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Designing for Situation Awareness in Complex System

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The Challenge of the Information Age

We are living in what has been termed the "information age". In many domains, this has meant a huge increase in systems, displays and technologies. From voice control to sophisticated line of sight head mounted displays, almost anything is possible in today's world, but too much is proving to be as big a challenge as too little once was. The problem is no longer lack of information, but finding what is needed when it is needed.

This problem is not isolated to cockpits or power plants. All around us, signs of this change are present. Whether you are working on the shop floor, in the world of business, or just trying to purchase a new computer for your home, the dizzying pace of technological change and vast amount of information present can be daunting. We are constantly being barraged with information through TV, radio, mailings and hundreds of magazines and journals. Within our companies, reports and forms have multiplied and every aspect of the business is recorded somewhere. Bringing all of this information together in a form that is manageable is quite a challenge. There is simply more information than anyone can handle.

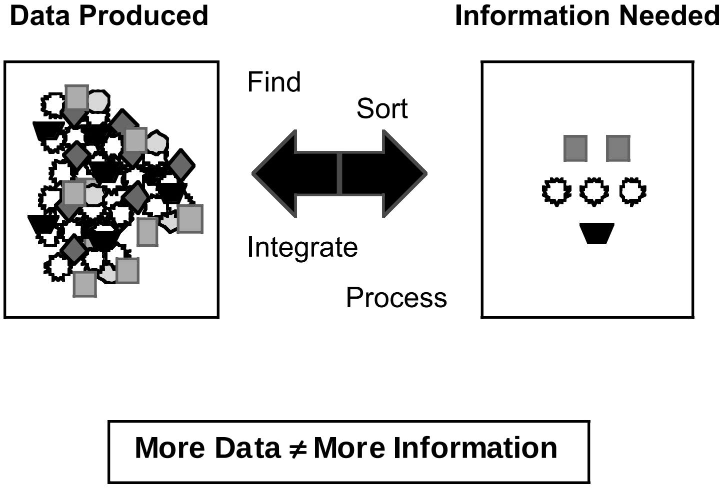

Figure 1. The Information Gap

Widespread communications networks allow us to communicate with colleagues in other cities and other continents as easily as we once communicated with our neighbors. Whether they be at home, in the office, flying over the Atlantic ocean or hiking through the Andes. Matching that access for voice communication are fax machines, email, and the world wide web which bring text and pictures just as easily. And the computerization of information is only the most recent off-shoot of this information explosion. A rapid proliferation in the publishing world has seen a deluge of magazines, journals, and books crowding our mailboxes and the shelves of our libraries. The world great libraries are doubling in size every 14 years; 1000 new books are published internationally every day and the number of scientific journals has increased to the extent that surveys show that the vast majority of articles go virtually unread. More new information has been produced in the last 30 years than the previous 5000 (Wurman, 1989). Yet, in the face of this torrent of "information", many of us feel even less informed than ever before. This is because there is a huge gap between the tons of data being produced and disseminated, and our ability to find the bits that are needed and process them together with the other bits to arrive at the actual information that is needed. This problem is real and ongoing, whether your job is in the cockpit or behind a desk. It is becoming widely recognized that more data does not equal more information.

From Data to Information

Coming to grips with the challenge of the explosion of data is paramount and can mean the difference between success and failure in many endeavors. "This post-technological age has been defined as one in which only those who have the right information, the strategic knowledge, and the handy facts can make it" (Bennis, 1977). This brings home a central truth of the age we live in. Success (and even survival) depends on rapidly sorting through, understanding and assimilating vast quantities of data. Whether one is in a commercial cockpit flying through thunderstorms and dealing with other air traffic, involved in a complex battlefield scenarios with distributed forces, or operating a business in a competitive and dynamic world market place, making the right decisions will depend on having a good grasp of the true picture of the situation.

Success in these endeavors involves far more than having a lot of data. It requires that the data be transformed into the required information in a timely manner. In most contexts, the body of available data will need to be processed and interpreted slightly differently by different individuals, each of whom has varied and dynamically changing but inter-related information needs, and properly understood by each within the context of a joint mission (for example the pilot, co-pilot and air traffic control). Creating information from data is complicated by the fact that, like beauty, what is truly "information" is largely in the eyes of the beholder. To support the information needs of all the parties in the system and to insure that they are all properly coordinated and "reading from the same page" is the critical task facing us. Achieving this goal depends on understanding how people process and utilize information in their decision making activities.

Understanding "Human Error"

In 1989, a US Air B-737 failed to take-off at New York’s LaGuardia Airport, landing in the nearby river (National Transportation Safety Board, 1990). The precipitating cause was an accidental disarming of the autothrottle. Neither the captain nor the first officer were aware of the critical flight parameters needed to detect and correct the problem, thus the take-off was not aborted in a timely manner, resulting in the loss of the aircraft and two passengers.

More recently, a fully functional 757 crashed into a mountain top in Cali, Columbia killing 159 people. In resolving an error resulting from entering an incorrect navigational fix, the pilots had lost awareness of where they were in relation to the mountainous terrain. Although GPWS provided a warning, they were unable to climb sufficiently to avoid the mountain top.

Outside of Strasbourg, an Airbus crashed short of the runway. The most likely cause has been found to be a miss-entered glide slope (3300 fpm instead of 3.3 degrees.). The crew was apparently unaware that they were in the wrong mode in entering the data and were not aware that the glide slope they were on placed in their path in the way of terrain.

Such accidents are not confined to aircraft system. Consider the following excerpt from an account of one of this centuries' major accidents. "Unknown to Dey, the pressure inside the tank was 2 psig only 40 minutes before at 10:20. But the buildup was not apparent because no historical trace of the pressure was shown within the control room, and the operator on the previous shift had not entered this into the log." (Casey, 1993). As many as 2500 died in the tragic accident at the Union Carbide plant in Bhopal, India in 1984. The design of the system's interface did not support this operator in detecting significant cues of the building problem or in preventing the events that led up to the accident.

As we move into the 21st century, the biggest challenge within most industries and the most likely cause of an accident receives the label of human error. This is a most misleading term, however, that has done much to sweep the real problems under the rug. It implies that people are merely careless or poorly trained or somehow not very reliable in general. In fact, if you examine the vast majority of these accidents you'll find that the human operator was striving against significant challenges. On a day to day basis they cope with hugely demanding complex systems. They face both data overload and technology overload. We drill into them long lists of procedures and checklists designed to cope with some of these difficulties, but from time to time they are apt to fail. Our response to this has been more procedures and more systems, but I'm afraid we only add to the complexity of the system in the process. The human being is not the cause of these errors, but the final dumping ground for the inherent problems and difficulties in the technologies we have created. The operator is usually the one who must bring it all together and overcome whatever failures and inefficiencies exist in the system.

Situation Awareness: The Key to Providing Information

So why are people having trouble coping with this technology and data explosion? The answer lies in understanding how people process the vast amount of data around them to arrive at effective performance. If we examine these accidents, and many more like them, we see that the operators have no difficulty in physically performing their tasks, and no difficulty in knowing what is the correct thing to do, but they continue to be stressed by the task of understanding what is going on in the situation. Developing and maintaining a highly level of situation awareness is the most difficult part of many jobs. It is one of the most critical and challenging tasks in many domains today.

Situation awareness (SA) can be thought of as an internalized mental model of the current state of the operator's environment. All of the incoming data from the many systems, the outside environment, fellow crew members, and others (e.g. (other aircraft and ATC) must all be brought together into an integrated whole. This integrated picture forms the central organizing feature from which all decision making and action takes place.

A vast portion of the operator's job is involved in developing SA and keeping it up to date in a rapidly changing 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.

The key to coping in the "information age" is developing systems that support this process. This is where our current technologies have left human operators the most vulnerable to error. 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 air carriers, 88% of those involving human error could be attributed to problems with situation awareness (Endsley, 1995b). A similar review of errors in other domains (such as air traffic control or nuclear power) shows that this is not a problem that is limited to aviation, but one we face with many of our complex systems.

Success will go to the developers who understand how to combine and present the vast amounts of data now available from the many technological systems present in order to provide true situation awareness (whether it be to the pilot, the physician, the business manager or the automobile driver). The key here is in understanding that true situation awareness only exists in the mind of the human operator. Therefore presenting a ton of data will do no good unless it is successfully transmitted, absorbed and assimilated in a timely manner by the human to form situation awareness.

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 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 design or training programs requires the guidance of a clear understanding of SA requirements in the domain, the individual, system and environmental factors that affect SA, and a design process that specifically addresses SA in a systematic fashion.

Situation Awareness Defined

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 operator'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 people 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. An army officer needs to detect enemy, civilian and friendly positions and actions, terrain features, obstacles, and weather An air traffic controller or automobile driver has a different set of information that is needed for situation awareness.

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 operators put 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 operator may be capable of achieving the same Level 1 SA as more experienced ones, 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. The ability to project can be similarly found to be critical in many other domains including driving, plant control and sports.

Theoretical underpinnings

Endsley (Endsley, 1988, 1990, 1991, 1995c) describes a theoretical framework model of SA. 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. According to most research on information processing (for a review see (Norman, 1976) or (Wickens, 1992)), the elements in the environment are initially processed in parallel through preattentive sensory stores where certain properties are detected, such as spatial proximity, color, simple properties of shapes, or movement, providing cues for further focalized attention. Those objects which are most salient, based on preattentively registered characteristics, will be further processed using focalized attention to achieve perception. The deployment of attention in the perception process acts to present certain constraints on the operator's ability to accurately perceive multiple items in parallel, and, as such, is a major limit on SA.

In addition to external factors, attention and perception can be directed by the contents of both working memory and long-term memory. Specifically, advance knowledge of the position of information, the form of the information, the spatial frequency, the color, or the overall familiarity and appropriateness of information can significantly facilitate perception. Information stored in long term memory also serves to shape the perception of objects in terms of known categories or mental representations. Ashby and Gott (Ashby & Gott, 1988) found that subjects based categorization upon integrated information about an object, typically in a deterministic, nearly optimal manner, which can occur almost immediately (Hinsley, Hayes, & Simon, 1977).

The perception of the elements in the environment, the first level of SA, therefore, will be largely guided by the contents of working and long term memory stores to direct attention, recognition and categorization. The operator will direct his/her attention to look for what is expected or needed based on memory stores, and will interpret what is perceived in light of them. Because the supply of attention appears to be limited, improvements in SA on some elements may mean decrements in SA on others once the limit is reached. And this limit may occur rather quickly in complex environments.

Once perceived, information is stored in working memory. In the absence of other mechanisms, most of the operator’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. Projections of future status and subsequent decisions as to appropriate courses of action will occur in working memory as well. In this circumstance, a heavy load will be imposed on working memory as it is taxed with simultaneously achieving the higher levels of situation awareness, formulating and selecting responses and carrying out subsequent actions. Wickens (Wickens, 1992) has stated that prediction of future states (the culmination of good SA) 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. Fracker (Fracker, 1987) hypothesized that working memory constitutes the main bottleneck for situation awareness.

In actual practice, however, long term memory structures can be used to circumvent the limitations of working memory. These structures may take the form of schema or mental models. Rouse and Morris (Rouse & Morris, 1985) define 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". From this definition, mental models can be described as complex schema that are used to model the behavior of systems, in this case the air traffic system.

The main key to using mental models rests on the ability of the individual to recognize key features in the environment that will map to key features in the model. The model then provides for determining associations between components and predictions of the behavior and status of elements over time. These structures can provide for much of the higher levels of SA (comprehension and projection) without loading working memory. Where scripts, set sequences of actions, have been developed for given situation conditions, much of the load on working memory for generating alternate behaviors and selecting among them is also diminished. These mechanisms allow the operator to simply execute a predetermined action for a given recognized class of situations (based on their SA). And the current situation need not be exactly like one encountered before due to the use of categorization mapping. As long as a mapping can be made into relevant categories, a situation can be recognized, comprehended in terms of the model, predictions made and appropriate actions selected. Of prime importance is that this process can be almost instantaneous due to the superior abilities of human pattern matching mechanisms.

Expertise, therefore, can be seen to play a major role in the SA process. For novices or those dealing with novel situations, decision making in this environment will be an arduous task, requiring detailed mental calculations based on rules or heuristics, placing a heavy burden on working memory. Where experience has allowed the development of long-term memory structures, pattern matching between the perceived elements in the environment and existing schema/mental models will occur on the basis of pertinent cues. When these long term memory structures exist, they can be utilized to provide the comprehension and future projection required for the higher levels of SA, thus off-loading working memory requirements substantially. When scripts have been developed, tied to these schema, the entire decision making process will be greatly simplified.

Another issue which is critical to understanding SA is the role that the operator's goals play in the process. These goals can be thought of as ideal states of the system model that the operator wishes to achieve. In what Casson (Casson, 1983) has termed a top-down decision making process, the operator's goals and plans will direct which aspects of the environment are attended to in the development of SA. (Conversely, in a bottom-up process, patterns in the environment may be recognized which will indicate to the operator that different plans will be necessary to meet goals or that different goals should be activated.)

Over time, the operator will match the observed situation to an internally held projection of system states (formed via the mental model). This provides expectations for not only what will be observed, but also for what should not be observed. When the two models (observed and internal projection for that time) match, all is well. When they do not match because values of some parameter are different, an event occurs that should not, or an event does not occur that should, this signals the operator that something is amiss, and indicates a need for a change in goals or plans due to a shift in situations, a revision of the system model, or selection of a new system model. The overall decision making process can be viewed, therefore, as a dual process whereby active schema or mental models are dictating which information to focalize attention on (conceptually driven), and simultaneously the presence of certain objects or attributes in the environment will activate new schema in memory (data driven). This process can act to change current operator goals by altering the relative importance of goals (as each goal can have antecedent rules governing situations in which each needs to be invoked over the others).

Designing for Situation Awareness Enhancement

One of the key benefits of looking at situation awareness is that it tells us how all that data needs to be combined and understood. Instead of loading the operator down with 100 pieces of miscellaneous data, provided in haphazard fashion, situation awareness requirements provide guidance as to what the real comprehension and projection needs are. Therefore it tells us, as system designers, how to bring those 100 pieces of data together to form meaningful integration and groupings of data that can be easily absorbed and assimilated in time critical situations. This type of systems integration usually requires very unique combinations of information and portrayals of information that go far beyond the black box "technology oriented" approaches of the past. In the past, it was up to the operator to do it all. This task left him or her overloaded and susceptible to missing critical factors. As we step up to the job of proving systems that support the SA process, however, we will do much towards aiding this critical challenge.

So how do we design our systems to meet this challenge? The answers are certainly not as straightforward as we all would like them to be, but neither are they as elusive as some might think. Over the past decade we have begun focusing research on this problem and have developed some understanding of the basic mechanisms that are important for situation awareness and the design features that will support those mechanisms. All of these factors are far too detailed to go into here, but three major steps can be discussed that will have much to do with how successful any company is in making its systems support situation awareness. A structured approach is required to incorporate SA considerations into the design process, including a determination of SA requirements, designing for SA enhancement, and measurement of SA in design evaluation.

SA Requirements Analysis

The problem of determining what aspects of the situation are important for a particular operator's SA has frequently been approached using a form of cognitive task analysis called a goal-directed task analysis, illustrated in Table 1. In such analysis, the major goals of a particular job class are identified, along with the major subgoals necessary for meeting each of these goals. Associated with each subgoal, the major decisions that need to be made are then identified. The situation awareness needed for making these decisions and carrying out each sub-goal are identified. These SA requirements focus not only what data the operator needs, but also on how that information is integrated or combined to address each decision. In this analysis process, SA requirements are defined as those dynamic information needs associated with the major goals or sub-goals of the operator in performing his or her job (as opposed to more static knowledge such as rules, procedures and general system knowledge). This type of analysis is based on goals or objectives, not tasks (as a traditional task analysis might). This is because goals form the basis for decision making in many complex environments.

Table 1 Format of Goal-Directed Task Analysis

- **Goal**
  - **Subgoal**
    - *Decision*
      - Projection (SA Level 3)
      - Comprehension (SA Level 2)
      - Data (SA Level 1)

Conducting such an analysis is usually carried out using a combination of cognitive engineering procedures. Expert elicitation, observation of operator performance of tasks, verbal protocols, analysis of written materials and documentation, and formal questionnaires have formed the basis for the analyses. In general, the analysis has been conducted with a number of operators, who are interviewed, observed and recorded individually, with the resultant analyses pooled and then validated overall by a larger number of operators.

An example of the output of this process is shown in Table 2. This example shows the SA requirements analysis for the subgoal “Maintain Aircraft Conformance” for the major goal “Avoid Conflictions” for an air traffic controller (Endsley & Rodgers, 1994). In this example, the sub-goal is even further divided into lower level sub-goals prior to the decisions and SA requirements being listed. In some cases, addressing a particular sub-goal occurs through reference to another sub-goal in other parts of the analysis, such as the need to re-address aircraft separation in this example. This shows the degree to which a particular operator’s goals and resultant SA needs may be very inter-related. The example in Table 2 shows just one major subgoal out of four that are relevant for the major goal of “Avoid Conflictions”, which is just one of three major goals for an air traffic controller.

This analysis systematically defines the SA requirements (at all three levels of SA) that are needed to effectively make the decisions required by the operator’s goals. Many of the same SA requirements appear throughout the analysis. In this manner, the way in which pieces of data are used together and combined to form what the operator really wants to know is determined.

Although the analysis will typically include many goals and sub-goals, they many all be active at once. In practice, at any given time more than one goal or subgoal may be operational, although they will not always have the same prioritization. The analysis does not indicate any prioritization among the goals (which can vary over time), or that each subgoal within a goal will always be active. Unless particular events are triggered, for instance the subgoal of assuring aircraft conformance in this example, may not be active for a given controller.

Table 2 Example of Goal-Directed Task Analysis for En-route Air Traffic Control (Endsley & Rodgers, 1994)

1.3 Maintain aircraft conformance

1.3.1 Assess aircraft conformance to assigned parameters

- *aircraft at/proceeding to assigned altitude?*
- *aircraft proceeding to assigned altitude fast enough?*
    - time until aircraft reaches assigned altitude
    - amount of altitude deviation
    - climb/descent
        - altitude (current)
        - altitude (assigned)
        - altitude rate of change (ascending/descending)
- *aircraft at/proceeding to assigned airspeed?*
- *aircraft proceeding to assigned airspeed fast enough?*
    - time until aircraft reaches assigned airspeed
    - amount of airspeed deviation
        - airspeed (indicated)
        - airspeed (assigned)
        - groundspeed
- *aircraft on /proceeding to assigned route?*
- *aircraft proceeding to assigned route fast enough?*
- *aircraft turning?*
    - time until aircraft reaches assigned route/heading
    - amount of route deviation
        - aircraft position (current)
        - aircraft heading (current)
        - route/heading (assigned)
    - aircraft turn rate (current)
        - aircraft heading (current)
        - aircraft heading (past)
        - aircraft turn capabilities
            - aircraft type
            - altitude
        - aircraft groundspeed
        - weather
        - winds (direction, magnitude)

The analysis strives to be as technology free as possible. How the information is acquired is not addressed, as this can vary considerably from person to person, from system to system, and from time to time. In some cases it may be through system displays, verbal communications, other operators, or internally generated from within the operator. Many of the higher level SA requirements fall into this category. The way in which information is acquired can vary widely between individuals, over time and between system designs.

The analysis seeks to determine what operators would ideally like to know to meet each goal. It is recognized that they often must operate on the basis of incomplete information and that some desired information may not be available at all with today's system. However for purposes of design and evaluation of systems, we need to set the yardstick to measure against what they ideally need to know, so that artificial ceiling effects based on today's technology are not induced in the process. Finally, it should be noted that static knowledge, such as procedures or rules for performing tasks, is outside the bounds of an SA requirements analysis. The analysis focuses only on the dynamic situational information that affects what the operators do.

To date, these analyses have been completed for many domains of common concern including en route air traffic control (Endsley & Rodgers, 1994), TRACON air traffic control (Endsley & Jones, 1995), fighter pilots (Endsley, 1993), bomber pilots (Endsley, 1989), commercial transport pilots (Endsley, Farley, Jones, Midkiff, & Hansman, 1998), aircraft mechanics (Endsley & Robertson, 1996), and airway facilities maintenance (Endsley, 1994). A similar process was employed by Hogg, Torralba and Volden (1993) to determine appropriate queries for a nuclear reactor domain.

SA-Oriented Design.

Second, the development of a system design for successfully providing the multitude of SA requirements that exist in complex systems is a significant challenge. A set of design principles have been developed based on a theoretical model of the mechanisms and processes involved in acquiring and maintaining SA in dynamic complex systems (Endsley, 1995c). These guidelines are focused on a model of human cognition involving dynamic switching between goal-driven and data-driven processing and feature support for limited operator resources, including:

1. Direct presentation of higher level SA needs (comprehension and projection) is recommended, rather than supplying only low level data that operators must integrate and interpret manually.
2. Goal-oriented information displays should be provided, organized so that the information needed for a particular goal is co-located and directly answers the major decisions associated with the goal.
3. Support for global SA is critical, providing an overview of the situation across the operator's goals at all times (with detailed information for goals of current interest) and enabling efficient and timely goal switching and projection.
4. Critical cues related to key features of schemata 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 and will facilitate goal switching in critical conditions.
5. Extraneous information not related to SA needs should be removed (while carefully ensuring that such information is not needed for broader SA needs).
6. Support for parallel processing, such as multi-modal displays should be provided in data rich environments.

An SA-oriented design is applicable to a wide variety of system designs. It has been successfully applied as a design philosophy for systems involving remote maintenance operations, medical systems and flexible manufacturing cells.

SA Design Evaluation

Many concepts and technologies are currently being developed and touted as enhancing SA. Prototyping and simulation of new technologies, new displays and new automation concepts is extremely important for evaluating the actual effects of proposed concepts with in the context of the task domain and using domain knowledgeable subjects. If SA is to be a design objective, then it is critical that it be specifically evaluated during the design process. Without this it will be impossible to tell if a proposed concept actually helps SA, does not effect it, or inadvertently compromises it in some way.

The Situation Awareness Global Assessment Technique (SAGAT) has been successfully used to provide this information by directly and objectively measuring operator SA in evaluating avionics concepts, display designs, and interface technologies

(Endsley, 1995a). A primary benefit of examining system design from the perspective of operator situation awareness is that the impact of design decisions on situation awareness can be objectively assessed as a measure of quality of the integrated system design when used within the actual challenges of the operational environment.

An example of the use of SAGAT for evaluating the impact of new system concepts can be found in (Endsley, Mogford, Allendoerfer, Snyder, & Stein, 1997). A totally new form of distributing roles and responsibilities between pilots and air traffic controllers was examined. Termed "free flight", this concept was originally described to incorporate major changes in the operation of the national airspace. It may include aircraft filing direct routes to destinations rather than along pre-defined fixed airways, and the authority for the pilot to deviate from that route, either with the air traffic controllers permission or perhaps even fully autonomously (RTCA, 1995). As it was felt that such changes could have a marked effect on the ability of the controller to keep up as monitor in such a new system, a study was conducted to examine this possibility (Endsley, Mogford, & Stein, 1997).

Results showed a trend towards poorer controller performance in detecting and intervening in aircraft separation errors with these changes in the operational concept and poorer subjective ratings of performance. Finding statistically significant changes in separation errors during ATC simulation testing is quite rare however. More detailed analysis of the SAGAT results provided more diagnostic detail as well as backing up this finding. As shown in Figure 2, controllers were aware of significantly fewer of the aircraft in the simulation under free flight conditions. Attending to fewer aircraft under higher workload has also been found in other studies (Endsley & Rodgers, 1998).

In addition to reduced Level 1 SA, however, controllers also had a significantly reduced understanding (Level 2 SA) of what was happening in the traffic situation, as evidenced by lower SA regarding which aircraft weather would impact on and a reduced awareness of those aircraft that were in a transitionary state. They were less aware of which aircraft had not yet completed a clearance, and for those aircraft whether it was received correctly and whether they were conforming. Controllers also demonstrated lower Level 3 SA with free flight. Their knowledge of where the aircraft was going to (next sector) was significantly lower under free flight conditions.

These findings were useful in pinpointing whether concerns over this new and very different concept were justified, or whether they merely represented resistance to change. The SAGAT results showed not only that the new concept did indeed induce problems for controller SA that would prevent them from performing effectively as monitors to back-up pilots with separation assistance; it also showed in what ways these problems were manifested. This information is very useful diagnostically in that it allows one to determine what sorts of aids might be needed for operators to assist them in overcoming these deficiencies.

For instance, in this example, a display that provides enhanced information on flight paths for aircraft in transitionary states may be recommended as a way of compensating for the lower SA observed. Far from just providing a thumbs-up or thumbs-down input on a concept under evaluation, this rich source of data is very useful in developing iterative design modifications and making tradeoffs decisions.

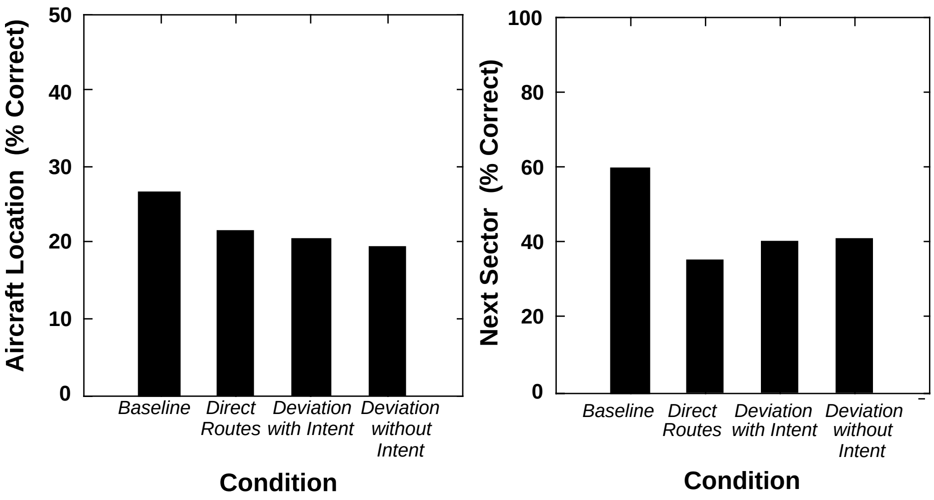

Figure 2. Example of SAGAT Results (Endsley, Mogford and Stein, 1997)

Conclusions

We spoke earlier about how the need to process and understand large volumes of data was critical to many endeavors, from the cockpit to military missions, from power plants to automobiles, and from space stations to day-to-day business operations. The lessons we are learning in advanced systems about the importance of good situation awareness, the challenges that we face in achieving it, and the design principles that are needed to support it, all provide valuable directions for these areas as well. We will not realize the benefits of the information age until we come to grips with the challenges of managing this dynamic information base to provide people with the situation awareness they need on a real-time basis. Doing so is the primary challenge of the next decade of technology.

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