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The Human Dimension of Battlespace Visualization: Research and Design Issues

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The Human Dimension of Battlespace Visualization: Research and Design Issues

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1. Background

Visualizing future battlespaces (including decidedly nonconventional ones) is an important goal for the Objective Force and Future Combat Systems (FCS). Technological advances will result in a knowledge-rich battlefield with virtual planning, multi-modal visualizations, disbursed operations, and highly intelligent automated systems. Too often, however, technological advances are designed without enough consideration for the warfighters who use them (Barnes, 1997). Obviously, the effects of visualization will cascade over the entire battlefield and will influence the common and specialized views of the battle at all echelons. Yet the demand for improved technology outpaces understanding of the benefits of the various techniques. The purpose of this report is to develop an understanding of the theoretical and empirical underpinnings of visualization research in order to create design principles for future military visualization systems. Visualization is the process that commanders use to envision new tactical alternatives. It is a bridge between human knowledge and "seeing" new solutions. However, the ability to visualize is based on heuristic processes that have cognitive costs as well as benefits. Effective synergy between humans and visualization systems must be based on design principles that engender human strengths and limitations.

The U.S. Army definition of battlespace visualization implies not only "imaging" the battlespace but also more significantly generating objectives and possible tactics to achieve these objectives:

> The process whereby the commander develops a clear understanding of his current state with relation to the enemy and environment, envisions a desired end state which represents mission accomplishments, and then subsequently visualizes the sequence of events that will move his forces from the current state to the end state (Department of the Army, 1997).

Thus, it is important not to confuse visualization with the depiction of battlespace information. Understanding the topographical, spatial, and force dispositions on the battlefield is a necessary component of visualization but is not sufficient. The ultimate purpose of visualization aids is to increase the commander's ability to understand the battle dynamics, consider options, and predict outcomes. For that reason, I have included a number of topics related to decision making in future battlespaces, including visualization issues raised by uncertainty representation, naturalistic decision making, automated systems, and complexity theory. The purpose of this report is to identify important visualization issues that impact the commander's ability to understand and predict the combat situation. The discussion focuses on design and research issues likely to impact FCS.

2. Overview and General Model of Visualization

Figure 1 portrays the visualization process from the beginning of the planning procedures to understanding the current state to mental projections of possible future states. Visualization is not concerned solely with the perception of the current combat environment. It is both historical and teleological; commanders are continuously planning and executing, based on past trends and their relation to the desired "end state." Perception is an important component of visualization, but in reality, visualization is more concerned with problem solving than with immediate awareness. However, the type of decision space in which the commander must operate is not straightforward. To illustrate the type of decision processes that the commander uses to "visualize the sequence of events that will move his forces from the current state to the end state," three basic decision types are shown as solid, short dashes, or long dashed lines. The expert commander quite often is able to visualize the battlespace in terms of a single preferred solution (Klein, 1999), and this type of visualization process is shown as the solid line representing an almost deterministic process.

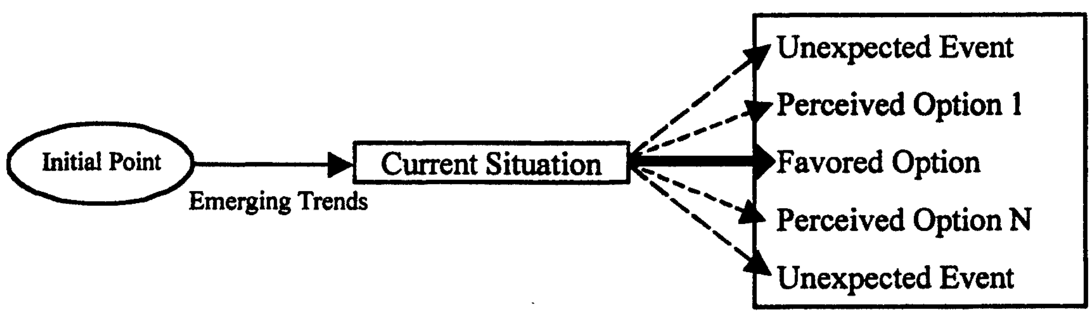

Figure 1. Deterministic, probabilistic, and complex decision processes for visualization of future events.

However, many decision processes and much of the traditional decision research assumes that the decision maker considers probabilities associated with multiple options (shown as dashed lines). For this class of decisions, the commander must consider a set of options, uncertainties, and consequences, all subject to cognitive biases that can distort the visualization process (Wickens & Hollands, 2000). Finally, decisions must be made in which there are neither single solutions nor probabilistic ones. These decisions are those that must be made in complex or chaotic decision spaces. The long dashed line is meant to convey the notion that not all the options are known or the decision space is so volatile that a stable probabilistic structure does not exist (Waldrop, 1992). In truth, actual combat decisions may not fit neatly into any of these categories. However, the categories subsume important research topics in decision making and the distinctions are useful in the delineation of many of the cognitive issues that impact human visualization processes.

Two basic processes underlie visualization: current situational understanding and prediction. Situational understanding entails the processes used to visualize (and understand) the current situation. The visualization technologies to support situational understanding in a military environment are fairly well developed; unfortunately, the human performance implications are not as well defined. The focus in these sections is on the human and operational design issues for the various technologies including terrain visualization systems, military symbology, knowledge walls, and some of the more recent cognitive concepts for abstract visualizations. Although the emphasis is on military related research, basic cognitive and human processing research is discussed whenever appropriate. The second major division is prediction. Prediction includes those processes that permit the warfighter to "see" possible solutions in order to achieve end states. Discussion entails design issues related to the decision processes outlined in Figure 1. In particular, military research based on traditional heuristic models of probabilistic decision making is contrasted to results based on naturalistic decision-making (NDM) models. I conclude that the two methods represent complementary approaches to understanding the role of visualization in prediction: NDM research indicates the efficiencies of expert decision making, whereas the heuristic research indicates the other side of the coin: cognitive biases. Visualization processes related to automation are discussed as a binary decision involving biases toward manual and automated choices, depending on the quality, presentation mode, and type of information presented. Finally, complex military environments are discussed in terms of various decision aiding and visualization techniques that are being developed to reduce the complexity in these environments. Again, the purpose of the report is to help designers and researchers understand the human issues related to visualizing future battlespaces. Design principles are suggested when the data so warrant; in other cases, unresolved research issues are discussed in their stead. Also, visualization is a large topic area; by necessity, this report covers only a limited portion.

3. Current Situational Understanding

3.1 Terrain

The history of warfare is replete with examples of the use of successful tactics that depend on a thorough understanding of the local terrain. From Vicksburg to the Plains of Abraham to the African deserts, victory depended on the use of terrain characteristics as part of the battle plan. Modern display technology allows the operator to see realistic views of the battlespace that use multiple angles, altitudes, and dimensional options. The visualization issue is to determine how well combatants perform military tasks when they use different terrain-viewing technologies. Dimensionality has been researched thoroughly in the aviation domain. Most of the research involves a comparison of two-dimensional (2-D) planar views with three-dimensional (3-D) rendered views while slant range and angle are varied. The general finding is that there are as many tasks in which 3-D displays impede performance as those for which they enhance performance (Banks & Wickens, 1999). This is not surprising; projecting a 3-D representation onto a 2-D surface results in space distortions, ambiguous locations along the line of sight (LOS), and foreshortening phenomena (St. John, Cowen, Smallman, & Oonk, 2001). For example, Banks and Wickens reported that in judging the relative positions of aircraft, most studies showed superior performance for 2-D formats, which indicated difficulties in keeping track of both the vertical and horizontal information for the 3-D displays. In contrast, they found that when the task involved terrain understanding, 3-D resulted in better performance. Naval researchers also found many useful applications for 3-D renderings of littoral operations such as mine warfare, command and control and air operations (Eddy & Kribs, 1999).

Specific Army-related experiments involved map tasks that used experienced cadres from the United States Military Academy. In a series of experiments, the cadres performed various tactical map tasks using 3-D oblique, immersed 3-D, or 2-D planar terrain views rendered on a silicon graphics system. For simple map tasks, distance judgments were superior with 2-D views, mobility judgments were unaffected by view type, and LOS judgments showed increased accuracy with an immersed 3-D view of the mountainous terrain. For tasks that required tactical decisions, immersion in the terrain appeared to cause cognitive tunneling among the surrogate tank commanders. The participants ignored important information that was not in the frontal field of view, even when this information was available on an insert; this was partly attributable to the difficulty of switching attention between two displays (Wickens, Thomas, & Young, 2000; Thomas & Wickens, 1999). In general, being immersed in the problem space has cognitive costs as well as benefits; it is easy for the operator to narrow his or her attentional focus and ignore important peripheral information. Other research has generalized these findings to more abstract 3-D domains which indicate that being immersed within the problem space helps one in navigating through and remembering local features; however, if the task is to comprehend global features of this space, then "god's eye" exocentric views (views from outside the problem space) proved superior (McCormick, Wickens, Banks, & Yeh, 1998).

U.S. Navy researchers investigated the dimensionality issue (2-D versus 3-D) as well and found very similar trends using terrain-related and abstract tasks. They concluded that 2-D displays were superior for understanding relative positions in space but that 3-D rendered views aided in tasks that required understanding terrain contour and depth cues (e.g., LOS judgments) (St. John et al., 2001). In summary, the research indicates that no one view of the terrain is superior in all situations. For force disposition and an overall tactical understanding, 2-D planar views have the advantage of simplicity and veridical scale. On the other hand, an understanding of the terrain itself, its general topography, and possible high and low spots is enhanced by 3-D views. Situations that require mobility through the terrain (such as rehearsal during the planning process) benefit from 3-D immersed displays with the caveat of the lowering of the attentional bandwidth of the observer (Wickens & Hollands, 2000).

The problem is more complicated when 3-D displays are used for portraying dimensions other than spatial ones. For example, Hollands, Pierce, and Magee (1998) investigated the ability of observers to track vehicular movements on the X-Y plane with time forming the third potential dimension. Judgments about the convergence or divergence of and distance between the two vehicles were generally more accurate for 2-D versus 3-D presentations, which again suggests that costs are associated with processing a third dimension. In an ensuing study, mesh and line enhancements were added to the 3-D representation; the results indicated a clear benefit for the enhanced 3-D conditions in contrast to the 3-D control and the 2-D conditions (Meserth & Hollands, 1999). What was disquieting about the latter study was the evidence of optical illusions related to curvature, which caused the observer to be biased toward convergence judgments when the vehicles were close together. Interestingly, the type of illusion seemed to interact with the type of enhancement. Problems with linear perspective apparently caused a divergence bias for vehicular tracks that were widely separated for conditions where a line was inserted between the tracks as a visual cue. This is important because the original intent of the research was to show that emergent cues aided in trend judgments; the experiments also suggest that emergent cues can display illusionary information.

The point to all this is that multiple viewing capabilities will be required for any sufficiently complex battlespace to respond to changing task requirements and to monitor various battlespace slices simultaneously (Barnes & Wickens, 1998). The commander will need to switch and compare battle views much like the television networks do in the so-called Monday night football paradigm (the television camera operator chooses the best view from multiple camera shots). The narrative of the battle situation must be maintained while views are switched—something that has proved to be a significant human performance issue. Attempting to maintain the correspondence between two views is difficult; doing the same thing among multiple views will tax the observer to an even greater extent. Somehow, a cognitive narrative needs to be woven so that the observer sees the different views as components of a perceptual whole (cf, Woods' notion of visual momentum; Woods, 1984). For military tasks that required combining and switching between 2-D and 3-D views, the Navy-sponsored researchers investigated five view correspondence strategies and found that two of the approaches were the most promising. Interestingly, the obvious solution of a side-by-side view was not effective because of the view-switching problem alluded to previously (see Figure 2). Based on operator performance for both the antenna-placing task and the terrain correspondence test, the two superior options were the time "morph" (i.e., gradually shifting software views) and the overlay displays. The time morph allowed the observer to replace a 2-D topographic map with a 3-D representation for a 2-second duration by holding down the space bar. The overlay option combined the 2-D topographic and the 3-D renderings on the same display. More research needs to be done to establish general principles and methods for view switching, but the initial research indicates that a number of clever software techniques may help humans maintain correspondence among multiple views of the battlespace (St. John, Smallman, & Cowen, 2002).

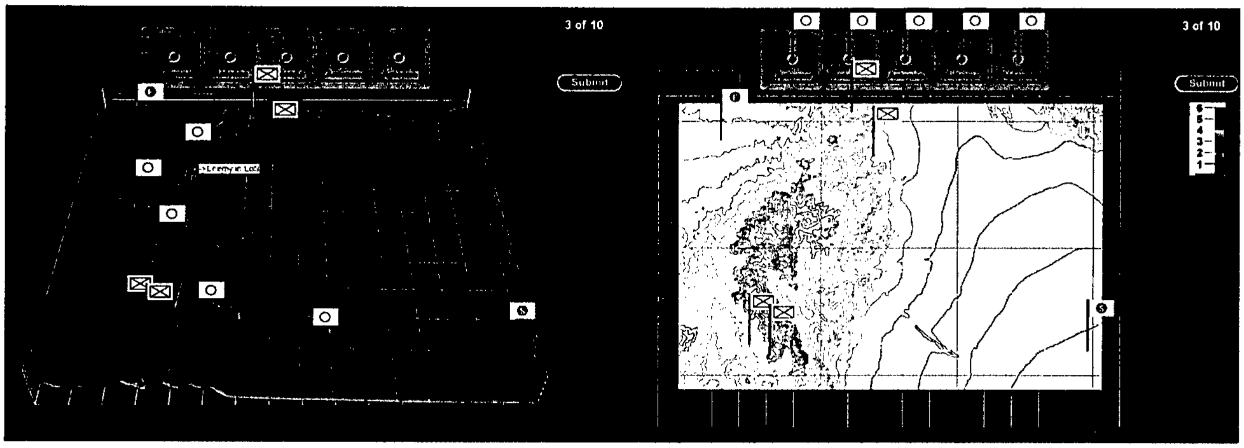

Figure 2. Views (2-D and 3-D) of the same terrain for the integrated display experiments (St. John et al., 2002).

This research pertained mainly to 3-D rendering on a flat surface. There are, however, two additional techniques that produce 3-D visualization effects: motion-induced cues and stereopsis (Kaiser & Profitt, 1992). At this time, few 3-D military displays use stereopsis or motion as techniques for producing 3-D; this should change as virtual technology becomes more accessible and the equipment required to obtain these effects becomes more cost efficient. Researchers investigating the different types of 3-D views found that combining induced motion and stereoscopic cues with monocular cues strengthened the perceived 3-D effects in a linear fashion, that is, each cue improved depth perception in an additive fashion (Sollenberger & Milgram, 1993). Although these cues show performance gains for certain tasks, they also have their drawbacks, including the obvious ones such as the specialized headgear necessary for some 3-D applications (Kaiser & Profitt, 1992; Wickens & Hollands, 2000; Yeh & Silverstein, 1992). The benefits of creating a virtual 3-D world with motion and stereoscopic cues need to be carefully assessed against possible costs. Costs associated with 3-D in general and alarming reports of simulation sickness in particular need to be investigated more thoroughly before these technologies are widely adopted in military environments. The relationship of these technologies to human performance is just beginning to be understood. Wickens and Hollands outline a variety of performance costs for virtual environments (VE): serious time lags between the observer's actions and VE, perceptual illusions, observer disorientation, and simulation sickness. As the technology improves, some of these costs will be ameliorated, but the prevalence of motion sickness symptoms with more conventional flight simulators (with only visual cues) should remind the designer that 3-D VE might cause serious disruptions if the human-related issues are not evaluated thoroughly.

3.2 Displaying Tactical Information

The military situation map and the use of standard symbols have been part of U.S. military tradition at least since the Civil War. These representations have allowed commanders and staff the ability to plan, discuss, and even rehearse the coming battle with virtually no technological overhead. The present discussion focuses on the perceptual and cognitive requisites for using standard military symbols as a visualization tool. Searching for target symbols is among the most primitive tasks that the commander performs in order to use the situation map, and yet, human performance of this seemingly simple task is fairly complex. In general, search time and accuracy degrade as a function of the total amount of information on the situation display (Teichner & Krebs, 1974; Teichner & Mocharnuk, 1979; Wickens & Hollands, 2000). However, at the same time, humans have developed a number of specialized mechanisms that allow them to process large amounts of information efficiently. The best understood of these skills is pre-attentive processing which early investigators noted in both the visual and auditory domains (cf, Neisser, 1967). Basically, humans scan their environment to note important target items (usually something out of place) without focusing attention on any particular item. This mechanism allows humans to process complex scenes while focusing on important change cues. The same processes can be used to search for target items in a complex display as long as the target item contains features that contrast with the non-target items. Pre-attentive processing (defined as search time being unrelated to the number of non-targets in the display) is particularly efficient because we can detect the target feature in the general clutter with minimal interference from non-targets. There are even cases when the target symbol is searched for more rapidly as the number of non-targets increases (Bacon & Egeth, 1991) (presumably because the non-targets create a contrasting background from which the target feature "pops out").

However, the number of symbol sets in which this is possible is limited. For most symbol searches, humans use focused attention, which is more time consuming and less efficient. Military symbols that are similar to other symbols or those for which the warfighter must tally more than a single attribute (e.g., unit type and status) must be searched for with the slower but generally more accurate focused search strategy. Apparently, this is a not an all-or-nothing phenomenon because certain target cues (such as color and size contrast) improve search rates among non-targets (shallower slope of search time versus number of items) even when the operator is searching for more than a single attribute (Treisman, 1982; Treisman & Paterson, 1984; Treisman & Sato, 1990). Even more interesting is the finding that pre-attentive search processes can respond to cognitive as well as perceptual information. For example, the location of a novel word is processed more rapidly when it is embedded in a set of familiar words and digits seem to "pop out" of displays that contain mostly letters (Johnston, Hawley, & Farnham, 1993; Teichner & Krebs, 1974). A related phenomenon is the "automatic" processing capability that allows humans to search for more than a single target type without sacrificing performance efficiency. In general, each additional symbol type that the operator searches for puts additional demands on short-term memory (e.g., simultaneously scanning for Taliban strongholds and

Northern Alliance defense structures). However, if the relationship between potential targets and responses is extremely well learned, then searching for multiple targets simultaneously is not affected by the additional memory requirement (Schneider & Shiffrin, 1977). Both of these phenomena have important visualization implications. The most important symbols should be chosen carefully to be easily discriminable from other display symbols (and their background), and the relationship between the symbol and the semantic response needs to be consistent and well practiced. A good situation display is one in which the commander can notice change instantly and be able to keep track of multiple situations concurrently with minimal cognitive loading. Other cueing techniques such as blinking and sound augmentation can be used to emphasize important changes, but in general, these techniques can be annoying and are apt to be ignored if they are used.

Of all the codes used for modern symbology, color codes seem to have the most attractive qualities. Color coding and color backgrounds are a favorite visualization technique to segregate boundaries and to code various important tactical situations. However, choosing the optimal color-coding schema is not trivial. In the 1930s, the International Commission on Illumination (CIE) developed a color discrimination schema for reflective light. More recent standards have been proposed for emissive light from cathode ray tube (CRT) displays (Carter, 1982). The standards have been modified and validated with human performance data, which indicate that the formula derived from the standards (CIE L*u*v) is a good predictor of human discrimination performance (Carter). Algorithms based on variations of the formula have improved the engineer's ability to pick color palettes that are maximally discriminable for CRT uses (De Corte, 1986). The problem is that it is difficult to use a formula to create optimal color schemes because many military symbols have been assigned colors based on traditional conventions (red: enemy or danger, blue: friendly, etc.), and map backgrounds are so variable. A related problem is that the number of color codes that can be assigned to important categories is limited to five to nine. Scenes can be portrayed in a nearly infinite array of color gradations, but the use of color codes for symbols is limited by human working memory limitations; too many codes degrade search performance (Wickens & Hollands, 2000). In general, color coding does not automatically increase search or memory performance, especially when compared to well-learned non-color codes. In fact, there are important instances when color coding leads to degraded performance (Christ, 1975; Christ & Corso, 1983; Van Orden, Osga, & Luaben, 1991). Usually, problems were found when the test subjects had to ignore color codes to search across another coding dimension. Color attracts the user's attention and it interferes with his or her ability to ignore color codes that are not useful for a particular task. Another problem is that a portion of the male population has problems with color discriminations and to make matters worse, color discrimination degrades with age. However, even when all the limitations and drawbacks of color are considered, most researchers agree that color codes enhance situational awareness (Nugent, Keating, & Campbell, 1995; Van Orden, Divita, & Shim, 1993).

Symbology sets are used successfully in many civilian applications and the icons that represent the various applications are chosen for their high associative value with the represented object (Collins, 1982). It has even been suggested that pictograms could be used to represent a formal universal language (Koler, 1969). However, symbology has been most successful when the applications are limited and the symbol set is extremely intuitive. Because of the complexity of military applications, military symbols have naturally inflated to subsume hundreds of different applications, some of which are intuitive and many of which simply have to be learned. For example, the original Navy Tactical Data System (NTDS) symbols were designed to be learned and discriminated easily. However, NTDS became unwieldy as more applications such as the Airborne Early Warning/Ground Environment Integration Segment (AEGIS) class cruisers (and the concomitant symbols) were added. Although military symbols are updated periodically, the basic Army symbols have remained fairly constant (cf, Department of the Army, 1985). The symbols are not ideal but they have been used for generations and would require extensive retraining if they were changed substantially (Weidenbacher & Barnes, 1997). The original symbol sets were overlaid on military maps and later innovations allowed frequent symbol changes with acetate overlays and grease pencils. As an unexpected bonus, the overlays allowed the commander and staff to review the trends of the military situation by flipping through the old overlays. New North Atlantic Treaty Organization (NATO) standards (NATO, 1990) have resulted in the addition of more human friendly symbology and the adoption of color standards. This in turn has influenced the United States to coordinate its symbol standards across services and to reformat its symbols to be in accord with human engineering standards and the NATO standards (Department of Defense, 1999). Still, the symbol sets remain fairly static for the reasons discussed before. The introduction of digitized displays on television monitors has precipitated its own problems. Many of the display surfaces are small, causing the symbols to cover too much surface area; this occludes neighboring symbols and gives the commander only an approximate location of a particular unit. Also, the color contrast between a symbol and its map background is often poor because the color contrast among emissive displays is variable and difficult to predict for all the possible map backgrounds that are used. In general, the traditional military symbology conventions are less than ideal for modern display technology. Data suggest that more compact symbols with greater contrast would lead to improved observer performance (Weidenbacher & Barnes, 1997). However, traditional symbol conventions are ubiquitous in military systems. The software replacement and training costs of introducing radically new symbol sets would most likely preclude the adoption of more effective concepts in the near future.

Future situation displays will be multi-media based and will combine knowledge sources from varied commercial and military sources. The U.S. Navy Space and Naval Warfare Systems Command (SPAWAR) system center is in the process of developing knowledge wall concepts to replace the traditional situation maps that are ubiquitous in modern operations centers. The purpose of the knowledge wall is to foster shared situational awareness, permit continuous revision of the military situation, and enhance the senior staff's ability to interact with supporting information systems. These concepts are still being developed. Figure 3 is only a notional prototype of an early design but it at least captures the variegated information sources and the live multi-media possibilities of the actual implementation. Imagery intelligence, smart knowledge portals, media from anywhere in the world, video of ongoing conflicts, and conferencing with world leaders and experts are some of the obvious possibilities for future knowledge systems. Based on extensive interviews with 30 senior Naval staff officers, the following crucial issues (directly quoted) were identified as important characteristics for the knowledge wall (Oonk, Smallman, & Moore, 2001):

- Shared situation awareness among its users
- The integration of relevant mission status information
- An intuitive graphical interface
- Consistently formatted information
- A tactical focus for the displayed information
- The display of information to supplement tactical data
- The display of mission goals and Commander's Critical Information Requirements (CCIR)
- The display of summary information provided by "anchor desk" or support staff
- The ability to connect and coordinate or collaborate with others at diverse locations
- A flexible configuration that can easily be changed by users
- The ability to drill down through displayed information for more detail
- Display of information age and reliability
- Tactical overlays to highlight different types of information

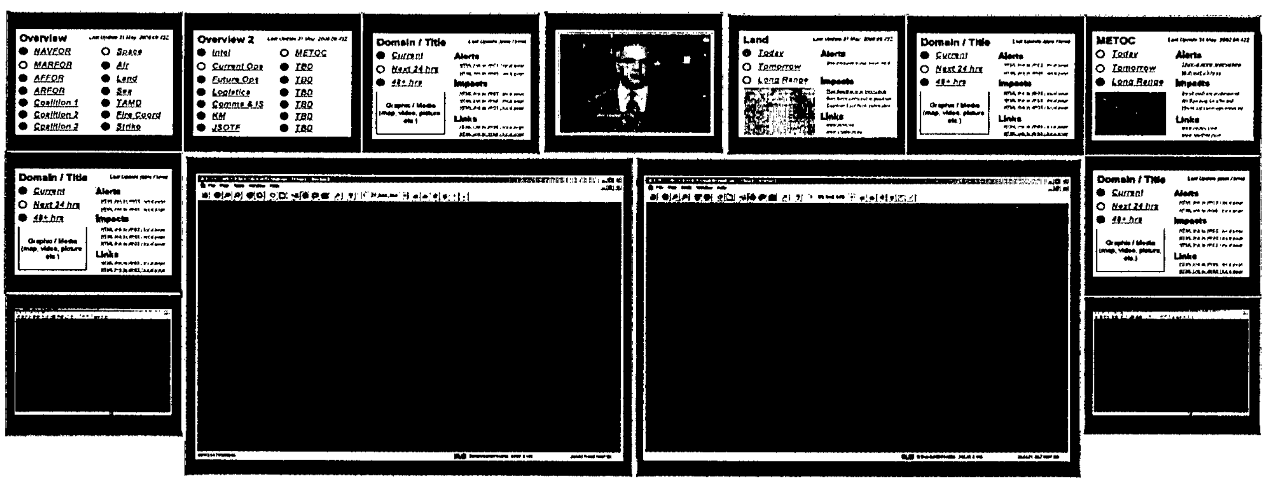

Figure 3. SPAWAR knowledge wall concepts (Oonk et al., 2001).

3.3 Abstract Processes

Ferren (1999), a design consultant for Walt Disney's Imagineering Division, attacked the notion that information overload was inevitable for battlespace visualization displays if the battle process were represented in detail. He argued that the problems were caused by poor design rather than human limitations. His thesis is that symbols and icons are not the natural manner of human processing; rather, he posits that if information could be presented in a naturalistic narrative format, most of the problems associated with cluttered situation displays could be circumvented. Many of the design principles he discussed are based on research which indicates that humans process information with holistic strategies rather than feature extraction processes. For example, Pomerantz, Sager, and Stoever (1977) found what they referred to as a "configural superiority effect". Their subject's task was to find simple physical features that were part of a larger configuration instead of trying to identify the same features in isolation. Counter-intuitively, adding information (as part of a configuration) decreased rather than increased processing time. Apparently, individual features that were part of a configuration were perceived as patterns that formed emergent cues, thus enhancing discrimination performance in contrast to the same cues in isolation. A similar linguistic phenomenon was discovered which showed improved recognition of a letter embedded in a word contrasted with the same letter presented alone (Wheeler, 1970). The design implication is that humans are particularly efficient at recognizing visual patterns compared to processing individual objects. This design principle holds for strategically grouped objects as well as a single configural object. For example, the changing visual relationships among bar graphs can be used as the emergent cue that allows humans to quickly understand higher order interactions among the individual indices (Sanderson, Flach, Buttigieg, & Casey, 1989).

However, an unresolved problem is that humans often require detailed symbolic information (unit type, readiness, location, mobility, etc.), and understanding patterns by themselves is not sufficient. There is evidence that when humans attend to global patterns, they miss changes in the individual components. Bennett and his colleagues (Bennett & Flach, 1992; Bennett, Toms, & Woods, 1993) attempted to solve this problem in the nuclear power plant domain by combining principles for emergent higher order features with basic human factors design principles to highlight individual components. The configural display they designed depicted higher order process features related to overload conditions with specific details of the individual components (steam and water flow information) annotated on the same display. The interactions among the components were displayed in terms of a dynamically changing rectangle whereas color-coded sides portrayed measurement data for individual components. Specifically, changes in area, shape, and rate of change of the rectangle were the emergent cues that signaled important state changes in the power plant process. After practice, the operators were able to respond to the interaction (emergent) cues without losing information concerning the specific component cues. This indicates that global and local processing cues can, at least in certain circumstances, be attended to concurrently. Barnes and Suantak (1996) used the same configural concept to design a command and control display that showed the relationship between combat readiness and mobility information of maneuver battalions with an integrated configural representation. Empirical results (with 16 officers at Fort Huachuca, Arizona) indicated that configural representations resulted in more effective situational awareness and simple tactical decisions than current Army display symbology.

Possibly, the most widely used abstract representation is the spatial metaphor. The idea is simple: display entities are arranged in space to show their relationships in the problem-solving domain of interest. For example, a spreadsheet is arranged in some temporal and categorical order to represent financial trends and relationships. For complex databases, the problem is to represent the data in such a manner as to capture the local relations without losing the big picture. A number of techniques have been suggested to visualize the abstract relationships among data clusters. Two-dimensional approaches use "fish eye" techniques that emphasize the most important current data clusters by displaying them in central locations, whereas other data relations cover smaller areas on the periphery. There are also a number of techniques that use cone representations, mathematical proximity functions, and various navigational and browsing utilities for understanding 3-D databases (Wickens & Hollands, 2000; Fairchild, Poltrock, & Furnas, 1988). An example of the mathematical techniques is "Pathfinder," which generates a network representation based on cognitive distances derived from expert judgments that use psychometric scaling techniques (Minkowski r-metric). Pathfinder and similar proximity functions can be used to display various cognitive relationships among data sources via map metaphors (McDonald & Schvanveldt, 1988). Such techniques are not without their drawbacks; there are no unique cognitive distance functions[1], and these functions may vary a great deal among experts. However, the military is beginning to use proximity functions to organize large intelligence databases to allow the analyst to "see" the big picture and to focus on similarity clusters that are pertinent to the current intelligence requirements.

On a more abstract level, Healy, Booth, and Enns (1998) demonstrated the use of pre-attentive cues (curvature and color) for efficient visual parsing of multivariate data sets (cf, Treisman, 1982). More recently, Healy and Enns (1999) combined textural, height, and color cues to design complex oceanographic displays that show shifting patterns of plankton density, current strength, and sea surface temperature. In particular, they were interested in the combination of color and textural cues as independent dimensions to code various oceanographic phenomena such as typhoon development. They found that a search for color-coded information was unaffected by a background of textural codes (density, size, height, regularity, etc.) but that there was a cost for searching for textural coded targets in a multi-hued display. Most of the search times were extremely rapid, which suggested again that color and textural codes could be processed pre-attentively. Perhaps the more interesting question of whether higher order emergent features could be abstracted from their displays was not addressed. For example, it would have been fascinating to know whether visualization patterns representing precipitation, wind, and ocean current cues and their interactions could be used to predict incipient weather changes. As Ferren (1999) noted, the human visualization system is able to extract complex cues to understand important trends in our often volatile environment. Precisely how our perceptual system

[1]For example, during the cold war, the United States and the Soviet Union were perceived as being close in terms of military power but distant in terms of political philosophy.

accomplishes this feat is still mostly a matter of empirical investigation rather than theoretical understanding.

4. Prediction

4.1 Visualization and Decision Making During Uncertainty

Because many military situations are inherently uncertain, displaying risk and associated concepts such as uncertainty and utility are important issues for FCS. There is a tradition of psychological research related to risky decisions that is still lively and controversial (cf, Gigerenzer & Hoffrage, 1999; Klein, 1999; Lopes, 1986). One school of thought emphasizes decision biases and the non-rational aspects of human decision making. Certainly, the type and severity of the cognitive biases reported in the decision-making literature are extensive (Wickens & Hollands, 2000). For example, in an Army-sponsored project, researchers found that nine types of cognitive biases had important impacts on the way intelligence analysis is performed (Thompson, Hopf-Weichel, & Geiselman, 1983). Much of the research suggests that humans do not compute probabilities among an exhaustive set of options; instead, they visualize concrete examples and use frequency judgments to assign uncertainty values. Thus, many of the decision biases are a result of the heuristic processes that humans use to visualize the problem space (Johnson-Laird, Legrenzi, Girotto, Legrenzi, & Caverni, 1999). The U.S. Army Research Laboratory (ARL), working with the University of Illinois, investigated the effects of these biases and possible visualization techniques to mitigate them in a series of missile defense simulations. In the initial experiment, Air Force officers acted as operators defending against a national missile attack. Figure 4 shows the visualizations for the simulation. The left-hand screen showed the trace history of the incoming missiles and the inventory of ground-based interceptors (GPIs). The right-hand top display portrayed the status of the incoming missiles and their probable targets. The bottom right-hand display indicated the GPI allocation scheme for each incoming missile. Periodically, the computer showed the uncertainties associated with successful defense (or possible loss) of the defended cities, based on the current number of incoming missiles and remaining inventory of interceptor missiles.

The first experiment, which used 16 trained national missile defense (NMD) potential operators (the system is still being developed), investigated different formats for displaying uncertainty. The NMD approach at the time of the experiment was to display probability of mission success (overall and for each defended target), which proved to be abstract and somewhat confusing because of the high degree of certitude required in such cases. The researchers displayed the same information in terms of expected frequency of enemy "leakers" (the expected rate of enemy missiles not intercepted), arguing that the expected frequency format was more concrete and more easily visualized than abstract probabilistic representations (cf, Gigerenzer & Hoffrage, 1999). The operators' overall situational awareness did improve with the concrete "leaker" format in terms of superior memory and search performance. However, the operators' decisions whether to add more reserve missiles to the current mission (thus leaving defended cities vulnerable to an ensuing attack) were not affected by the uncertainty format, which indicated that no bias was introduced by the "leaker" metric. There was an interaction between current risk and the probability of an ensuing attack. Basically, operators were responsive to the possibility of an ensuing attack but they were much more concerned about the known risks involved in the current mission. The results of this experiment suggest that a concrete representation of uncertainty in terms of expected frequencies of "leaker" missiles is a promising format for aiding operators in visualizing uncertainty, but more research needs to be done to generalize beyond the specific task used for this experiment. What is particularly interesting is the fact that the visualization improvement was not the result of pictorial or graphical variables but involved a simple change in numerical format that allowed the operator to visualize risk in terms of concrete examples rather than abstract concepts. There is also a disturbing suggestion that operators may focus too heavily on the immediate fight to the detriment of planning for future engagements, which suggests that visualization factors related to future shortages of interceptor missiles need to be investigated.

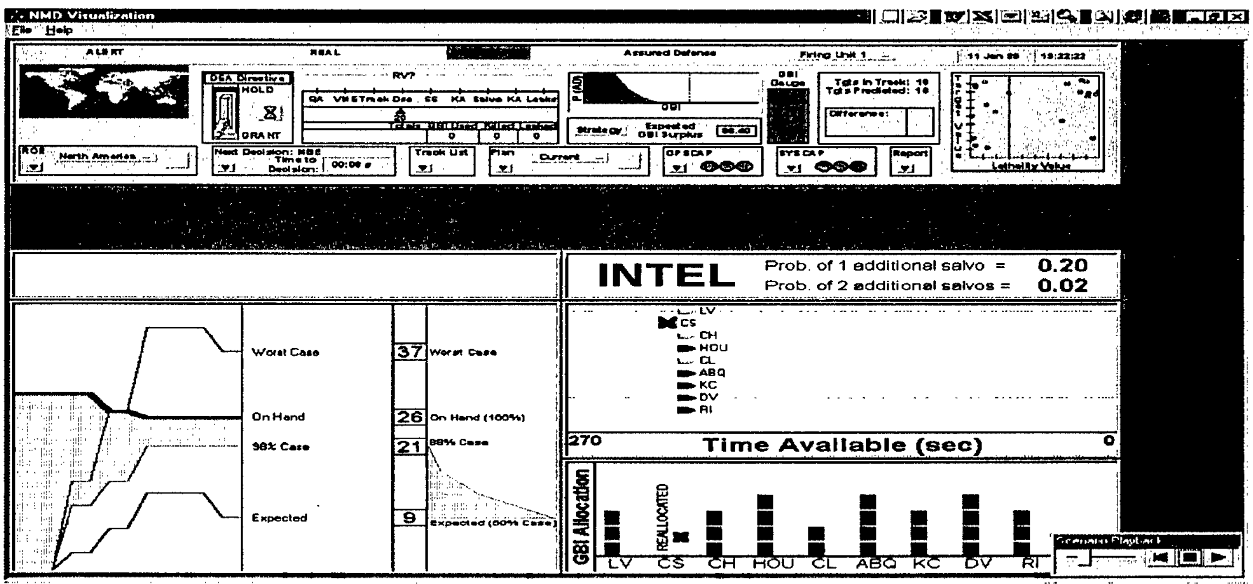

Figure 4. Risk management visualizations for missile defense simulations (Barnes, Wickens, & Smith, 2000).

Another series of studies investigated biases related to how military personnel visualize sequences of hits and misses of interceptor missiles against incoming missiles (Smith & Wickens, 1999). In general, humans tend to visualize independent stochastic processes using easily imaged heuristics such as things getting better (or worse) or they use anchoring stratagems to perceive trends that do not exist. For example, test subjects tend to see trends in data that are, in fact, stochastically independent even when they are informed of the mathematical relationships (Wickens & Hollands, 2000). In two separate experiments, Patriot missile operators perceived nonexistent trends, anchoring their decisions to the first or last piece of information they received, which indicated individual differences as well as effects caused by slight changes in experimental conditions (Adelman & Bresnick, 1992; Adelman, Bresnick, Black, Freeman, & Sak, 1996). In a second NMD experiment, 16 Reserve Officer Training Corps students and 4 active duty officers stationed at the University of Illinois were used to investigate trend effects related to observing the sequence of hits or misses of interceptors against the incoming enemy missiles. The trend data were investigated in the simulation game mentioned; the participants were informed of the stochastically independent properties of hits and misses in the simulation. As in the Patriot case, the trend effects were complex. In particular, the perception of things getting worse caused the operators to over-react and take more missiles out of reserve than they would for an equivalent case when the hits and misses seem to be of a more random nature (Barnes, Wickens, & Smith, 2000). In the real world, trends are often of the type where events start to improve or deteriorate. The problem posed here is how to analyze and then present information to the operator so that the difference between random fluctuations and actual battle trends can be visualized. It is worth noting that the problems investigated for the NMD will surface for many of the new automated systems being developed for military intelligence, Patriot and other missile defense systems, and sensor-to-shooter field artillery systems (Thompson et al., 1983). As evolving systems become more sophisticated, the display of states of uncertainty and the concomitant cognitive biases will require innovative cognitive engineering solutions. Visualization techniques and more effective ways of portraying uncertainty are at least part of the solution.

4.2 Naturalistic Decision Making and Mental Simulation

Whereas the previous reported research focused on the negative aspects of human decision making and their heuristic processes, many researchers have pointed out the efficiencies of the same processes. The laboratory research has been criticized as being unrealistic and unrelated to tasks that humans, especially experts, usually perform. In particular, a number of researchers have questioned the generality and the construct validity of research that was not conducted in more naturalistic situations (Klein, 1999; Lopes, 1986). Much of the early research about decision making assumed a normative process underlying human decision making. Humans deviated from this process but they could be trained to use prescriptive techniques that would enhance their decision-making skills. This approach influenced U.S. Army doctrine, causing the Command and General Staff College at Fort Leavenworth, Kansas, to train staff officers to evaluate three courses of action (COAs) and enumerate their strengths and weaknesses (and the inherent uncertainties involved) before making a recommendation to the commander. This paradigm is very similar to the traditional structured approach based on the tenets of decision analytical theory being taught at most university business schools. The theoretical implication is that the successful decision maker needs to know what options are available, the uncertainties and utilities involved, and the general structure of the decision space (usually some sort of a decision tree) before he or she chooses an optimal solution. The principal weakness of this paradigm is that it has little to do with how experts actually make decisions. For example, Klein, in a now classic study, found that expert firemen did not generate options but simply "knew" the correct thing to do. Klein found the same basic process for experienced business executives and military officers. Experts, especially in time-constrained situations, focus on situational understanding and then make decisions rapidly, usually without considering options. Klein refers to this process as recognition-primed decision making (RPD). Experts "see" familiar patterns and visualize solutions using external cues that trigger memories of successful actions for similar events. The evolutionary advantage is obvious; primitive man had scant opportunities to construct decision trees. Klein does not assume that all decision making is this rapid; in more ambiguous situations, the expert may visualize various scenarios and COAs, thus creating a mental simulation of the possibilities and their consequences before making a decision.

The key to military decision making is not a normative process but the warfighter's ability to visualize a solution that is highly dependent on past experience and situational understanding. Kobus, Proctor, Bank, and Holste (2000) investigated 52 marines making COA decisions in a dynamically changing military situation during both high and low uncertainty conditions. The most important differences were between experienced and inexperienced marines. The results indicated that experienced marines took longer to make their situational assessment but made COA decisions more accurately and rapidly than inexperienced marines. The experienced marines were also less affected by the degrees of uncertainty concerning the validity of the intelligence information they received. The advantage of experience seem to be that it allowed the officers to visualize an effective COA rapidly once enough knowledge was digested for them to understand the military situation. Also, other research confirms that introducing uncertainty has a significantly more deleterious effect on inexperienced military decision makers than on their more experienced peers (St. John, Callan, Proctor, & Holste, 2000).

In a different domain, researchers found that the ability of an expert to adapt to new problem sets depends on a rich interconnectedness among the expert's knowledge structures, allowing generalization to the problem space. Experts are not necessarily more logical than the novice but have more stored patterns (and their stored relationships to other patterns) to compare to the new situation. For example, researchers found important differences in problem-solving abilities between experts and less experienced Unix[2] programmers. Experts were more adept at combining Unix commands to solve novel programming problems than were programmers with less than 2 years' experience. Experts were able to visualize multi-step solutions, whereas the relative novices were still at the individual software command level (Mannes & Doane, 1991; Doane, Alderton, Sohn, & Pelligrino, 1996; Doane, Sohn, McNamara, & Adams, 2000). Holyoak and Spellman (1993) point out that solving new problems requires more than RPD processes. Humans must not only retrieve past memories but must also mix and match them to the current problem until a new solution emerges. The thought processes themselves tend to be

[2]Unix® is a registered trademark of The Open Group.

"imagery" based and to depend on the investigation of more likely solutions rather than on an assessment of all possible solutions (Johnson-Laird et al., 1999). The research results suggest that training via visualization techniques and role playing in various military vignettes may aid in the development of the "expertise" to adapt to new environments. Another product of naturalistic approaches involves a better understanding of how humans tend to use visualizations in real-world situations. Interviews with experts suggest that humans visualize in terms of analogies to past experiences, making metaphors and narratives effective forms of exposition. The implication is that the knowledge presentation should tell a story because a narrative presentation involves observers in a mental dialogue with the presentation material, thus allowing them to fill the blanks (Gershon & Page, 2001). Commanders do not need to be overwhelmed with details but need to be presented only with that part of the story that directly impacts their decisions (Ferren, 1999; Klein, 1999). This is an important contrast to the traditional wisdom of how to present information. Humans were modeled as passive information receivers who at best could decode all the information on the display (cf, information theory in Wickens & Hollands, 2000). In the naturalistic view, humans are active creators of information, based on their past experience and their ability to understand the current situation using analogical reasoning and metaphorical examples. As intuitively appealing as the naturalistic view is, there are obvious drawbacks. It is difficult to scientifically define "storytelling" formats and to show that narration improves situational awareness or decision making more than well-designed information displays (or more precisely, during what conditions it does or does not do so). The research implications are that we need to collect data and evaluate concepts in realistic military environments. However, this is a difficult and not easily accomplished task. Too often, data collected in realistic exercises are not useful because of the complete lack of controls. A more measured approach would be to combine the strengths of controlled experiments with the realism of field work via a hybrid research program (Barnes & Beevis, in press). The same is true in investigating human biases as opposed to expert strengths. It is a matter of a glass half full or half empty; both phenomena exist, and any realistic research effort must investigate the warfighter's limitations as well as strengths. However, we do need to focus our efforts more on using realistic simulation and experimental paradigms that capture the important issues of specific military domains if we are going to understand these phenomena in the correct military context. Eventually, the resulting concepts must be validated during actual military exercises.

4.3 Visualization Issues for Supervisory Control of Automated Battlefields

An important question in future combat environments is how much trust the commander will have in automated systems. Commanders will never relinquish their decision prerogatives even though processing and execution will become increasingly automated. The commander must be able to understand and visualize the consequences of each of these systems as they execute on the battlefield in order to achieve his or her intended end states. Trust does not mean that the commander will assume that systems will operate perfectly. For the foreseeable future, an operator will be in the loop at a supervisory level. Rather, appropriate trust is an ability to visualize how automated systems will operate in a specific military environment and when to intervene with redundant systems. At the operator level, appropriate trust in automated solutions will become an increasingly important component of executing the commander's intent. Early research is pessimistic, indicating many cases of misuse (over-reliance on automated systems) and disuse (over-reliance on manual solutions) (Parasuraman & Riley, 1997). The results can be disastrous: airplane crashes when pilots relied too much on automated landing systems, train crews ignoring the speed regulators leading to rail accidents, or the infamous K-007 Korean aircraft incident when the crew ignored evidence of route deviation once the automatic pilot was set (miss-set). The problem is fuzzy because there seem to be biases toward relying too little and too much on automated systems. Researchers sponsored by ARL at Fort Sill, Oklahoma, have done a number of studies investigating trust issues in Army-related tasks. They have varied motivational, social, and cognitive factors and they found examples of misuse and disuse of automated systems (Dzindolet, Pierce, Beck, & Dawe, 2002).

In a series of experiments using a simulated automatic target recognition (ATR) device, Dzindolet et al. found that the test subjects were more willing to rely on their own estimates even when they were informed that the ATR solutions were superior to their own, based on the last 200 trials. Subjects were also more willing to trust the same estimates if they were told that they came from a peer. Thus, subjects in this series of experiments showed a bias against automation; some of the participants even suggested that they had a moral imperative to trust their own judgment over a machine's (Dzindolet et al., 2002). However, another study using a similar paradigm (Dzindolet, Pierce, Beck, Dawe, & Anderson, 2001) indicated a complete shift in strategy, with the participants more prone to misuse than to disuse. They tended to over-rely on the aid when the aid was incorrect. The crucial factor was the order of the decision making. In the latter experiment, the machine's solution was displayed before the operator made a decision, whereas in the former experiments, the operator's decision preceded the machine's. A comparison of the experiments indicates that the shift from a manual bias ("I make the decisions") to an automation bias ("let the machine do it") is based on type of feedback and time stress but mainly by whether the operator had already made a decision before the machine solution was known. The results are important because it gave insight into the dynamics of automation bias, which has some of the characteristics of social loafing (if the machine has already made the decision, the operator's uncertainty could be resolved simply by agreeing). However, if operators have already set their minds by the time they see the automated decision, then they have a vested interest in following their own dictates. Again, it is an example of a very simple manipulation, apparently changing the operator's visualization of the problem space from one where the operator is the controller and the computer is the assistant (under-reliance) to one where the computer is authority and the operator the backup (over-reliance).

Ensuing experiments indicated that the precision of the feedback as well as the decision order was important in instilling appropriate trust in the operator. An experimental condition in which the operator was given feedback about each trial and when obvious errors were not displayed to the operator resulted in nearly optimal operator automation decisions. In this condition, the operator was able to visualize a rational strategy in regard to the machine error rate and was able to intervene appropriately (Pomranky, Dzindolet, & Peterson, 2001). One issue that became obvious in this series of experiments and the NMD experiments is the importance of training as well as improvements in visualization technology. The Pomranky et al. experiment showed that optimal synergy depended on the operator learning the characteristics of the automated device. The displayed information is only meaningful if combined with training with feedback that stresses consequences ("you just missed an obvious target"). Visualization depends on memory of past incidences combined with cues relating to the current situation. When these cues are properly understood, the operator can visualize his or her appropriate role within the automated system.

Another important issue related to supervisory control is the degree of automation and reliability problem (Parasuraman, Sheridan, & Wickens, 2000). FCS will depend on unmanned aerial and ground robotic systems with varying amounts of autonomy. The crucial issue for these systems is how much autonomy to assign to the unmanned systems—a question that depends on the operator's situational awareness as well as the reliability and degree of automation of the unmanned systems. For example, it may be beneficial from a systems point of view to keep operators actively engaged in the control of a semi-autonomous vehicle because it forces them to maintain good situational awareness for those instances when the operator is truly needed. Complacency effects are a problem even when the automation is implemented only at the information level. Horrey and Wickens (2001) found benefits and costs of partially automating military situation displays. Overall, automated highlighting and the presentation of diagnostic information concerning enemy movements aided military decision making; however, their subjects were misled by unreliable automation, causing them to miss important cues that may have been spotted in manual conditions. Galster, Bolia, Roe, and Parasuraman (2001) found the same trends using a military aviation display. More intriguing is the "automation paradox" effect found in a number of military and applied experiments. Researchers found that the more reliable the automation, the more likely the operator was to make mistakes when the automation proved unreliable (Rovira, Zinni, & Parasuraman, 2002). This suggests that the engineering solution of designing more reliable systems has its own human performance costs. Especially for more reliable aids, humans can become too complacent and fail to anticipate automation failures (even when they know they can occur) (Rovira & Parasuraman, 2002).

Trust is a pervasive combat issue that affects all command decisions. In the future, the issues will not only involve subordinate commanders and their individual characteristics but also subordinate intelligent systems and their characteristics. The most important research issues involve determining the cognitive engineering paradigms that best allow the commander to understand the operations of automated systems so that the degree of autonomy and trust for systems is a natural and effective part of the overall command process. Some combination of training and improved visualization concepts is required so that the commander (and his or her operator surrogates) can understand and predict automated performance. The research about the automation paradox and complacency also implies that it is important to engage the operator in the decision process even for completely automated systems. However, we need to know more about the degree of autonomy, complacency, feedback effects, and the automation paradox in realistic military settings before we can design effective visualization aids.

4.4 Visualization and Prediction in Complex Military Environments

Perhaps the most influential scientific change in the 20th century is a shift from a belief in a deterministic Newtonian world to a scientific zeitgeist that accepts the notion of inherent uncertainties. More recently, even the notion of a being able to make probabilistic predictions has been challenged. Chaos theory, for example, assumes that minor events can radically alter the outcome of nonlinear processes in a world with many such processes. Complexity theory is a group of related concepts that is predicated on two important concepts: information and emergence. The first involves the overwhelming number of possible outcomes in any large set of interacting parts. The second involves the result of the possible interactions in a complex system. For example, there are 2^n possible states for a system with n components. For any one of the myriad interactions, it is possible for unpredictable behaviors to "emerge" that can have minor or major impacts on the system as a whole (Bar-Yam, 1997; Waldrop, 1992). Considering the battlefield as a complex system, complexity theory implies that the dynamics of battlefield skirmishes become unpredictable as the number of interacting elements increase. This is true even in a successful battle. For these situations, the commander (through training, doctrine, and tactical redundancy) has accounted for unexpected events, and the resulting divergence from the battle plan has only minor impacts. However, as the inherent uncertainty of the situation increases, "emergence" of unexpected events and chaotic behaviors will start to play an increasingly important role in determining the outcome.

Unfortunately, future military missions will tend to be the type for which doctrine and preconceived notions of war fighting will be challenged in many different situations. In particular, opposition forces have shown the ability to adapt to western preconceptions and to use asymmetric tactics to defeat superior force and firepower, especially when political and psychological factors are being exploited. Complexity and the effects of unforeseen interactions have become topics of intense debate among military researchers. However, empirical and applied research in this area is still in the beginning stages. Currently, ARL is investigating new prediction and visualization paradigms to enhance the commander's situation understanding in these environments. New visualization techniques have been proposed to help us understand the historical trends, political changes, ethnic conceptions, and changing perceptions of various combatant and non-combatant groups in a particular area of concern (Zacharias & Hudlicka, 2001). One area of particular concern for missions in unfamiliar environments is the use of information aids to assist the intelligence analyst in interpreting the streams of data that can overwhelm military capacity during critical situations. University of Illinois researchers in support of ARL have developed a series of decision support systems using Bayesian belief nets that can be used as tools for an individual analyst or in a collaborative environment to structure and categorize incoming intelligence reports (Mengshoel & Wilkens, 2001; Asaro, Hayes, & Jones, 2001). The results are promising but the systems are still very much laboratory tools. The main problem is that the probability structure must be created to account for each new battle situation. The advantage of these systems is that they handle large data streams and show inferential networks to the trained analyst, which will allow him or her to visualize the emerging trends. More research needs to be done to determine how robust these systems are when the military situation changes. They show promise in helping to ameliorate an important consequence of complexity: the overwhelming amount of battlefield information.

Another approach to predicting outcomes on the battlefield is the use of genetic algorithms to "search" dynamically for the underlying structure by rapidly comparing possible solutions. The solutions are generated by the combination of important characteristics ("genes") to examine hundreds of thousands of options with surprisingly little computer overhead. The FOX[3] genetic algorithm (GA), which was crafted at the University of Illinois, was developed to generate and evaluate solutions to tactical problems in conventional warfare environments. The algorithm, which is combined with a display that portrays the results, assisted surrogate commanders from Fort Leavenworth, Kansas, by helping them visualize twice as many new COAs as they could with the manual planning condition (Hayes, Fiebig-Brodie, Winkler, & Schlabach, 2001). Hillis and Winkler (2001) have taken the genetic algorithm concept one step further by introducing co-evolutionary solutions to FOX-GA. This approach allows the analyst to observe multiple iterations of the genetic solution by playing the red and blue force best solutions against each other. The tactics of red and blue co-evolve as the best solution in game n-1 is challenged by the adversary in game *n* from which the best solution then determines the initial point of game n+1, etc. The advantage is that solutions emerge that would go undetected in a simpler one-way game such as the original FOX-GA. The empirical question is whether the added complexity aids or hinders the analyst's ability to understand the military environment. ARL is in the process of investigating this issue by redesigning the basic algorithms that underlie the co-evolutionary and genetic approaches and by generating visualization for the non-traditional multi-agent, volatile situation such as anti-terrorist campaigns in Afghanistan. The results will be evaluated with experienced analysts to help design better visualization systems and to pinpoint problems with the basic concept. Tools based on co-evolutionary processes show particular promise for understanding complexity in that they deliberately mimic the chaos of battlefield situations by using dynamic algorithms that have no predetermined solutions and are particularly useful for discovering unanticipated results (Hillis & Winkler, 2001).

An unfortunate mistake in trying to evaluate systems that are being designed for complex environments is the belief that these systems must be subjected to realistic validation early in their development process. Evaluations must be a multi-step process from early modeling with expert feedback to controlled experiments to field validations. Too often in the attempt to capture

[3]Not an acronym

combat complexity, the temptation to skip steps leads to disastrous field experiences because promising technologies are introduced prematurely (Barnes & Beevis, in press). An example of an attempt to introduce realism and control early in the design process is an ARL-supported project at the University of Arizona. The researchers are trying to circumvent these problems by developing a simple simulation environment for initial evaluations of visualization and decision support concepts. The purpose is to combine the efficiencies of iterative feedback from experts and controls of laboratory experiments with at least some of the complexity of full-scale simulations. The 3-D visualization architecture has been used to investigate the utility of employing various predictive and assessment aids to enhance the commander's ability to operate in nonconventional situations such as Kosovo, Afghanistan, and Somalia (Rozenblit, Barnes, Momen, Quijada, & Fichtl, 2000; Ziegler, Rozenblit, Barnes, & Hudlicka, 2000). This architecture allows the experimental manipulation of visualization and algorithmic techniques via realistic military vignettes with active duty officers as test subjects. Figure 5 portrays examples of concepts that were demonstrated to groups of military experts to assess the military utility of various 3-D animation and configural display concepts. Future efforts include data collection during realistic simulated small-scale contingency operations.

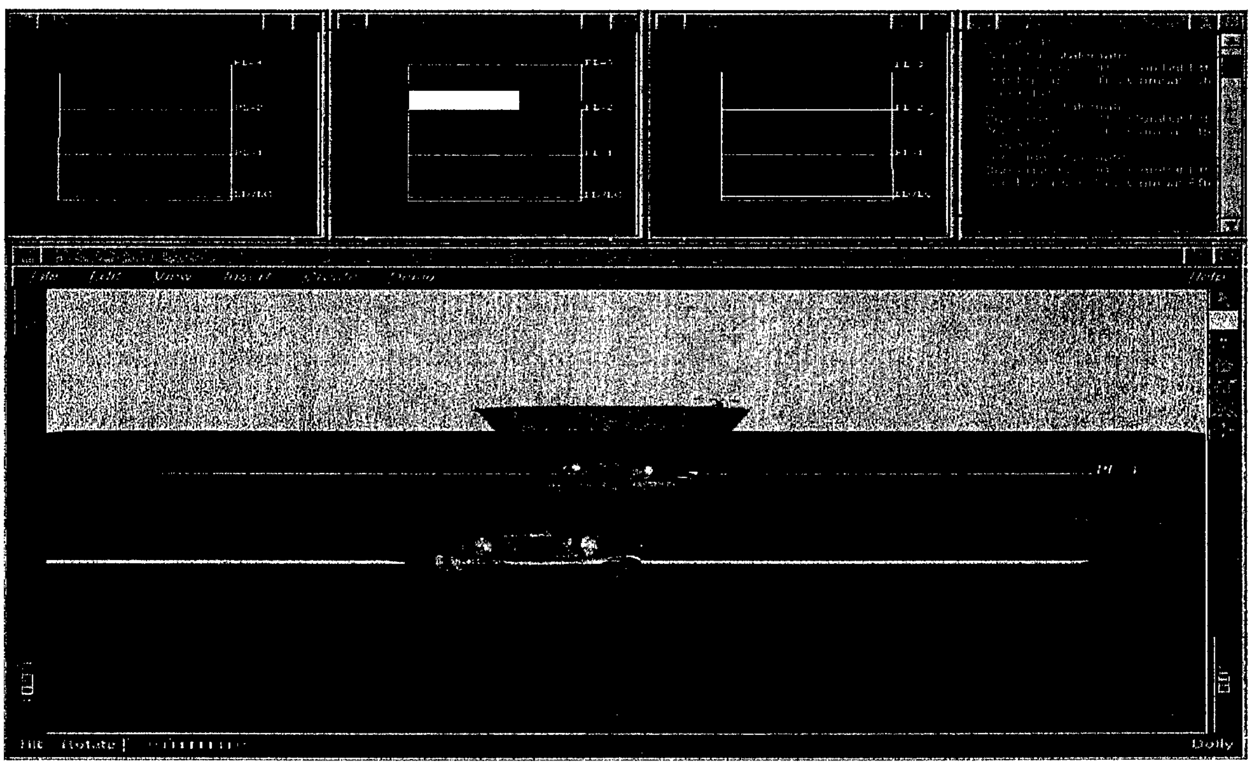

Figure 5. Three-dimensional visualizations showing possible options combined with predictive software and configural displays that show the consequences of the animated vignettes (Rozenblit et al., 2000).

5. Conclusions

Visualization is a problem-solving stratagem that uses internal and external images to enhance the commander's ability to understand the current situation and to envision the actions necessary to attain combat goals. Viewing battlefield terrain is a complicated process that requires 2-D planar views for the understanding of tactical and spatial relationships, 3-D views for topographical understanding, and immersed 3-D views for mission rehearsal and detailed understanding of the battlefield "dirt." The principal research issue is to develop principles for the integration (or separation) of various views so that battle managers can perceive tactical and topographical battle conditions as a seamless narrative. Military symbols are products of tradition rather than human engineering efficiency. Coding techniques such as color and creation of more uniform symbol sets have increased the processing efficiency of modern symbol sets without solving the basic problems of clutter and poor contrast. New display concepts based on research findings related to pre-attentive processing and emergent perceptual cues may circumvent at least some of the problems related to the portrayal of the complexity of modern battlefields. Also, knowledge wall technologies are being developed to display all pertinent information (including live battlefield imagery) to the commander as a mosaic of various knowledge sources. The problem remains as to how to present multiple sources of information with techniques that aid the commander in visualizing not only the current situation but also in predicting the most effective responses and future COAs. The most important human-related design issues are

- Projecting a 3-D representation onto a 2-D surface results in space distortions, ambiguous locations along the line of sight, and foreshortening phenomena. Visualization cues such as mesh and line enhancements help us understand 3-D views.

- Tactical information is displayed more effectively with 2-D planar formats, whereas understanding the topography is best visualized with 3-D formats.

- There is a cognitive cost in switching between dimensionality and slant range views. Software utilities that allow the observer to morph between slant range and dimensionality views of the same terrain have proved effective in laboratory experiments.

- In the future, warfighters may be able to visualize their military situation using VE. However, many costs are currently associated with VE, which must be overcome before the technology becomes used widely: motion sickness, perceptual illusions, time lags, and observer disorientation.

- A small set of symbols with distinct shapes permits observers to use pre-attentive processing mechanisms to maintain overall battle awareness.

- Military symbols in general and Army symbols in particular are only minimally effective in portraying complex military situations. Because many of these symbol sets have been used for generations, they are unlikely to be supplanted.

- Properly designed color coding, even with its own perceptual costs, can be used effectively to enhance understanding of situation displays via military symbol sets.

- New visualization techniques, such as configural displays, proximity functions, and narrative formats, which are based on human pattern recognition abilities, are promising techniques to display complex military situations without clutter or information overload.

- Knowledge walls using modern digital technology are being designed for real-time, multi-source, interactive, and shared command views of future battlefields.

- Expert users emphasize that future systems must be collaborative, intuitive, broad based, have "drill-down" capabilities, and be predicated on the CCIRs.

Prediction is an important but controversial component of the visualization process. The literature about biases suggests that the use of heuristics will result in humans who are visualizing only a limited portion of the underlying problem space, which will lead to sub-optimal decisions. The literature about naturalistic decision making implies the opposite, mainly that heuristic processes allow the expert to react to difficult situations by rapidly finding a satisfactory solution. There is some truth in both assertions; humans are prone to certain biases but also show an amazing ability to adapt to difficult situations that fall into their area of expertise. The crucial task for the designer is to find visualization cues that alert observers to critical decision parameters that are consonant with their level of expertise. The literature suggests that even simple manipulations of displayed information (such as when information was presented in the decision process, type of feedback, and how uncertainty was presented) can have positive effects on performance. In contrast, cognitive biases such as complacency, anchoring effects, automation paradox, and distrust of automated systems resulted in ineffective military decisions.

The general conclusion is that most of these biases could be overcome by a combination of training and improved methods of visualization. In particular, visualization concepts based on storytelling would seem to be a creative approach for both training and operational knowledge presentation. However, these methods must be developed in realistic environments and evaluated in actual field environments to be effective. Finally, cognitive technologies that are being developed to help us better understand military complexity were assessed. Bayesian techniques to sort masses of intelligence indicators into possible enemy actions and genetic and co-evolutionary algorithms were found to be potentially useful (but as yet unproven) techniques to help an analyst visualize possible sources of complexity for conventional and contingency operations. Methods to evaluate these technologies were also reviewed:

- Measures of uncertainty based on frequency counts offer a promising method for displaying uncertainty.

- Because cognitive biases are often based on rational expectations of real-world processes, training with realistic simulations is necessary to allow the operator to visualize the outcome of these processes.

- Results from the NDM literature suggest that simulations, role-playing and story-telling exercises should improve the novice's ability to visualize solutions to novel situations.

- When information is presented in the decision cycle, the type of feedback and type of automation errors influence the operator's perceived role in using automated systems.

- To achieve automation synergy, visualization systems must be designed to keep the operator actively engaged and knowledgeable about the expected outcomes of the automated decision process.

- Tools based on co-evolutionary processes show particular promise for visualizing complexity in that they deliberately mimic the chaos of battlefield situations by using dynamic algorithms that have no predetermined solutions and are particularly useful for discovering unanticipated results.

- Evaluating visualization tools is a multi-step process that requires early modeling and experimentation, continual user involvement, as well as realistic validation exercises.

We are just beginning to understand how to design a visualization architecture that is responsive to the human's natural decision-making style. However, certain features of this architecture are evident. The top-level display process will focus on situational understanding. The visualization will be knowledge rich but data sparse, focusing on the decision elements that allow the commander to follow the course of the battle narrative. Beneath the display surface, multiple battle parameters will be continuously updated, and triggers will surface information that indicates possible problems. More sophisticated predictive algorithms and collaborating humans will be computing in the background and forecasting the battle process. These human and machine analysts will interrupt only if objectives are threatened or unusual trends develop. A variety of tools that address specific problems and planning requirements is also needed. This suggests that the visualization architecture will be collaborative, with each component having private and public visualization aids. The components will be widely disbursed and will consist of battle staff, off-site expertise, and autonomous intelligent systems networked into a common cognitive architecture. An important design issue will be to ensure that the individual components act synergistically to create a unified and coherent view of the battlespace, which suggests the importance of filters and knowledge management protocols in future systems. Principles based on the use of narrative formats are possible cognitive solutions for improving coherency. The visualization architecture will be analogous to human consciousness. The visualizations themselves will be the top-level component that imparts meaning and understanding to the diverse information and decision-making components serving the command structure.

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14. ABSTRACT

The purpose of the report was to explore the human dimension of battlefield visualization in order to generate design principles and suggest future research topics. The author reviewed cognitive engineering research sponsored by the U.S. Army Research Laboratory, other military related research, and pertinent open literature publications. A descriptive model of visualization is discussed in terms of the ability of the commander to understand the current combat situation, generate courses of action (COAs) and predict COA results. Specific topics covered as part of situation understanding included terrain visualization, situation displays that use symbology, techniques for abstract visualizations, and multi-media knowledge walls. Military decision-making research was reviewed in order to explore specific topics related to the commander's ability to use visualization tools to predict combat results. Based on the reviewed research, the author discusses design principles for the following issues:

Dimensionality, slant range, degree of terrain immersion, and virtual environments
Methods of combining terrain views
Limitations of and ways to enhance military symbology
Configural, narrative, and pattern recognition advantages of abstract displays
Operator-derived principles for knowledge walls
Uncertainty representation, trend perceptions, and visualization biases
Story telling as a visualization aid for naturalistic decision making
Information presentation, feedback, and the automation paradox effects on visualized automated systems
Visualization aids for complex and nonconventional military environments

Based on these principles, generalized design guidelines were proposed for a commander-centered architecture as a basis for future battlefield visualization and knowledge management systems.

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