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11

Situation Awareness In Aviation Systems

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SA Technologies

In the aviation domain, maintaining a high level of situation awareness is one of the most critical and challenging features of an aircrew's job. Situation awareness (SA) can be thought of as an internalized mental model of the current state of the flight environment. This integrated picture forms the central organizing feature from which all decision making and action takes place. A vast portion of the aircrew's job is involved in developing SA and keeping it up to date in a rapidly changing environment. Consider this excerpt demonstrating the criticality of situation awareness for the pilot and it frequent elusiveness.

> Ground control cleared us to taxi to Runway 14 with instructions to give way to two single-engine Cessnas that were enroute to Runway 5. With our checklists completed and the Before Takeoff PA [public announcement] accomplished, we called the tower for a takeoff clearance. As we called, we noticed one of the Cessnas depart on Runway 5. Tower responded to our call with a "position and hold" clearance, and then cleared the second Cessna for a takeoff on Runway 5. As the second Cessna climbed out, the tower cleared us for takeoff on Runway 5.
>
> Takeoff roll was uneventful, but as we raised the gear we remembered the Cessnas again and looked to our left to see if they were still in the area. One of them was not just in the area, he was on a downwind to Runway 5 and about to cross directly in front of us. Our response was to immediately increase our rate of climb and to turn away from the traffic. ... If any condition had prevented us from making an expeditious climb immediately after liftoff, we would have been directly in each other's flight path. (Kraby, 1995)

The problem can be even more difficult for the military pilot who must also maintain a keen awareness of many factors pertaining to enemy and friendly aircraft in relation to a prescribed mission in addition to the normal issues of flight and navigation, as illustrated by this account.

> We were running silent now with all emitters either off or in standby... We picked up a small boat visually off the nose, and made an easy ten degree turn to avoid him without making any wing flashes...
>
> Our RWR [radar warning receiver] and ECM [electronic counter measures] equipment were cross checked as we prepared to cross the worst of the mobile defenses. I could see a pair of A-10's strafing what appeared to be a column of tanks. I was really working my head back and forth trying to pick up any missiles or AAA [anti-aircraft artillery] activity and not hit the ground as it raced underneath the nose. I could see Steve's head scanning outside with only quick glances inside at the RWR scope. Just when I thought we might make it through unscathed, I picked up a SAM [surface to air missile] launch at my left nine o'clock heading for my wingman! .... It passed harmlessly high and behind my wingman and I made a missile no-guide call on the radio...
>
> Before my heart had a chance to slow down from the last engagement, I picked up another SAM launch at one o'clock headed right at me! It was fired at short range and I barely had time to squeeze off some chaff and light the burners when I had to pull on the pole and perform a last ditch maneuver... I tried to keep my composure as we headed down towards the ground. I squeezed off a couple more bundles of chaff when I realized I should be dropping flares as well! As I leveled off at about 100 feet, Jerry told me there was a second launch at my five o'clock.... (Isaacson, 1985)

In order to perform in the dynamic flight environment, aircrew must not only know how to operate the aircraft and the proper tactics, procedures and rules for flight, but they must also have an accurate, up-to-date picture of the state of the environment. This is a task that is not simple in light of the complexity and sheer number of factors that must be taken into account in order to make effective decisions. Particularly since situation awareness does not end with the simple perception of data, but also depends on a deeper comprehension of the significance of that data based on an understanding of how the components of the environment interact and function, and a subsequent ability to predict future states of the system.

Having a high level of SA can be seen as perhaps the most critical aspect for achieving successful performance in aviation. Problems with SA were found to be the leading causal factor in a review of military aviation mishaps (Hartel, Smith, & Prince, 1991) , and in a study of accidents among major aircarriers, 88% of those involving human error could be attributed to problems with situation awareness (Endsley, 1995a) . Due to its importance and the significant challenge it poses, finding new ways of improving SA has become one of the major design drivers for the development of new aircraft systems. Interest has also increased within the operational community which is interested in finding ways to improve SA through training programs. The successful improvement of SA through aircraft design or training programs requires the guidance of a clear understanding of SA requirements in the flight domain, the individual, system and environmental factors that affect SA, and a design process that specifically addresses SA in a systematic fashion.

SITUATION AWARENESS DEFINITION

Situation awareness is formally defined as “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” (Endsley, 1988) . Situation awareness therefore involves perceiving critical factors in the environment (Level 1 SA), understanding what those factors mean, particularly when integrated together in relation to the aircrew's goals (Level 2), and at the highest level, an understanding of what will happen with the system in the near future (Level 3). These higher levels of SA allow pilots to function in a timely and effective manner.

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 needs to perceive important elements such as other aircraft, terrain, system status and warning lights along with their relevant characteristics. In the cockpit, just keeping up with all of the relevant system and flight data, other aircraft and navigational data can be quite taxing.

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 one's goals. The aircrew puts together Level 1 data to form a holistic picture of the environment, including a comprehension of the significance of objects and events. For example, upon seeing warning lights indicating a problem during take-off, the pilot must quickly determine the seriousness of the problem in terms of the immediate air worthiness of the aircraft and combine this with knowledge on the amount of runway remaining in order to know whether it is an abort situation or not. A novice pilot may be capable of achieving the same Level 1 SA as more experienced pilots, but may fall far short of being able to integrate various data elements along with pertinent goals in order to comprehend the situation as well.

Level 3 SA — Projection Of Future Status.

It is the ability to project the future actions of the elements in the environment, at least in the very near term, that forms the third and highest level of situation awareness. This is achieved through knowledge of the status and dynamics of the elements and a comprehension of the situation (both Level 1 and Level 2 SA). Amalberti and Deblon (1992) found that a significant portion of experienced pilots' time was spent in anticipating possible future occurrences. This gives them the knowledge (and time) necessary to decide on the most favorable course of action to meet their objectives.

SITUATION AWARENESS REQUIREMENTS

Clearly understanding SA in the aviation environment rests on a clear elucidation of its elements (at each of the three levels of SA), identifying which things the aircrew needs to perceive, understand and project. These are specific to individual systems and contexts, and, as such, must be determined for a particular class of aircraft and missions (e.g. commercial flight deck, civil aviation, strategic or tactical military aircraft, etc...). In general, however, across many types of aircraft systems certain classes of elements are needed for situation awareness that can be described.

Geographical SA - location of own aircraft, other aircraft, terrain features, airports, cities, waypoints and navigation fixes; position relative to designated features; runway & taxiway assignments; path to desired locations; climb/descent points.

Spatial/Temporal SA - attitude, altitude, heading, velocity, vertical velocity, G's, flight path; deviation from flight plan and clearances; aircraft capabilities; projected flight path; projected landing time.

System SA - system status, functioning and settings; settings of radio, altimeter and transponder equipment; ATC communications present; deviations from correct settings; flight modes and automation entries and settings; impact of malfunctions/system degrades and settings on system performance and flight safety; fuel; time and distance available on fuel.

Environmental SA - weather formations (area and altitudes affected and movement; temperature, icing, ceilings, clouds, fog, sun, visibility, turbulence, winds, microbursts; IFR vs VFR conditions; areas and altitudes to avoid; flight safety; projected weather conditions.

In addition, for military aircraft, elements relative to the military mission will also be important.

Tactical SA - identification, tactical status, type, capabilities, location and flight dynamics of other aircraft; own capabilities in relation to other aircraft; aircraft detections, launch capabilities and targeting; threat prioritization, imminence and assignments; current and projected threat intentions, tactics, firing and maneuvering; mission timing and status.

Determining specific SA requirements for a particular class of aircraft is dependent on the goals of the aircrew in that particular role. A methodology for determining SA requirements has been developed and applied to fighter aircraft (Endsley, 1993) , bomber aircraft (Endsley, 1989) , and air traffic controllers (Endsley & Rodgers, 1994) .

INDIVIDUAL FACTORS INFLUENCING SITUATION AWARENESS

In order to provide an understanding of the processes and factors that influence the development of SA in complex settings such as aviation, a theoretical model describing factors underlying situation awareness has been developed (Endsley, 1988; 1994; 1995c) . Key features of the model will be summarized here and are shown in Figure 1. (The reader is referred to Endsley (1995c) for a full explanation of the model and supporting research.) In general, SA in the aviation setting is challenged by the limitations of human attention and working memory. The development of relevant long-term memory stores, goal-directed processing, and automaticity of actions through experience and training are seen as the primary mechanisms used for overcoming these limitations to achieve high levels of SA and successful performance.

Processing Limitations.

Attention. In aviation settings, the development of situation awareness and the decision process are restricted by limited attention and working memory capacity for novice aircrew and those in novel situations. Direct attention is needed for perceiving and processing the environment to form SA, for selecting actions and executing responses. In the complex and dynamic aviation environment, information overload, task complexity and multiple tasks can quickly exceed the aircrew's limited attention capacity. Because the supply of attention is limited, more attention to some information may mean a loss of SA on other elements. The resulting lack of SA can result in poor decisions leading to human error. In a review of NTSB aircraft accident reports, poor SA

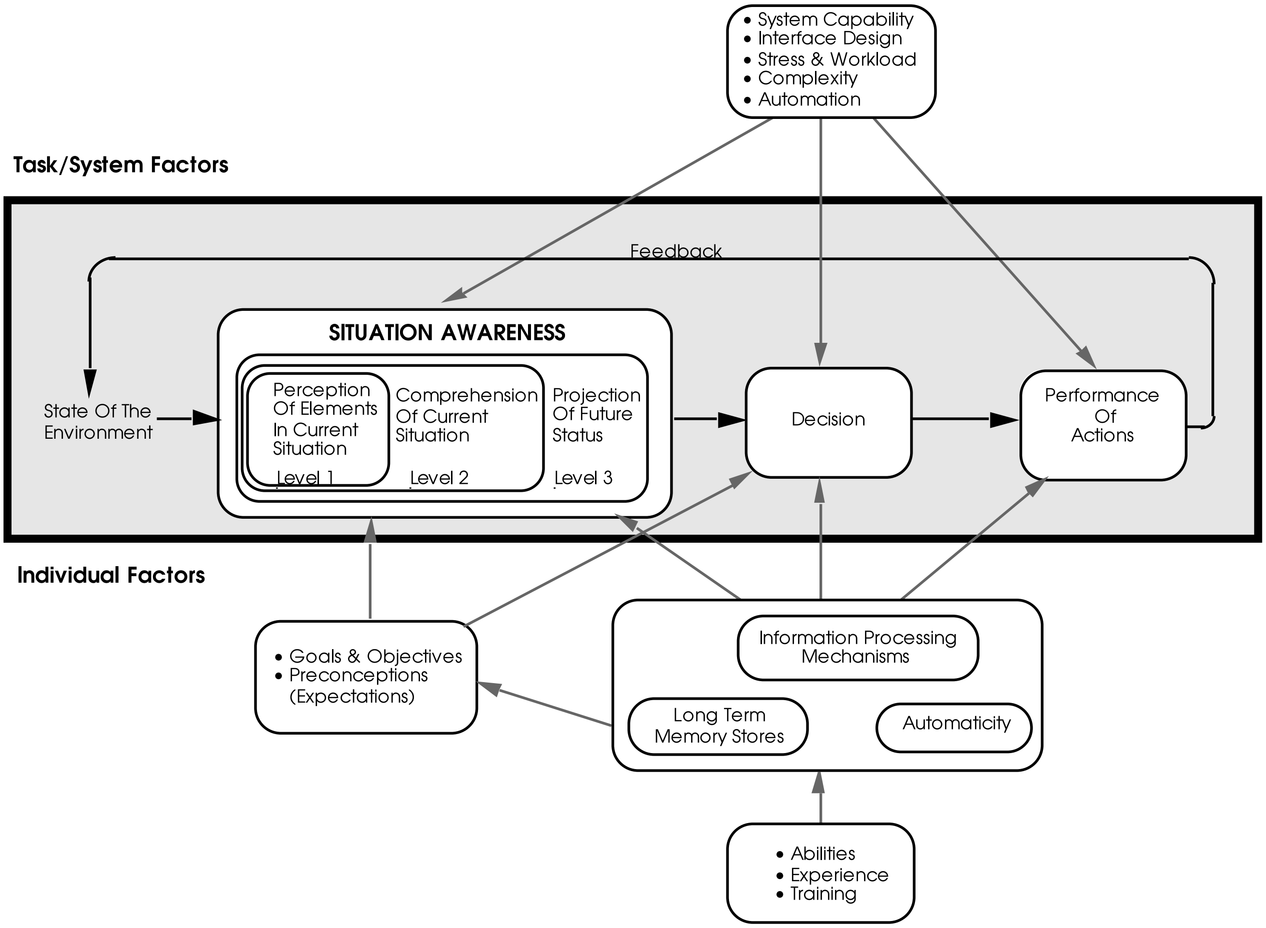

FIG. 11.1 Model of Situation Awareness. From Endsley (1995c). Reprinted by permission.

resulting from attention problems in acquiring data accounted for 31% of accidents involving human error (Endsley, 1995a) .

Pilots typically employ a process of information sampling to circumvent attention limits, attending to information in rapid sequence following a pattern dictated by long-term memory concerning the relative priorities and the frequency with which information changes. Working memory also plays an important role in this process, allowing the pilot to modify attention deployment on the basis of other information perceived or active goals. For example, in a study of pilot SA, Fracker (1990) showed that a limited supply of attention was allocated to environmental elements on the basis of their ability to contribute to task success.

Unfortunately, people do not always sample information optimally. Typical failings include: 1) forming non-optimal strategies based on a misperception of the statistical properties of elements in the environment, 2) visual dominance — attending more to visual elements than information coming through competing aural channels, and 3) limitations of human memory, leading to inaccuracy in remembering statistical properties to guide sampling (Wickens, 1984) . In addition, in the presence of information overload, a frequent occurrence, pilots may feel that the process of information sampling is either not sufficient or not efficient, in which case the pilot may choose to attend to certain information, to the neglect of other information. If the pilot is correct in this selection, all is well. However, in many instances this is not the case.

As a highly visible example, reports of controlled descent into the terrain by high performance fighter aircraft are numerous (McCarthy, 1988) . While various factors can be implicated in these incidents, channelized attention (31%), distraction by irrelevant stimuli (22%), task saturation (18%) and preoccupation with one task (17%) have all been indicated as significant causal factors (Kuipers, Kappers, van Holten, van Bergen, & Oosterveld, 1989) . Some 56% of respondents in the same study indicated a lack of attention for primary flight instruments (the single highest factor) and having too much attention directed towards the target plane during combat (28%) as major causes. Clearly, this demonstrates the negative consequences of both intentional and unintentional disruptions of scan patterns. In the case of intentional attention shifts, it is assumed that attention was probably directed to other factors that the pilots erroneously felt to be more important, because their SA was either outdated or incorrectly perceived in the first place. This leads to a very important point. In order to know which information to focus attention on and which information can be temporarily ignored, the pilot must have at some level an understanding about all of it — i.e. "the big picture".

The way in which information is perceived (Level 1 SA) is affected 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 & Folkard, 1972; Biederman, Mezzanotte, Rabinowitz, Francolin, & Plude, 1981; Davis, Kramer, & Graham, 1983; Humphreys, 1981; Palmer, 1975; Posner, Nissen, & Ogden, 1978) . This type of knowledge is typically gained through experience, training or pre-flight planning and analysis. One’s preconceptions or expectations about information can effect the speed and accuracy of the perception of information. Repeated experience in an environment allows people to develop expectations about future events that predisposes them to perceive the information accordingly. They will process 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) . As a classic example, readback errors, repeating an expected clearance instead of the actual clearance to the air traffic controller, are common (Monan, 1986) .

Working Memory. Working memory capacity can also act as a limit on SA. In the absence of other mechanisms, most of a person’s active processing of information must occur in working memory. The second level of SA involves comprehending the meaning of the data that is perceived. New information must be combined with existing knowledge and a composite picture of the situation developed. Achieving the desired integration and comprehension in this fashion is a very taxing proposition that can seriously overload the pilot's limited working memory and will draw even further on limited attention, leaving even less capacity to direct towards the process of acquiring new information.

Similarly, projections of future status (Level 3 SA) and subsequent decisions as to appropriate courses of action will draw upon working memory as well. Wickens (1984) has stated that the prediction of future states imposes a strong 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. A heavy load will be imposed on working memory if it is taxed with achieving the higher levels of situation awareness in addition to formulating and selecting responses and carrying out subsequent actions.

Coping Mechanisms

Mental Models. In practice, however, experienced aircrew may use long-term memory stores, most likely in the form of schemata and mental models to circumvent these limits for learned classes of situations and environments. These mechanisms provide for the integration and comprehension of information and the projection of future events. They also allow for decision making on the basis of incomplete information and under uncertainty.

Experienced aircrew often have internal representations of the system they are dealing with — a mental model. 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 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). During active decision making, a pilot’s perceptions of the current state of the system may be matched to related schemata in memory that depict prototypical situations or states of the system model. These prototypical situations provide situation classification and understanding and a projection of what is likely to happen in the future (Level 3 SA).

A major advantage of these mechanisms is that the current situation does not need to be exactly like one encountered before due to the use of categorization mapping (a best fit between the characteristics of the situation and the characteristics of known categories or prototypes). The matching process can be almost instantaneous due to 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, it will provide (a) for the dynamic direction of attention to critical environmental 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, providing very rapid decision making.

The use of mental models also provides useful default information. These default values (expected characteristics of elements based on their classification) may be used by aircrew to predict system performance with incomplete or uncertain information, providing more effective decisions than novices who will be more hampered by missing data. For example, experienced pilots are able to predict within a reasonable range how fast a particular aircraft is traveling just by knowing what type of aircraft it is. Default information may furnish an important coping mechanism for experienced aircrew in forming SA in many situations where information is missing or overload prevents them from acquiring all the information they need.

Well developed mental models and schema can provide the comprehension and future projection required for the higher levels of SA almost automatically, thus greatly off-loading working memory and attention requirements. A major advantage of these long-term stores is that a great deal of information can be called upon very rapidly, using only a very small amount of attention (Logan, 1988) . When scripts have been developed, tied to these schema, the entire decision making process can be greatly simplified, and working memory will be off-loaded even further.

Goal-driven processing. In the processing of dynamic and complex information, people may switch between data-driven and goal-driven processing. In a data-driven process, various environmental features are detected whose inherent properties determine which information will receive further focalized attention and processing. In this mode, cue salience will have a large impact on which portions of the environment are attended to and thus SA. People can also operate in a goal-driven fashion. In this mode, situation awareness is affected by the aircrew’s goals and expectations which influence how attention is directed, how information is perceived, and how it is interpreted. The person's goals and plans direct which aspects of the environment are attended to; that information is then integrated and interpreted in light of these goals to form level 2 SA. On an on-going basis, one can observe trade-offs between top-down and bottom-up processing, allowing the aircrew to process information effectively in a dynamic environment.

With experience, aircrew will develop a better understanding of their goals, which goals should be active in which circumstances, and how to acquire information to support these goals. The increased reliance on goal directed processing allows the environment to be processed more efficiently than with purely data-driven processing. An important issue for achieving successful performance in the aviation domain lies in the ability of the aircrew to dynamically juggle multiple competing goals effectively. They need to rapidly switch between pursuing information in support of a particular goal to responding to perceived data activating a new goal, and back again. The ability to hold multiple goals has been associated with distributed attention which is important for performance in the aviation domain (Martin & Jones, 1984) **.**

Automaticity. SA can also be effected by the use of automaticity in processing information. Automaticity may be useful in overcoming attention limits, but may also leave the pilot susceptible to missing novel stimuli. Over time, it is easy for actions to become habitual and routine, requiring a very low level of attention. When something is slightly different, however, for example a different clearance than usual, the pilots may miss it and carry out the habitual action. Developed through experience and a high level of learning, automatic processing tends to be fast, autonomous, effortless and unavailable to conscious awareness in that it can occur without attention (Logan, 1988) . Automatic processing is advantageous in that it provides good performance with minimal attention allocation While automaticity may provide an important mechanism for overcoming processing limitations thus allowing people to achieve SA and make decisions in complex, dynamic environments like aviation, it also creates an increased risk of being less responsive to new stimuli as automatic processes operate with limited use of feedback. When using automatic processing, a lower level of SA can result in non-typical situations, decreasing decision timeliness and effectiveness.

Summary. In summary, situation awareness can be achieved by drawing upon a number of internal mechanisms. Due to limitations of attention and working memory, long-term memory may be heavily relied upon to achieve SA in the highly demanding aviation environment. The degree to which these structures can be developed and effectively used in the flight environment, the degree to which aircrew can effectively deploy goal driven processing in conjunction with data driven processing, and the degree to which aircrew can avoid the hazards of automaticity will ultimately determine the quality of their SA.

CHALLENGES TO SITUATION AWARENESS

In addition to SA being effected by the characteristics and processing mechanisms of the individual, many environmental and system factors will have a large impact on SA. Each of these factors can act to seriously challenge the ability of the aircrew to maintain a high level of SA in many situations.

Stress

Several types of stress factors exist in the aviation environment which may affect SA, including:

1. Physical stressors - noise, vibration, heat/cold, lighting, atmospheric conditions, boredom, fatigue, cyclical changes, G’s and

2. Social/Psychological stressors - fear or anxiety, uncertainty, importance or consequences of events, self-esteem, career advancement, mental load, and time pressure (Hockey, 1986; Sharit & Salvendy, 1982) .

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, including attentional narrowing, reductions in information intake and reductions in working memory capacity. Under stress a decrease in attention has been observed for peripheral information, those aspects which attract less attentional focus (Bacon, 1974; Weltman, Smith, & Egstrom, 1971) , and there is an increased tendency to sample dominant or probable sources of information (Broadbent, 1971) . 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 person’s perceived central task that prove to be lethal. An L-1011 crashed in the Florida Everglades killing 99 people when the crew became focused on a problem with a nose gear indicator and failed to monitor the altitude and attitude of the aircraft (National Transportation Safety Board, 1973) . In military aviation, many lives are lost due to controlled flight into the terrain accidents, with attentional narrowing serving as a primary culprit (Kuipers, et al., 1989) .

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 & Friedland, 1987) . This includes considering less information and attending more to negative information (Janis, 1982; Wright, 1974) . Several authors have also found that scanning of information under stress is scattered and poorly organized (Keinan, 1987; Keinan & Friedland, 1987; Wachtel, 1967) . A lowering of attention capacity, attentional narrowing, disruptions of scan patterns and premature closure may all negatively effect Level 1 SA under various forms of stress.

A second way in which stress may negatively effect SA is by decreasing working memory capacity and hindering information retrieval (Hockey, 1986; Mandler, 1979) . The degree to which working memory decrements will impact SA depends on the resources available to the individual. In tasks where achieving SA involves a high working memory load, a significant impact on SA Levels 2 and 3 (given the same Level 1 SA) would be expected. If long-term memory stores are available to support SA, however, as in more learned situations, less effect will be expected.

Overload/Underload

High mental workload is a stressor of particular importance in aviation that can negatively affect SA. If the volume of information and number of tasks are too great, SA may suffer as only a subset of information can be attended to, or the pilot may be actively working to achieve SA, yet suffer from erroneous or incomplete perception and integration of information. In some cases, SA problems may occur from an overall high level of workload, or, in many cases, due to a momentary overload in the tasks to be performed or in information being presented.

Poor SA can also occur under low workload. In this case the pilot may have little idea of what is going on and not be actively working to find out due to inattentiveness, vigilance problems or low motivation. Relatively little attention has been paid to the effects of low workload (particularly on long haul flights, for instance) on SA, however, this condition can pose a significant challenge for SA in many areas of aviation and deserves further study.

System Design

The capabilities of the aircraft for acquiring needed information and the way in which it presents that information will have a large impact on aircrew SA. While a lack of information can certainly be seen as a problem for SA, too much information poses an equal problem. Associated with improvements in the avionics capabilities of aircraft in the past few decades has been a dramatic increase in the sheer quantity of information available. Sorting through this data to derive the desired information and achieve a good picture of the overall situation is no small challenge. Overcoming this problem through better system designs that present integrated data is currently a major design goal aimed a alleviating this problem.

Complexity

A major factor creating a challenge for SA is the complexity of the many systems that must be operated. There has been an explosion of avionics systems, flight management systems and other technologies on the flight deck that have greatly increased the complexity of the systems aircrew must operate. System complexity can negatively effect both pilot workload and SA through an increase in the number of system components to be managed, a high degree of interaction between these components and an increase in the dynamics or rate of change of the components. In addition, the complexity of the pilot's tasks may increase through an increase in the number of goals, tasks and decisions to be made in regard to the aircraft systems. The more complex the systems are to operate, the greater the increase the mental workload required to achieve a given level of SA. When that demand exceeds human capabilities, SA will suffer.

System complexity may be somewhat moderated by the degree to which the person has a well developed internal representation of the system to aid in directing attention, integrating data and developing the higher levels of SA. These mechanisms may be effective for coping with complexity, however, developing those internal models may require a considerable amount of training. Pilots have reported significant difficulties in understanding what their automated flight management systems are doing and why (Sarter & Woods, 1992; Wiener, 1989) . McClumpha and James (1994) conducted an extensive study of nearly 1000 pilots from across varying nationalities and aircraft types. They found that the primary factor explaining variance in pilots' attitudes towards advanced technology aircraft was their self-reported understanding of the system. Although pilots are eventually developing a better understanding of automated aircraft with experience, many of these systems do not appear to be well designed to meet their SA needs.

Automation

SA may also be negatively impacted by the automation of tasks as it is frequently designed to put the aircrew "out-of-the-loop". 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 to manual performance on the same tasks (Billings, 1991; Moray, 1986; Wickens, 1992; Wiener & Curry, 1980) . In 1987, a Northwest Airlines MD-80 crashed on take-off at Detroit Airport due to an improper configuration of the flaps and slats, killing all but 1 passenger (National Transportation Safety Board, 1988) . A major factor in the crash was the failure of an automated take-off configuration warning system which the crew had become reliant on. They did not realize the aircraft was improperly configured for take-off and had neglected to check manually (due to other contributing factors). When the automation failed, they were not aware of the state of the automated system or the critical flight parameters they counted on the automation to monitor. While some of the out-of-the-loop performance problem may be due to a loss of manual skills under automation, loss of SA is also a critical component leading to this accident and many similar ones.

Pilots who have lost SA through being out-of-the-loop may be both slower to detect problems and additionally will require extra time to re-orient 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, including (a) a loss of vigilance and increase in complacency associated becoming a monitor with the implementation of automation, (b) being a passive recipient of information rather than an active processor of information, and (c) a loss of or change in the type of feedback provided to the aircrew concerning the state of the system being automated (Endsley & Kiris, 1995) . 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 under 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 which provide integrated information through automation. In commercial cockpits, Hansman, et. al. (1992) found automated flight management system input was superior to manual data entry, producing better error detection of clearance updates. Automation which 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 needs to be determined.

ERRORS IN SITUATION AWARENESS

Based on this model of SA, a taxonomy for classifying and describing errors in SA was created (Endsley, 1994; Endsley, 1995c) . The taxonomy, presented in Table 1, incorporates factors affecting SA at each of its three levels. Endsley (1995a) applied this taxonomy to an investigation of causal factors underlying aircraft accidents involving major air carriers in the United States based on National Transportation Safety Board (NTSB) accident investigation reports over a four year period. Of the 71% of the accidents that could be classified as having a substantial human error component, 88% involved problems with SA. Of 32 SA errors identified in these accident descriptions, twenty-three (72%) were attributed to problems with Level 1 SA, a failure to correctly perceive some pieces of information in the situation. Seven (22%) involved a Level 2 error in which the data was perceived but not integrated or comprehended correctly, and two (6%) involved a Level 3 error in which there was a failure to properly project the near future based on the aircrew's understanding of the situation.

More recently, Jones and Endsley (1995) applied this taxonomy to a more extensive study of SA errors based on voluntary reports in NASA's Aviation Safety Reporting System (ASRS) database. This provides some indication of the types of problems and relative contribution of causal factors leading to SA errors in the cockpit, as shown in Figure 2.

Level 1 - Failure To Correctly Perceive The Situation.

At the most basic level, important information may not be correctly perceived. In some cases, the data may not be available to the person, due to a failure of the system design to present it or a failure in the communications process. This factor accounted for 11.6% of SA errors, most frequently occurring due to a failure of the crew to perform some necessary task (such as resetting the altimeter) to obtain the correct information. In other cases, the data is available, but is difficult to detect or perceive, accounting for another 11.6% of SA errors in this study. This included problems due to poor runway markings and lighting and problems due to noise in the cockpit.

TABLE11.1:
SA error taxonomy

- Level 1: Failure to correctly perceive information
  - Data not available
  - Data hard to discriminate or detect
  - Failure to monitor or observe data
  - Misperception of data
  - Memory Loss
- Level 2: Failure to correctly integrate or comprehend information
  - Lack of or poor mental model
  - Use of incorrect mental model
  - Over-reliance on default values
  - Other
- Level 3: Failure to project future actions or state of the system
  - Lack of or poor mental model
  - Overprojection of current trends
  - Other
- General
  - Failure to maintain multiple goals
  - Habitual schema

Note: From Endsley (1995a). Adapted with permission.

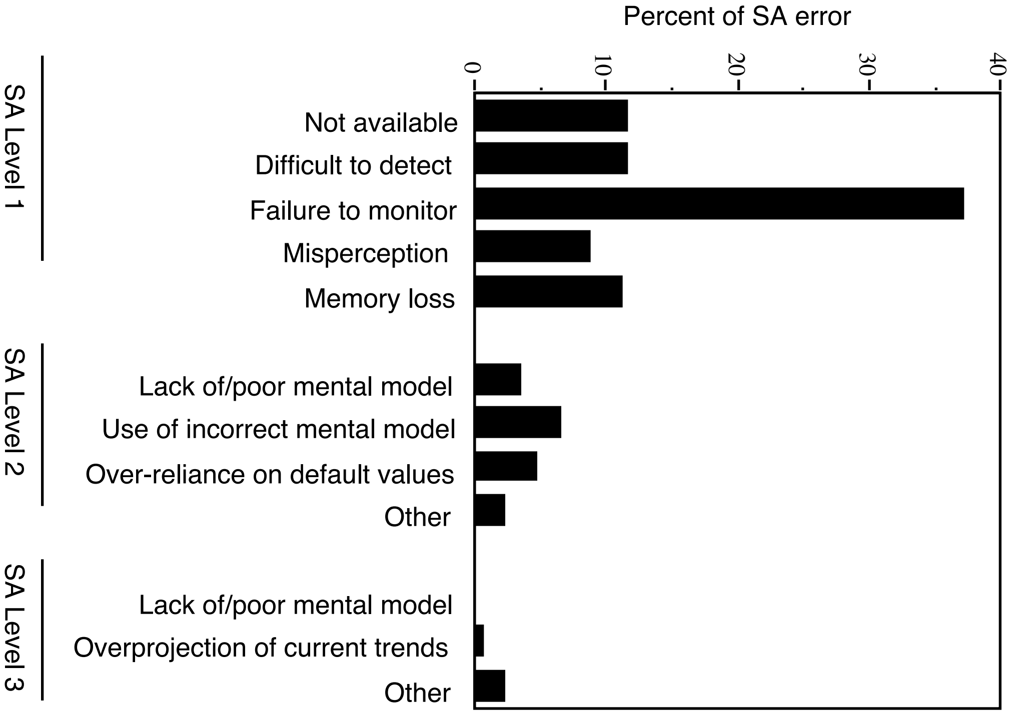

FIG. 11.2. SA error causal factors. From Jones & Endsley (1995). Reprinted by permission.

Many times, the information is directly available, but for various reasons, is not observed or included in the scan pattern, forming the largest single causal factor for SA errors (37.2%). This is due to several factors, including simple omission — not looking at a piece of information, attentional narrowing and external distractions that prevent them from attending to important information. High taskload, even momentary, is another a major factor that prevents information from being attended to.

In other cases, information is attended to, but is misperceived (8.7% of SA errors), frequently due to the influence of prior expectations. Finally, in some cases it appears that a person initially perceives some piece of information but then forgets about it (11.1% of SA errors) which negatively effects SA as it relies on keeping information about a large number of factors in memory. Forgetting was found to be frequently associated with disruptions in normal routine, high workload and distractions.

Level 2 SA - Failure To Comprehend The Situation

In other cases, information is correctly perceived, but its significance or meaning is not comprehended. This may be due to the lack of a good mental model for combining information in association with pertinent goals. 3.5% of SA errors were attributed to the lack of a good mental model, most frequently associated with an automated system.

In other cases, the wrong mental model may be used to interpret information, leading to 6.4% of the SA errors in this study. In this case, the mental model of a similar system may be used to interpret information, leading to an incorrect diagnosis or understanding of the situation in areas where that system is different. A frequent problem is where aircrew have a model of what is expected and then interpret all perceived cues into that model, leading to a completely incorrect interpretation of the situation.

In addition, there may also be problems with over-reliance on defaults in the mental model used, as was found for 4.7% of the SA errors. These defaults can be thought of as general expectations about how parts of the system function that may be used in the absence of real-time data. In other cases, the significance of perceived information relative to operational goals is simply not comprehended or several pieces of information are not properly integrated. This may be due to working memory limitations or other unknown cognitive lapses. 2.3% of the SA errors were attributed to miscellaneous factors such as these.

Level 3 SA - Failure To Project Situation Into The Future

Finally, in some cases, individuals may be fully aware of what is going on, but be unable to correctly project what that means for the future, accounting for 2.9% of the SA errors. In some cases this may be due to a poor mental model or due to over projecting current trends. In other cases, the reason for not correctly projecting the situation is less apparent. Mental projection is a very demanding task at which people are generally poor.

General

In addition to these main categories, two general categories of causal factors are included in the taxonomy. First some people have been found to be poor at maintaining multiple goals in memory, which could impact SA across all three levels. Secondly, there is evidence that people can fall into a trap of executing habitual schema, doing tasks automatically, which render them less receptive to important environmental cues. Evidence for these causal factors was not apparent in the retrospective reports analyzed in the ASRS or NTSB databases.

SA IN MULTI-CREW AIRCRAFT

While SA has been discussed mainly at the level of the individual, it is also relevant for the aircrew as a team. This team may be constructed of a two or three member crew in a commercial aircraft to as many as five to seven member crews in some military aircraft. In some military settings, several aircraft may also be deployed as a flight, forming a more loosely coupled team in which several aircraft must work together to accomplish a joint goal.

Team SA has been defined as “the degree to which every team member possesses the SA required for his or her responsibilities” (Endsley, 1989) . If one crew member has a certain piece of information, but another who needs it does not, the SA of the team has suffered and their performance may suffer as well unless the discrepancy is corrected. In this light, a major portion of inter-crew coordination can be seen as the transfer of information from one crew member to another, as required for developing SA across the team. This coordination involves more than just sharing data. It also includes sharing the higher levels of SA (comprehension and projection) which may vary widely between individuals depending on their experiences and goals.

The process of providing shared SA can be greatly enhanced by shared mental models which provide a common frame of reference for crew member actions and allow team members to predict each other’s behaviors (Cannon-Bowers, Salas, & Converse, 1993; Orasanu, 1990) . A shared mental model may provide more efficient communications by providing a common means of interpreting and predicting actions based on limited information, and therefore may be important for

SA. For instance, Mosier and Chidester (1991) found that better performing teams actually communicated less than poorer performing teams.

Impact of CRM on SA

Crew Resource Management (CRM) programs have received a great deal of attention and focus in aviation in recent years, as a means of promoting better teamwork and use of crew resources. Robertson and Endsley (1995) investigated the link between SA and CRM programs and found that CRM can have an effect on crew SA by directly improving individual SA, or indirectly through the development of shared mental models and by providing efficient distribution of attention across the crew. They hypothesized that CRM could be used to improve team SA through various behaviors measured by the Line/LOS Checklist (LLC), as shown in Figure 3, which have been shown to be positively impacted by CRM (Butler, 1991; Clothier, 1991) .

Individual SA. First, improved communication between crew members can obviously facilitate effective sharing of needed information. In particular, improved inquiry and assertion behaviors by crew members helps to insure needed communication. In addition, an understanding of the state of the human elements in the system (inter-crew SA) also forms a part of SA. The development of good self-critique skills can be used to provide an up-to-date assessment of one's own and other team member's abilities and performance, which may be impacted by factors such as fatigue or stress. This knowledge allows team members to recognize the need for providing more

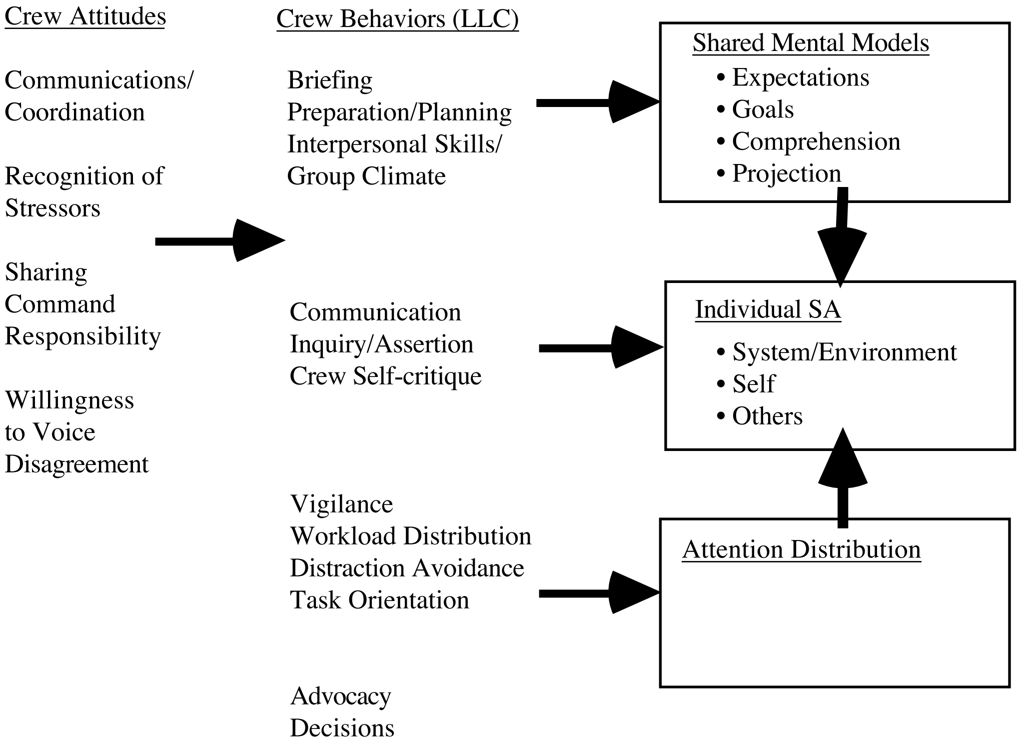

FIG. 11.3 CRM factors affecting SA. From Robertson and Endsley (1995). Reprinted by permission.

information and taking over functions in critical situations, an important part of effective team performance.

Shared mental models. Several factors can help to develop shared mental models between crew members. The crew briefing establishes the initial basis for a shared mental model between crew members, providing shared goals and expectations. This can increase the likelihood that two crew members will form the same higher levels of SA from low level information, improving the effectiveness of communications. Prior preparation and planning similarly can help establish a shared mental model. Effective crews tend to "think ahead" of the aircraft, allowing them to be ready for a wide variety of events. This is closely linked to Level 3 SA — projection of the future. The development of interpersonal relationships and group climate can also be used to facilitate the development of a good model of other crew members. This allows individuals to predict how others will act, forming the basis for Level 3 SA and efficiently functioning teams.

Attention Distribution. The effective management of the crew's resources is extremely critical, particularly in high task load situations. A major factor in effectively managing these resources is ensuring that all aspects of the situation are being attended to — avoiding attentional narrowing and neglect of important information and tasks. CRM programs that improve task orientation and the distribution of tasks under workload can directly impact how crew members are directing their attention, and thus their SA. In addition, improvements in vigilance and the avoidance of distractions can be seen to directly impact SA.

Thus, there are a number of ways that existing CRM programs can effect SA at the crew level, as well as within individuals. Further development of CRM and other training programs to focus on the problems of SA is a current need.

FUTURE DIRECTIONS

Design

Cockpit design efforts can be directed towards several avenues for improving SA, including searching for (a) ways to determine and effectively deliver critical cues, (b) ways to ensure accurate expectations, (c) methods for assisting pilots in deploying attention effectively, (d) methods for preventing the disruption of attention, particularly under stress and high workload, and (e) ways to develop systems which are compatible with pilot goals. Many ongoing design efforts are aimed at enhancing SA in the cockpit by taking advantage of new technologies such as advanced avionics and sensors, datalink, global positioning systems (GPS), three-dimensional visual and auditory displays, voice control, expert systems, helmet mounted displays, virtual reality, sensor fusion, automation and expert systems. The glass cockpit, advanced automation techniques and new technologies such as TCAS have become a reality in today's aviation systems.

Each of these technologies provides a potential advantage: new information, more accurate information, new ways of providing information, or a reduction in crew workload. Each can also effect SA in unpredicted ways, however. For instance, recent evidence shows that automation, which is often cited as a potential benefit to SA through the reduction of workload, can actually reduce SA, thus contributing to the out-of-the-loop performance problem (Carmody & Gluckman, 1993; Endsley & Kiris, 1995) . Three-dimensional displays, also touted as beneficial for SA, have been found to have quite negative effects on pilots' ability to accurately localize other aircraft and objects (Endsley, 1995b; Prevett & Wickens, 1994) .

As many factors surrounding the use of new technologies and design concepts may act to both enhance and degrade SA, significant care should be taken to evaluate the impact of proposed concepts on SA. Only by testing new design concepts in carefully controlled studies can the actual impact on these factors be identified. This testing needs to include not only an examination of how the technologies effect basic human processes, such as accuracy of perception, but also how they effect the pilot's global state of knowledge when used in a dynamic and complex aviation scenario where multiple sources of information compete for attention and must be selected, processed and integrated in light of dynamic goal changes. Real-time simulations employing the technologies can be used to assess the impact of the system by carefully measuring aircrew performance, workload and situation awareness. Direct measurement of situation awareness during design testing is recommended for providing sufficient insight into the potential costs and benefits of design concepts for aircrew SA, allowing a determination of the degree to which the design successfully addresses the issues put forth. Techniques for measuring SA within the aviation system design process are covered in more detail in Endsley (in press) .

Training

In addition to improving SA through better cockpit designs, it may also be possible to find new ways of training aircrew to achieve better SA with a given aircraft design. The potential role of CRM programs in this process has already been discussed. It may also be possible to create "SA oriented " training programs that seek to improve SA directly. This may include programs that provide aircrew with better information needed to develop mental models, including information on their components, the dynamics and functioning of the components and projection of future actions based on these dynamics. The focus should be on training aircrew to identify prototypical situations of concern associated with these models by recognizing critical cues and what they mean in terms of relevant goals.

The skills required for achieving and maintaining good SA also need to be identified and formally taught in training programs. Factors such as how to employ a system to best achieve SA (when to look for what where), appropriate scan patterns, or techniques for making the most of limited information need to be determined and explicitly taught in the training process. A focus on aircrew SA would greatly supplement traditional technology-oriented training that concentrates mainly on the mechanics of how a system operates.

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

Conclusion

Maintaining situation awareness is a critical and challenging part of an aircrew's job. Without good SA, even the best trained crews can make poor decisions. Numerous factors that are a constant part of the aviation environment make the goal of achieving a high level of SA at all times quite challenging. Enhancing SA through better cockpit design and training programs remains the major challenge for aviation research through the next decade.

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