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GOLDEN ANNIVERSARY SPECIAL ISSUE

Situation Awareness: Understanding Dynamic Environments

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Objective: We present a snapshot of the work on situation awareness, which involves operators' comprehension of the dynamic situation that they are monitoring or controlling. **Background:** Although human factors has always been concerned with helping the operator in his or her work environment, research exploded in the mid-1990s on one relevant construct, situation awareness. **Method:** We discuss how a distinction present years ago, the product of comprehension versus the process of comprehension, not only continues today but characterizes different research directions. Research on situation awareness has benefited and can continue to benefit from an analogy to the better understood comprehension of narrative and expository text, although such an analogy between text and dynamic environments will ultimately have limits. **Results:** Situation awareness as a notion that organizes and focuses research efforts has rightfully spread to research in virtually every industrial domain, and it is an essential part of work on automation and design. **Conclusion:** Work on situation awareness has had a ubiquitous influence on cognitive engineering and has even pushed the envelope of basic cognitive psychology into dynamic domains. **Application:** Considering situation awareness is also important in cognitive ergonomic issues relevant to training, teamwork, and the design of new human-technical systems.

In the 50 years of the journal *Human Factors,* there always has been a focus on helping operators deal with the situations in which they find themselves. An important construct that continues this tradition is situation awareness (SA). The purpose of this article is to reflect on SA and how it has progressed theoretically since it irrupted in the researchers' consciousness, as well as how it has helped address some of the practical problems that operators in dynamic environments face every day.

SA originated with aviation practitioners; it spread to the aviation research community (e.g., Endsley, 1987a; Spick, 1988) and then to cognitive tasks of numerous work environments. The end of the 20th century saw Endsley's pair of *Human Factors* papers (1995a, 1995b) as well as work on air traffic controllers, nuclear power plant operators, anesthesiologists, military commanders, electronic warfare tacticians, automobile drivers, and so on. Reviews, analyses, and critiques began at that time (e.g., Adams, Tenney, & Pew, 1995; Durso & Gronlund, 1999; Flach, 1995; Sarter & Woods, 1991; Smith & Hancock, 1995) and continue today (e.g., Bedny, Karwowski, & Jeng, 2004; Durso, Rawson, & Girotto, 2007; Tenney & Pew, 2006).

Performance failures resulting from a loss of SA were noted, and now there are numerous examples of accidents caused by a failure of SA and not, for example, nonadherence or proficiency/skill failure: controlled flight into terrain (e.g., Cooper, 1995; Woodhouse & Woodhouse, 1995), operational errors in air traffic control (e.g., Durso, Truitt, Hackworth, Crutchfield, & Manning, 1998), and driving accidents (e.g., Horswill & McKenna, 2004), to mention a few. In fact, Horswill and McKenna (2004) argue that of all the components of driving, the *only* component that correlates with safety is hazard detection, a measure of situation awareness, and not factors such as vehicle control skills.

Methods for measuring SA were proposed and

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grew in use, number, and sophistication (e.g., Jeannot, Kelly, & Thompson, 2003). The researcher's toolkit includes subjective measures such as the Situation Awareness Rating Technique (SART; Taylor, 1990), query methods such as the Situation Awareness Global Assessment Technique (SAGAT; Endsley, 1987b, 1995a) and Situation Present Assessment Method (SPAM; Durso & Dattel, 2004; Durso et al., 1998), and implicit performance methods (e.g., Andre, Wickens, Boorman, & Boschelli, 1991; Wickens, 1996).

Finally, theoretical work continues (e.g., Durso et al., 2007; Endsley, 2000; Tenney & Pew, 2006; Wickens, 2002). For example, Durso et al. (2007) flesh out the analogy between reading comprehension and situation awareness. By analogy with the work of Kintsch and van Dijk (1978), they distinguish among three representations in dynamic environments: a surface level that contains perceptual details of an event, an event base representation that is the bottom-up integration across glances and scenes of objects and ideas, and a knowledge/expectation-influenced situation model that emerges from the application of preexisting mental models to the situation-specific event base. Reading researchers have made considerable progress in determining the dimensions of a textual situation and the way in which continuity along these dimensions affects understanding. For example, Zwaan, Radvansky, and colleagues (e.g., Zwaan, Magliano, & Graesser, 1995; Zwaan & Radvansky, 1998; Zwaan, Radvansky, Hilliard, & Curiel, 1998) have argued that situation models differ in terms of protagonist, space, time, causality, and intention. In one study, Zwaan et al. (1995) showed that reading times increased with increases in the number of dimensions of mismatch between the text and the situation model. Similar results were also found in the more dynamic domain of film comprehension (e.g., Magliano, Miller, & Zwaan, 2001). More recently, Radvansky and Copeland (2006) showed that when spatial shifts occurred (i.e., when participants moved from one room to another in a virtual environment), information about objects associated with the participants (i.e., objects being carried by the participants) was less available to them. That is, spatial shifts required the participants to update their situation model of the environment, which demanded cognitive effort, which then made information about associated objects less available.

Extending, or delimiting, an analogy from reading comprehension to a dynamic environment requires empirical work. For example, in Garsoffky, Schwan, and Hesse (2002), participants watched short clips of soccer goals and then made recognition memory judgments about video stills. Recognition hits showed a dependency on the viewpoint from which the participant originally saw the goal. Thus, in dynamic environments, the perceptual information may not be purged as it is in reading but instead may travel into the comprehension process and indeed influence it. The fact that this dependency occurred for both devout and casual soccer fans suggests that it is not eliminated by top-down influences from the expert's mental model or knowledge base.

PRODUCT OR PROCESS?

But how has SA been characterized? A critical distinction that has obfuscated the construct since its inception is whether SA is a product or a process. The distinction remains important because it is a factor today in how research is conducted: what questions are asked, what methods are used, and what conclusions emerge. In addition, the distinction can still trouble current work when, for example, a researcher uses a process definition of SA but measures it using a methodology that recovers the product of comprehension.

Situation Awareness as a Product

Consider the product of reading text (Durso et al., 2007). You could read this article and, at the end, have retained particular facts. This product of comprehension can be assessed by asking you to remember information from the article, through questions such as those at the end of an SAT passage or even through a summary essay. There is no doubt that this product of comprehension is important. The information one retains in awareness can be passed to another individual, incorporated into explanations offered for a decision, be useful in aiding design, and so on. Researchers interested in the product of comprehension often use SAGAT or other memory-based methods (e.g., Endsley, 1995a; Kaber, Perry, & Segall, 2006). Results from product-oriented SA research are often of operational value in a specific domain, but they can also be useful in making general claims, as we will see in the later section on automation.

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Situation Awareness as a Process

On the other hand, the product of comprehension tells us nothing about how the reader came to comprehend. Logically, a reader could memorize the previous paragraph well enough to summarize it, perhaps repeat it verbatim, but not understand the concepts or ideas in it. On the other hand, readers of *Human Factors* will understand the paragraph, although they may not remember the specifics afterward. Similarly, a driver may not remember whether she stopped at the intersection a moment ago, although SA was perfect at the time. Of course, a scientific appreciation of the process of SA, sometimes called *situation assessment* or, more recently, *sensemaking* (Klein, Moon, & Hoffman, 2006), is important in its own right, but we and others (Croft, Banbury, Butler, & Berry, 2004) believe that understanding the process, including the implicit components of SA (e.g., Croft et al., 2004), can also directly affect performance, as when a firefighter leaves a room just in time even though he or she may not be able to tell you why (Klein, 1989).

Understanding the process has practical value. If one knows how SA comes about, training programs can be developed; interventions to prevent loss of SA can be employed. For example, in reading, it was once believed that the eye movement pattern of poor readers was the *cause* of their slow reading speed. Thus, the intervention of forcing people to follow a finger or window across the page without backtracking was developed. However, modern research has made it clear that both slow reading and inefficient eye movements are more likely two symptoms caused by the same underlying limits, such as working memory.

Many kinds of studies have relied on the notion of SA as a process. For example, the SPAM (Durso & Dattel, 2004) uses latency as well as accurate responses to queries to infer underlying SA. But much interesting work is done outside of SA research proper (e.g., Abernethy, Maxwell, Jackson, & Masters, 2007; Underwood, Crundall, & Chapman, 2007): For example, Chapman and Underwood (1998) showed that when both expert and novice drivers encountered a dangerous situation, their fixation durations increased. Dwell time is longer when drivers are not able to anticipate correctly, similar to effects found in reading comprehension. Stokes, Kemper, and Kite (1997) had pilots listen to air traffic control (ATC) radio communications. Pilots were asked to "build a mental picture" of the situation and then select from a set of diagrams the one that best represented the situation. Experienced pilots outperformed apprentices in matching the correct diagram with the dialogue, and thus they "make practical use of situational schemata to impose form on sensory data in real time" (p. 191).

Thus, there seems to be two lines of SA research developing, both able to make contributions to human-technical systems. One line focuses on the product of SA, uses recall techniques, is domain specific, and uncovers that of which the operator is consciously aware. Another line focuses on the process of SA; uses a variety of techniques, including response time; and uncovers the underlying mechanisms and processes, including implicit ones that allow an operator to understand the situation.

CONSTITUENTS OF SITUATION AWARENESS

Some of the most interesting work involves efforts to understand empirically what constitutes SA. There have been two not unrelated approaches. In one, researchers try to predict SA or predict performance using SA. In the other, researchers try to identify the underlying cognitive mechanisms of SA.

There is evidence that some individuals develop better SA than others. These differences among individuals are attributed to the differences in the underlying cognitive processes that constitute SA (e.g., Durso & Gronlund, 1999; Endsley & Bolstad, 1994). For example, Carretta, Perry, and Ree (1996) showed that when flight experience was controlled, verbal working memory, spatial reasoning, divided attention, and spatial working memory predicted the SA of F-15 pilots. More recently, Gugerty and Tirre (2000) showed that working memory, perceptual-motor ability, dynamic visual processing ability, and temporal processing ability correlated with SA measures in a driving task.

Durso, Bleckley, and Dattel (2006) tried to predict performance on an ATC task first by using a battery of cognitive and noncognitive tests and then by adding a measure of SA to that battery. For example, ATC errors were predictable from measures of conscientiousness, spatial working memory span, and closure-flexibility. That is,

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conscientious students with a larger working memory for spatial information, who were able to find embedded figures, made fewer errors. Nevertheless, when SPAM measures of SA were added, predictability improved an additional 15%. (Interestingly, off-line queries of SA did not add to prediction.)

Another way to decompose SA is to try and distinguish the contributions made by various information-processing mechanisms (Doane & Sohn, 2004; Sohn & Doane, 2004). In Doane and Sohn (2004), expert and novice pilots viewed a sequence that showed a control statement (e.g., "left pressure on aileron"), a flight situation using a pictorial depiction of cockpit displays, and a flight change description. The pilots had to judge whether the change in the flight situation was consistent or inconsistent with expectations. Novice pilots were especially poor at predicting the result of multiple, meaningfully related control activities, presumably because they did not have the appropriate mental model. In Sohn and Doane (2004), a measure of domain-independent spatial working memory (WM; i.e., rotation span task) was compared with a domain-dependent measure of long-term working memory (LTWM; i.e., delayed recall of meaningful vs. nonmeaningful pairs of cockpit displays). As reliance on LTWM increased, the predictive value of WM decreased. Thus, SA sometimes is improved by knowledge, sometimes by mental capacity.

APPLICATIONS

We end by considering the applied value of SA. The value of SA can be found in training, teamwork, automation, and design, to mention a few applications. Training programs targeted to improve SA have been of interest in various domains for several years (e.g., Endsley, 1993; Endsley & Rodgers, 1994) and continue today. For example, Matthews, Strater, and Endsley (2004) identified SA requirements of infantry platoon leaders through semistructured interviews and then used these requirements to develop SA metrics for training such as checklists and rating scales.

SA is also critical to team performance (e.g., Salas, Prince, Baker, & Shrestha, 1995; Stout, Cannon-Bowers, & Salas, 1996). Team SA can be measured by aggregating the SA scores of the individual team members (e.g., Endsley & Jones, 1997) to more holistic measures such as asking team members to make interrelatedness ratings of domain-relevant concepts, team communication, and positional and interpositional accuracy (Cooke, Gorman, & Winner, 2007; Cooke, Salas, Kiekel, & Bell, 2004). Team SA may be more than the sum of its parts. Although all of these areas are bearing fruit, our interest in the proposed Next Generation (NextGen) plan for the U.S. National Airspace System led us to focus this section of practical applications on automation and design.

AUTOMATION

Automation has become an important part of modern work settings. However, a potential consequence of automated systems is the out-of-the-loop performance (OOP) problem (e.g., Billings, 1991; Endsley & Kiris, 1995; Sarter & Woods, 1995b; Wickens, 1992; Wiener & Curry, 1980). Operators working with fully automated systems presumably passively monitor the automation and are therefore slower to intervene (performing the task manually) when the automation fails (Endsley & Kiris, 1995).

Level of Automation

One approach to improve SA and reduce the OOP problem is to use varying levels of automation (LOAs). The central concept of the LOA is that automation is not an all-or-none phenomenon but instead can be implemented at various levels (e.g., Billings, 1991; Lorenz & Parasuraman, 2007; Parasuraman, Sheridan, & Wickens, 2000; Wiener & Curry, 1980). Using an automobile driving task, Endsley and Kiris (1995) showed that intermediate LOAs kept the operators in the decision-making loop, resulting in better SA, compared with operators in the fully automated condition. Consequently, operators working with intermediate LOAs were better able to perform the task manually when the automation failed. Similarly, Kaber, Onal, and Endsley (2000) found that intermediate LOAs kept the operators in the control loop during normal operations, increasing operator SA prior to automation failure and thereby resulting in faster recovery from failures and improved performance compared with high LOAs. More recently, Kaber and Endsley (2004) showed that intermediate LOAs facilitated higher SA even in a dual-task environment. These studies suggest that although fully automated systems are technically feasible, these are not recommended if the operator is to be

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kept in the loop. Another approach to reduce the OOP problem is to use adaptive automation where responsibility is flexibly assigned to the human or the machine (e.g., Kaber & Riley, 1999; Parasuraman, 1993; Parasuraman, Mouloua, & Molloy, 1996).

DESIGN

It is important that an operator be provided with tools that help in building and maintaining SA. Endsley, Bolte, and Jones (2003) identified eight factors that can reduce operator SA while working with information systems: attentional tunneling, requisite memory trap, workload and other stressors, data overload, misplaced salience, complexity creep, errant mental models, and OOP syndrome. Designing an interface that minimizes these influences begins with identification of the dynamic information needs or SA requirements of the operator (Endsley et al., 2003). From there, with design guidance (Endsley et al., 2003; Sarter & Woods, 1995a; Woods, 1984), interfaces that support operator SA can be developed. Some of the principles include organizing information around operator goals, providing support for comprehending as well as projecting future events, reducing attentional narrowing by providing a high-level overview of the situation, filtering information not related to SA needs, providing support for keeping the operator in the loop, minimizing system modes, making the system state salient, minimizing task complexity, and providing appropriate feedback about the system state.

CONCLUSIONS

We know more about how operators understand dynamic environments now than we did when the journal *Human Factors* began. Not all of this knowledge has come from research that calls itself SA, but much of it has. Our knowledge of SA requirements in particular domains, which is the product of comprehension needed, has advanced considerably since the mid-1990s, but our knowledge of *how* operators come to understand, which is the process of SA, is less well understood. Nevertheless, the research has illuminated some general issues that go beyond specific operational domains, such as the relationship of SA and automation and design principles that improve SA. In addition, programs targeted at improving SA of individuals and teams have also been developed. In some ways, we are where educational research was at the beginning of the 20th century: We know which questions are hard and which are easy, and we know that the good student (operator) will get more of those questions right. However, we do not know much about how they do it.

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