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COGNITIVE SYSTEMS ENGINEERING FOR BATTLESPACE DOMINANCE

Gilbert G. Kuperman
Human Effectiveness Directorate
Air Force Research Laboratory
Wright-Patterson Air Force Base, Ohio

INTRODUCTION

Battlespace Dominance, across the entire conflict spectrum, is a primary objective of Joint Vision 2010, the roadmap for the United States military into the twenty-first century. Within the Air Force, "Global Engagement" (Fogelman & Widnall, 1996) serves to explicate the Joint Vision as it impacts the air and space forces. One of the six core competencies of the Air Force (along with Rapid Global Mobility, Precision Engagement, Global Attack, Air and Space Superiority, and Agile Combat Support) is Information Superiority over the future battlespace. They observe that "the strategic perspective and the flexibility gained from operating in the air-space continuum make airmen uniquely suited for information operations." Information Superiority, from one perspective, is centered on affecting the Observe-Orient-Decide-Act (or OODA) loop (Boyd, 1987) of the decision making process. The OODA loop model is depicted in Figure 1.

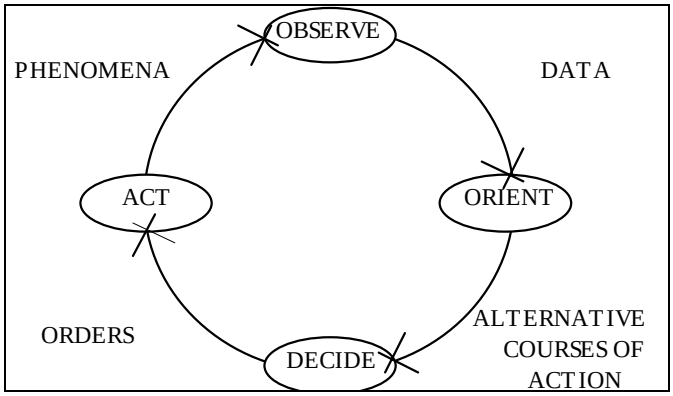

Figure 1. The OODA Loop Model

The OODA model is frequently depicted as a pair of adversarial loops. "Winning" the information war may be viewed as achieving a state in which the friendly OODA loop is cycled

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14. ABSTRACT
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more quickly and with greater certainty than that ascribed to the adversary. This state may be achieved through some combination of actions which deny, disrupt, degrade or destroy the enemy's decision making process, while maintaining/protecting/enhancing the integrity and speed of one's own information processes and functions. The OODA loop is essentially human-centered, particularly at the Orient node. Here, (alphanumeric) data and, perhaps, raw imagery and/or signals, are transformed into information having the attributes of spatial, temporal, geographic, functional, and/or (organizational) hierarchical structure. This transformation process may directly involve the fusion of data from multiple sensor sources (from the Observe node) and/or the correlation of sensed and archived data sets (i. e., data bases). The Orient node is also where contextual information is applied. The Commander's military objectives, the experience and training of the intelligence analyst (or other first level decision maker), cultural biases, individual differences (e. g., risk seeking/aversion behavior) between analysts, etc., all may affect this Orient process. The Orient node is also critical because it is here that the significant cognitive components of decision making are found. Figure 2 depicts some of the cognitive attributes of the Orient node.

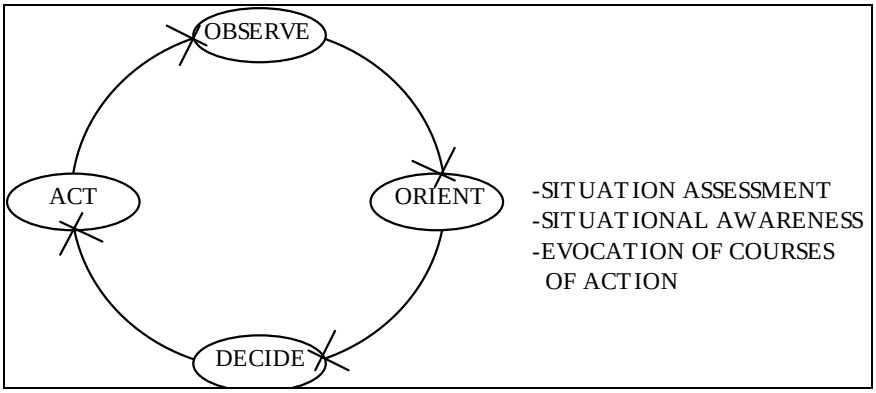

Figure 2. The Orient Node of the OODA Loop Model

Situation assessment is essentially an alignment or association of the observed data in the context of the situation. The analyst has a mental model of the activity being observed. This contextual model may be humanitarian relief efforts, counterterrorist activity, peacekeeping, as well as conventional military operations. Thus, there are obvious differences between the mental models. There are also significant differences within military missions. Signals intelligence, for example, may be exploited to provide data regarding the radio wavelength emissions. These data will be vastly different in both form and meaning if they arise from a commercial airport rather than from an element in the integrated air defense system. The analyst has an understanding as to the activity being observed (airport or air defense) and expectations as to the data associated with each such activity (communications or ground control intercept). Situation assessment, then, is the process of reconciling the observed data (or pre-processed intelligence information) with expectations regarding the behavior of the facility nor activity being observed. The data either support the hypothesized situation or contradict it.

Situation awareness (SA) is also associated with the Orient node. SA is associated with knowledge, in terms of the cognitive hierarchy. While we are most used to thinking of SA in

terms of the knowledge possessed by a single operator, SA may be more and more frequently distributed across members of short-term , task-oriented, non-collocated, “teams.” The “team” may in fact be members of separate crews whose actual systems are widely separated across the battlespace and whose missions must become synchronized for brief periods of time.

Endsley’s model (1994) can be extended to account for distributed SA (Endsley, 1997). (Figure 3 presents an extract from her model.) Endsley depicts and describes the close interrelationships between the stages of SA as being nested. In many other ways, it relates directly to the cognitive hierarchy (Figure 4, below). There is a presumed flow from perception, to comprehension, and, then, to projection. SA is presumed to underlie a decision-making process which, in turn, results in the execution of a set of actions directed at affecting the environment. In her structural model, Endsley suggests that SA is founded on the preconceptions, mission priorities, and expectations of the operator (or team). These attributes and the Levels of SA themselves are modified by individual differences, experience, training, proficiency, and “comfort level” of the operators. Workload is directly associated with the establishment and maintenance of SA, with the decision stage, and with the action stage. Additionally, these latter stages are constrained or modified by established tactical doctrine, rules of engagement, special and general orders, and procedures.

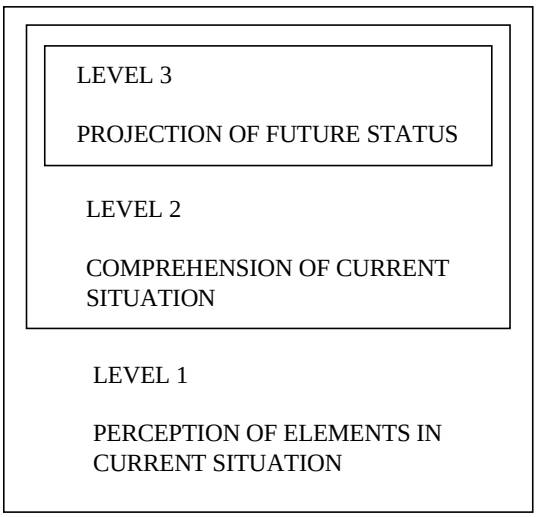

Figure 3. Model of Situational Awareness (extracted from Endsley, 1994)

The cognitive hierarchy (Figure 4; FM 100-6, “Information Operations”) describes the states and processes by which raw data are transformed first into information, then into knowledge, and, finally, into understanding. Information possesses some sort of spatial, temporal, or other structure and is achieved by the associative processes of correlation and fusion. Knowledge has both integrative and synoptic attributes, scaled in breadth and depth to the information requirements of the specific command echelon.. But it is only with the attainment of understanding that a predictive capability (i. e., “What are the expected

consequences of each course of action?) is achieved and operational orders may be issued based on the expected consequences of the execution of those orders.

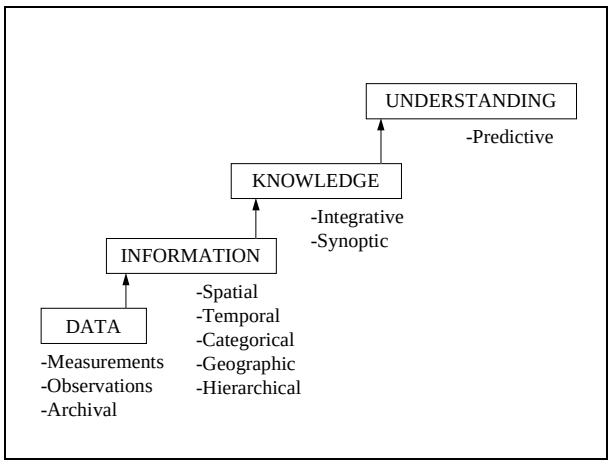

Figure 4. The Cognitive Hierarchy

This hierarchy resembles the four levels of data fusion adopted by the Department of Defense (JDL, 1991) (and depicted in Figure 5). Again, a series of transformations is performed resulting, at the end, in the initiation of a set of actions. Waltz (1997) makes the similarities to the cognitive hierarchy explicit. Although he does not apply the term "cognitive hierarchy," Waltz does state the "the upward flow of the data fusion process" transforms "data to information, then [to] knowledge."

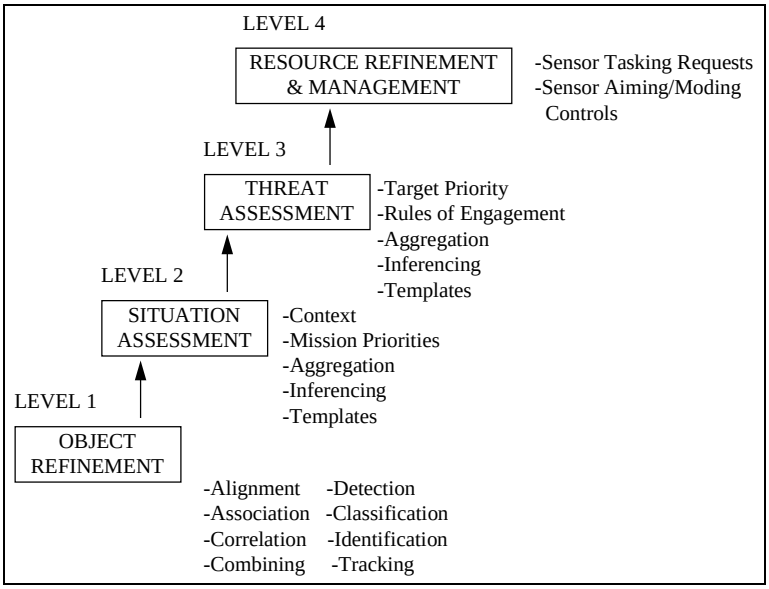

Figure 5. Data Fusion Hierarchy

DATA OVERLOAD

The problem of data overload is not unique to either military systems, in general, or to information operations, in particular. Discrimination between the terms data and information may be useful in understanding the concept of data overload. Data exist in isolation. They do not have contextual or other situation-specific associations. Without these associations, specific elements of data cannot have intrinsic importance. Viewed from a slightly different perspective, all data are equally important. Existing and emerging sensor and data base management capabilities can easily provide billions of pixels of raw imagery or bytes of alphanumerics. It becomes manifestly impossible for the intelligence or imagery analyst to access and assess all available data in a timely fashion.

There are essentially two strategies, which may be followed in overcoming the data overload problem. Filtering may be used to reduce the sheer volume of data provided to the operator. Fusion may be used to organize the available into a more usable form. (The two approaches may be applied either singly or in combination.)

There is a fundamental limitation to the filtering approach: "How do we know, *a priori*, which data are not relevant to the current problem of interest (so that they may be filtered out)?" It is exactly the capacity to differentiate between relevant and irrelevant data, within the context of a specific problem domain, that the human operator brings so powerfully to the analysis and decision making processes. Similarly, the human brings a wealth of prior life and training experiences to each situation.

Fusion, for the purposes of this paper, includes both the value-adding transformations of the original data and advanced information visualization (AIV) technologies, which may be applied at the operator interface. In this usage, fusion goes beyond simple combination of data into logically organized sets and the visualization requirements go beyond conventional approaches to human-computer interface design. The transformations and technologies must be purposeful and responsive to the decision making needs of the operator. Hence, cognitive systems engineering (CSE) approaches are required to support the design of effective interfaces.

CSE AND INFORMATION DOMINANCE

Beginning in FY97, the Human Effectiveness (HE) Directorate (formerly the Armstrong Laboratory) of the Air Force Research Laboratory (AFRL) began to execute a strategic investment plan seeking to mature and demonstrate human-centered technologies for application in achieving the stated core competency of the USAF in Information Superiority (Fogelman & Widnall, 1997). The plan, based on the assumption that the OODA loop was inherently based on the perceptions of the human decision maker, was developed by assessing the core competencies of the Directorate (e. g., information display and performance aiding, design integration, personnel selection, etc.) to generate project proposals for assessment and prioritization by the

Air Force Air Intelligence Agency (AIA, the forwarding operating agency responsible for information operations missions and requirements) and the Air Force Information Warfare Center (AFIWC), the performing organization. The Laboratory provided a dedicated funding line to expand on, accelerate and/or more finely focus existing science and technology (S&T) programs across the Directorate.

A colloquium was held at the Crew Systems Integration Division of the AFRL on 10 and 11 December 1997 which brought together in-house and extramural researchers who were carrying out the research program. The meetings had two primary objectives: to provide the Directorate and AIA with a progress and planning review and to facilitate communications across the several research organizations. Table 1 presents the CSE-related project titles (as proposed to AIA by AFRL/HE) versus the specific research efforts being conducted under them, together with performing/supporting research organizations. (It should be noted that three of the five projects include multiple S&T efforts.)

Table 1. CSE-Related S&T Projects

	PROJ TITLE:	**Human as Info Processor**	**Knowledge Capture of Intelligence Domain**	**Cognitive Engineering Tools & Applications**	**Indications & Warnings Decision Aid**	**Deception & Denial for Information Warfare**
S&T Effort:	**Research Org**					
***Extramural*:**						
"Human as Information Processor" (Lit Review)	LTSI	X				
Information Operations Center (IOC)	ASI		X	X	X	X
Visual Perception Modeling	OMI					X
Data Overload	OSU		X	X		
"	WSU			X		
***In-house*:**						
"Datawall"	LTSI			X		
Decision Making under Dissonance	SUNY		X	X		
Distrib Situational Awareness	SATI		X	X		
CSE Method	WSU			X		
CSE Systems	KAI			X		
CSE Peer Review	LTSI			X		

(LTSI = Logicon Technical Services Inc.; ASI = Adroit Systems Inc.; OMI = OptiMetrics Inc.; OSU = Ohio State University; WSU = Wright State University; SUNY = State University of New York [Buffalo]; SATI = Situation Awareness Technologies Inc.; KAI = Klein Associates Inc.)

Figure 6 (adapted from Homer, 1996) presents a generalized view of a decision support system (DSS) being developed by the Information Directorate (IF) of the AFRL with support from HE in the areas of CSE and AIV. (The AIV portion of the DSS effort is receiving

additional support from the Air Force Office of Scientific Research under the Global Awareness project of the New World Vistas program.) This Figure will serve to set the stage for a description of several of the S&T efforts presented at the Colloquium.

The DSS is operator-centered. The informational requirements of the analyst is central to its functioning. These requirements may become even more critical a military force downsizing leads to reductions in both the number and experience level of the intelligence analyst population. ("Knowledge Capture of the Intelligence Domain" was the AFRL/HE project identified by AIA as being a "critical need.") Further, the decision maker being supported by the DSS is the critical actor in producing the output of the DSS, i. e., operational orders. The process structure of the DSS is associated with the nodes of OODA loop to emphasize the congruence between these representations.

Returning to processes depicted in the Figure, the primary data source is a massive free text data base. Derived from multiple sources, the data base is too massive to be manually searched in any efficient way. The IF Directorate is conducting risk reduction to develop a natural language understanding (NLU) "parser" which will extract relevant (i. e., filtered) data which are appropriate to the type of analysis being attempted. This stage of the DSS provides the "information push" component of the system. The problem domain may vary from task to task. In our case, problem domain models may include commercial air traffic control systems, integrated air defense systems, command and control systems, military and/or civilian communications systems, etc., located within a geopolitical region essentially anywhere in the world. Satisfaction of the information requirements of the analyst is critical to the functioning of the DSS. The analyst forms an appreciation of what he/she believes is occurring within the observed problem domain. This assessment is derived from information presented to the analyst and may include the status, phase, mode, or other descriptors of the problem domain model. This situation (assessment) model also supports the "information pull" component of the system. The analyst, as subject matter expert (SME), responds to missing information which is required to confirm (or refute) the assumed situation and to apparently conflicting information which must be resolved. The AIV provides the analyst with access to the data base. AIV techniques may include geospatial, temporal, hierarchical, functional, or other data organizations. (The specific AIV approaches eventually recommended for implementation in the DSS may be based on innovative logic, including semiotics.) CSE is required to design these "fusion" applications.

The DSS is a dynamic process. Feedback control, possibly based on application of cybernetics, provides a dynamic balance between the "information push" and "information pull" threads by explicitly comparing the situation model against normative representations and identifying the highest leverage information elements. This objective self-adjustment capability complements the experience-based subjective information search function performed by the analyst. The result is a set of recommended, alternative courses of actions (COAs), the set of military options.

The situation assessment prepared by the analyst provides the decision maker (or commander) with meaningful contextual knowledge within which to select the COA most compatible with the military objectives to be achieved and with the overall strategy and rules of

engagement. The decision maker selects among the COAs and issues operational orders with a realistic expectation that they are based on a realistic understanding of likely outcomes.

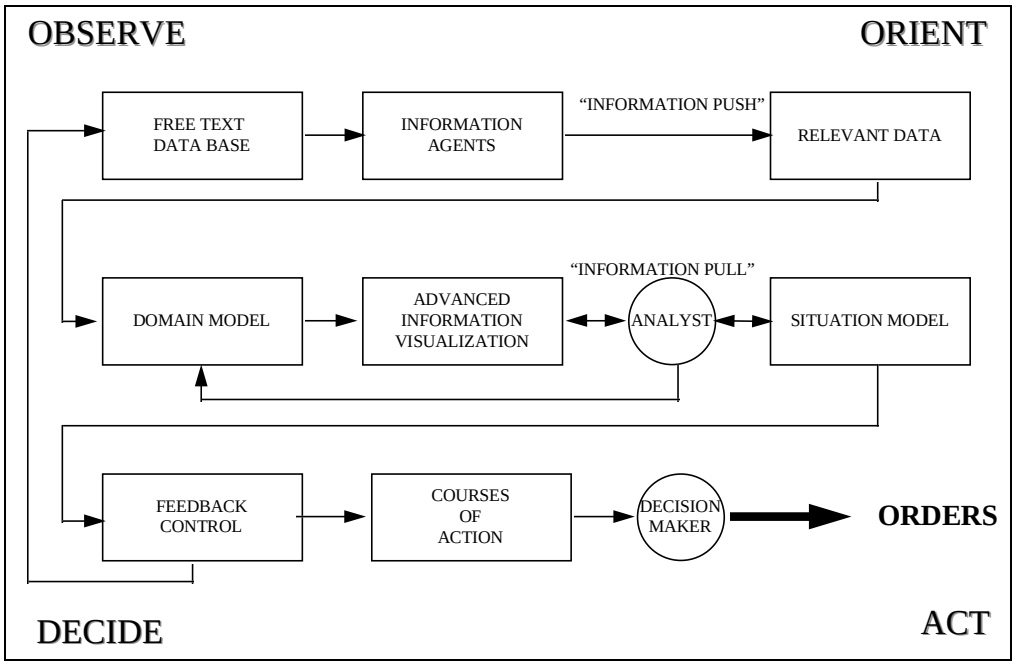

Figure 6. The Decision Support System Concept

The Knowledge Capture, CSE, and AIV components of the DSS are being explored by Dr. David Woods (Ohio State University). While he is addressing a classical data overload problem, it is compounded by the "culture" of the intelligence analysts. (Figure 7 depicts this problem.) The analyst is a highly motivated, trained, and experienced professional, very much aware of the possibly severe adverse consequences that might follow from incomplete, inaccurate or late intelligence appreciations (situation assessments). Because of this, and reinforced by training and on-the-the-job experience, there is a powerful compulsion to be the recipient of ALL data. But this is manifestly impossible. There are too many pieces of data, much of it absolutely extraneous to the problem domain. Further, there isn't enough time to review everything. Eventual resolution of this dilemma may require an extensive "confidence building" stage during the introduction of an operational DSS. The analyst would then experience the impossibility of "seeing everything" while forming an appreciation of the benefits accruing from the interaction of the NLU, AIV, and feedback control automation technologies.

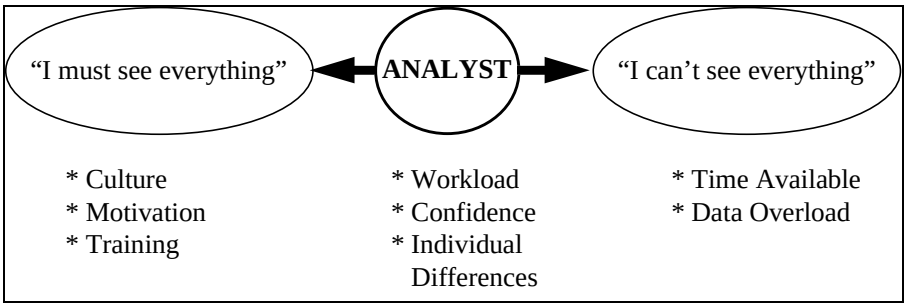

Figure 7. "The Analyst's Dilemma"

Several of the S&T projects were focused on the Information Operations Center (IOC) of the AIA. The IOC is charged with the mission of monitoring the "health" of Air Force computer systems and information processes and functions around the world, assessing any indications of impending information operations directed against them, providing warning with respect to any developing information attacks, and informing warfighter commands of such activities. The IOC provides the "INFOCON" (Information [Warfare] Condition) level (similar to the DEFCON [or Defense Condition] level of nuclear confrontation). The IOC draws its data from the Air Force Computer Emergency Response Team (AFCERT) reports of intrusions, hacking, and other incidents developed from worldwide USAF computer facilities. The AFCERT reports include the what, when, where, and how of each incident. The IOC seeks to develop assessments of the meaning of these incidents.

The IOC has been operational as the "Watch Center" for about two years. Its mission is still being translated into processes and functions. In parallel, several planning initiatives are underway to provide the IOC with mission-essential capabilities well into the next century.

Figure 8. Notional Information Operations Center

Mr. Jeffrey Bradford (Adroit Systems Inc.) reported on several efforts being pursued in support of the IOC. CSE methods are being applied in order, to better understand the information requirements and flows within the IOC. For example, concept mapping is being applied to assist in visualizing the IOC's internal structure and critical incident analyses are being conducted (e. g., the Khobar Tower bombing event) to better understand the dynamic function of the Center. Related efforts are focused on defining indications and warnings (situation assessment) templates that are meaningful in the context of the IOC's mission and on developing a better understanding of deception and denial practices in information warfare in terms of their expected impacts on the IOC's assessment capabilities.

Dr. Randall Whitaker (of Logicon Technical Services Inc.), supporting a cooperative research and development effort being conducted jointly with the AFRL Command and Control (C2) Directorate, described a project in which alternative operator interfaces will be demonstrated and assessed in the context of the "IOC of the future." CSE methods are being applied to project the IOC's mission into the future. Scenarios will be developed from these representations and then instantiated in the AFRL/C2's "Datawall" multimedia research facility. The scenarios will be conducted by operational personnel. The fundamental research issue will be to compare a shared, collaborative C2 work environment against multiple, dedicated workstations. Assessments of the competing interface technologies will be conducted by AIA and AFIWC SMEs.

Figure 9. “Datawall” Multimedia Research Facility

Dr. Gary Klein (President of Klein Associates Inc.) reported on his team’s work in establishing a more standardized methodology, for applying CSE methods to information operations problem domains. Studying the IOC as an example, he reported that CSE appeared to offer potentially significant benefits when applied in support of facility design and analysis tasks. He reported on the development of a set of criteria for guiding the selection of the most appropriate ensemble of CSE tools and methods to apply to these problems. His presentation also took exception to the formal Cognitive Hierarchy (as depicted in Figure 4). He suggested that this view was an oversimplification and that multiple perceptions coexisted throughout each stage of complex man-machine systems. Klein also described six barriers to expertise:

- excessive data
- pre-processed data
- excessive procedures
- performing formal analyses (which might mask significant relationships)
- passive data handling (limited ability for information seeking)
- interfaces that obscure the big picture

In many respects, these barriers are natural features of the information technology landscape that can only be avoided by careful planning and smart “maneuvering” through that terrain.

Dr. Mica Endsley (Situation Awareness Technology Inc.) has been extending her model of SA (Figure 4) to include information operations teams. These teams may be drawn from multiple operational systems (e. g., surveillance, battle management, command and control, attack), widely distributed across the theater (or even located within the continental United States). They must synchronize their activities, sometimes only for brief periods, in order to accomplish a common task. Shared SA is required to provide a common set of assumptions and to support consistent, intra-system decision making. Her research suggests that distributed SA is not the “sum of its parts” but, rather, limited by the “weakest link” in the team. (This assertion has significant operational implications for the design and implementation of advanced information technologies such as the Common Operating Picture.)

Drs. James Llinas and Ann Bisantz (Center for Multisource Information Fusion, State University of New York at Buffalo) described their applied research in the area of aided, adversarial decision-making. A top, level view of their model is presented in Figure 10. In their presentation at the Colloquium, they described the use of this modeling framework to explore the value of information in two-sided decision-making, the effects of human error (possible induced by the presence of dissonant information resulting from information operations), the broad concept of operator trust in automated systems and specific attributes of operator trust, the possible effects of cross-cultural differences on adversarial situational awareness and action planning, means for possibly assessing the sensitivity of the decision-making process to loss or corruption of information.

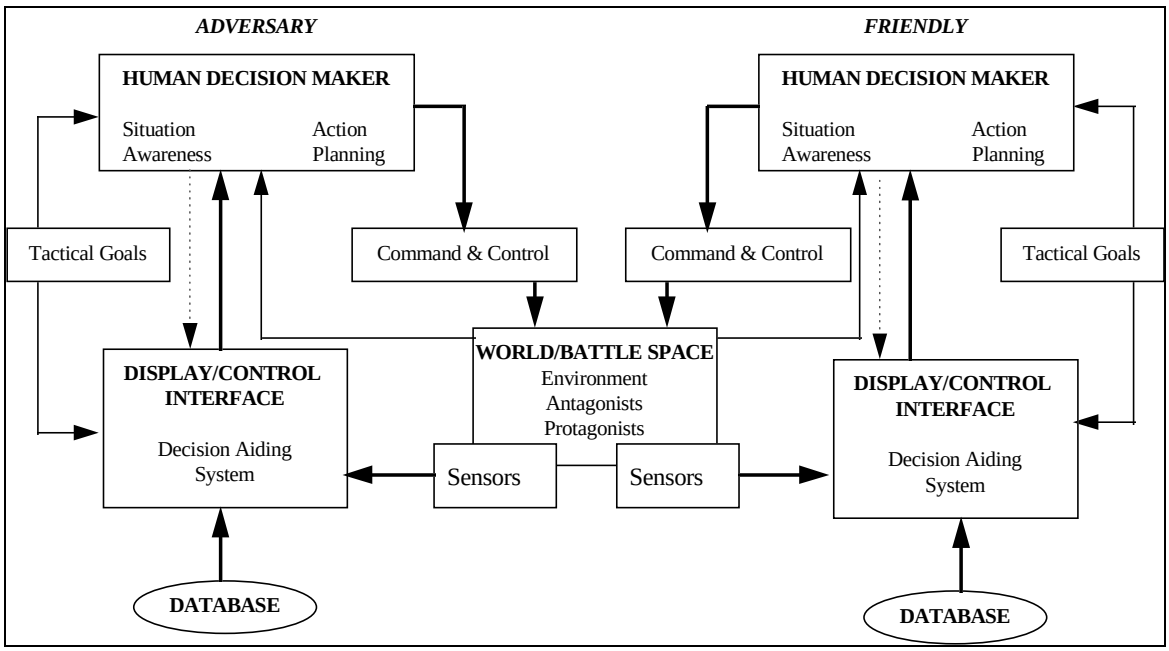

Figure 10. Two-Sided, Aided, Adversarial Decision Making Model (After Llinas, 1997)

Dr. John Flach (Wright State University) described his personal experience in applying CSE methods to the preliminary design of a future weapon system (an uninhabited aerial vehicle tasked with performing lethal suppression of enemy air defenses). He originally approached this problem as a classical function allocation problem. As he progressed in gaining understanding of the mission and weapon system concept, he realized that the problem was fundamentally that of information management under severe time constraint. This insight, independently developed, substantiates the relevance of CSE approaches to complex human-automation interactions. (Dr. Flach, along with Dr. Jens Rasmussen [Rasmussen, Pejtersen, & Goodstein; 1994], are providing peer review of the methodology and scientific quality of these CSE/Information Dominance projects).

CONCLUSIONS

Achieving Battlespace Dominance is a daunting challenge. It must be pursued because the potential benefits are vast. CSE methods and techniques, developed on a firm scientific foundation, provide valuable tools with which to overcome the challenge and reap the rewards.

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