanding of the nature of mental models in specific domains.

SA measurement. The ability to objectively measure SA is seen as critical for future progress in this field. It provides a means of evaluating the efficacy of design concepts and technologies, providing diagnostic data for design iteration, and a means of evaluating and developing training concepts. It also provides a means of researching the SA construct, investigating the impact of various factors in SA, and explicitly testing the hypotheses concerning SA. Without this capability, no real progress in the area of SA design or theory can be made. Methodologies for measuring SA are discussed in the subsequent paper (Endsley, 1995, this issue), based on the model presented here.

Summary

A model of SA has been presented in relation to decision making in complex systems. Building on research in naturalistic decision making, a person's SA is viewed as a critical focal point of the decision process. In this role, SA is presented as a general construct, applicable across a wide variety of environments and systems.

SA is viewed as consisting of a person's state of knowledge about a dynamic environment. It incorporates the perception of relevant elements, comprehension of the meaning of these elements in combination with and in relation to operator goals, and a projection of future states of the environment based on this understanding. Using this knowledge, individuals with good SA will have a greater likelihood of making appropriate decisions and performing well in dynamic systems. By learning more about SA requirements and the SA construct as a whole, more effective interface designs and training programs can be established to support decision making in complex environments.

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