Human Dimension of Future Battlespace Visualization Architectures

Mr. Michael J. Barnes
U.S. Army Research Laboratory
2520 Healy Avenue, Suite 1172
Fort Huachuca, Arizona 85613-7069
UNITED STATES

Email: michael.barnes@hua.army.mil

The U.S. Army definition of battlespace visualization implies not only imaging the battlespace but also more significantly generating objectives and imaging 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 depicting battlespace information. Understanding the topographical, spatial, and force dispositions on the battlefield is a necessary component of visualization but not sufficient. The ultimate purposes of visualization aids are to increase the commander's ability to understand the battle dynamics, consider options, and predict outcomes. For that reason, 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 have been included. The purpose of this paper is to identify important visualization issues that impact the commander's ability to understand and predict the combat situation. The discussion will focus on design and research issues likely to impact future combat systems.

OVERVIEW AND GENERAL MODEL OF VISUALIZATION

This definition of visualization has two components: situation understanding and decision processes concerning future options. To delineate situation understanding in a combat environment more clearly, three topics will be discussed: terrain feature identification, tactical symbolic representation, and process displays (see Figure 1). In cognitive terms, these processes are analogous to object identification, understanding abstract relations among objects and understanding the transformation principles that drive the underlying processes (Barnes, 1997). These topics are indebted to Rasmussen's theories (Barnes & Wickens, 1998) but the discussion will emphasize higher-level processes subsumed under Rasmussen's discussion of symbolic knowledge and the present discussion is not influenced by semiotic theory. The first topic involves terrain and feature analysis. Historically, commanders have won or lost battles depending on how well they understood their relationship of their forces to the physical terrain. Besides discussing issues related to understanding physical characteristics of the battlefield, the review of the second topic will cover the literature on tactical situation displays emphasizing the role of standard modern symbology. Also, recent advances in video and display technology related to tactical knowledge walls will be discussed as well. Finally, advances in cognitive engineering related to more abstract displays that focus on understanding processes and interactions among components rather than generating yet another symbol set will be discussed.

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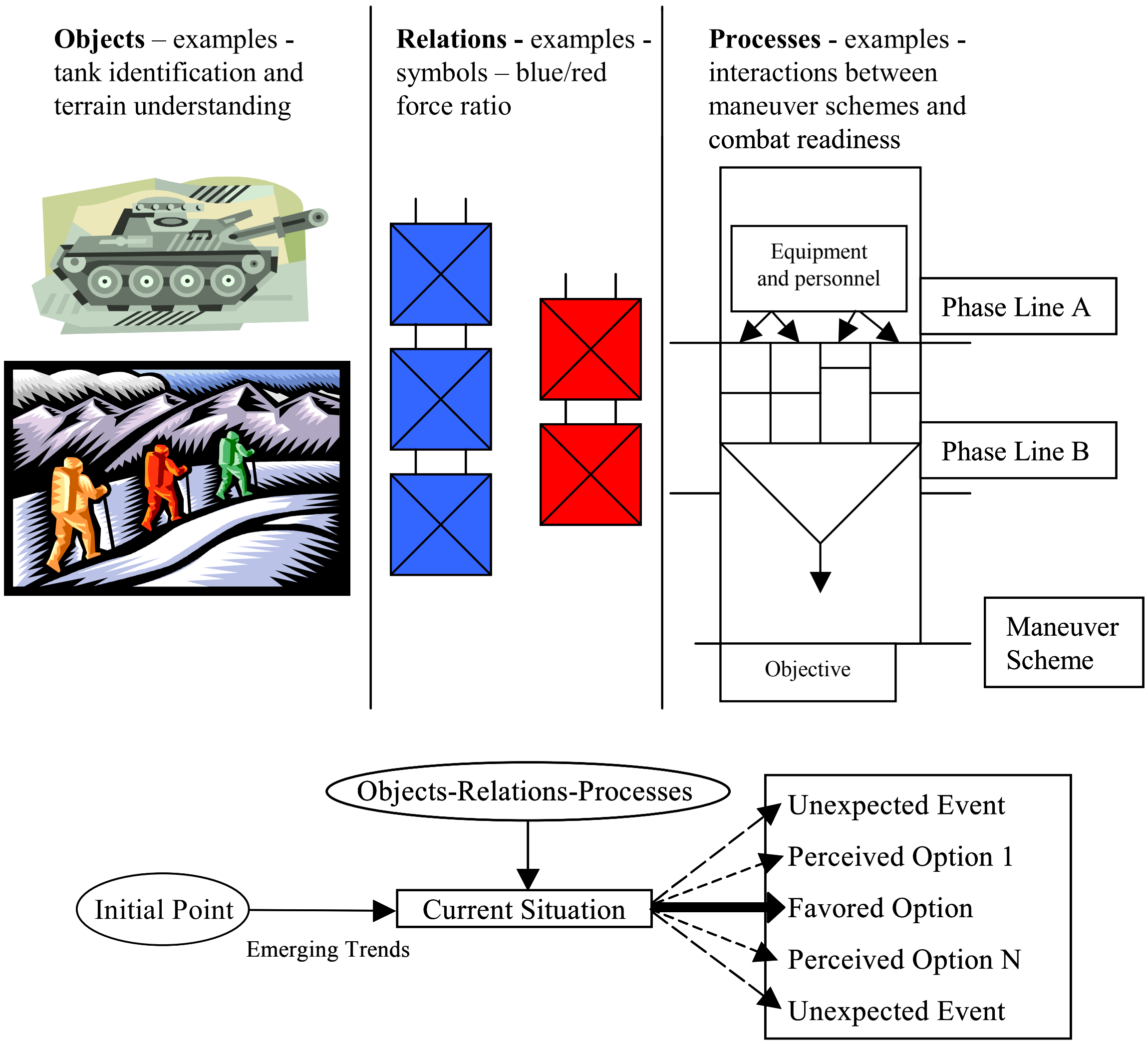

Figure 1: Model of the Visualization Process Indicating Cognitive Components for Understanding the Current Situation and Possible Decision States for Predictive Processes.

The second general component involves prediction and decision processes. 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 and decision processes than with immediate awareness. However, the type of decision space the commander must operate in is not straightforward. To illustrate the type of decision processes 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 in terms of the type of options that must be considered. The set of options pertaining to a particular decision type 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. However, many decision processes and much of the traditional decision research assumes that the decision-maker (DM) 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, there are decisions that 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). The paper will focus on the relationship between recent theories in decision-making and battlefield visualization. Specifically, the paper will review literature pertinent to designing modern combat visualization systems focusing on the military literature and the germane academic literature. The purpose will be two-fold: to develop visualization principles that enhance situation understanding and military decision-making and also to purpose a general architecture for future battle visualization systems.

FEATURE AND TERRAIN IDENTIFICATION

The history of warfare is replete with examples of the use of successful tactics depending on a thorough understanding of the local terrain. From Vicksburg to the Plains of Abraham to the African deserts, victory depended on utilization of terrain characteristics as part of the battle plan. Modern display technology allows the operator to see realistic views of the battlespace using multiple angles, altitudes, and dimensional options. The visualization issue is to determine how well combatants perform military tasks using different terrain viewing technologies. Dimensionality has been researched thoroughly in the aviation domain. Most of the research involves comparing two-dimensional (2-D) planar views with three-dimensional (3-D) rendered views while varying slant range and angle. The general finding is that there are as many tasks in which 3-D displays impede performance as those for which it enhances performance (Banks & Wickens, 1999). This is not surprising, projecting a 3-D representation on a 2-D surface result in space distortions, ambiguous locations along the line of sight, and foreshortening phenomena (St. John, Cowen, Smallman, & Oonk, 2001). For example, Banks and Wickens reported that in judging the relative positions of aircrafts most studies showed superior performance for 2-D formats indicating 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 as well as command and control and air operations (Eddy & Kribs, 1999).

Specific Army related experiments involved map tasks using experienced cadre from the U.S. Military Academy (USMA). In a series of experiments, the cadres performed various tactical map tasks using either 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 unaffected by view type, and line of sight (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 not in the frontal field of view even when this information was available on an insert; this was due, in part, 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 ignoring important peripheral information. Other research has generalized these findings to more abstract 3-D domains indicating that being immersed within the problem space helps in navigating through and remembering local features; whereas, if the task is to comprehend global features of this space then "gods-eye" exocentric views (views from outside the problem space) proved superior (McCormick, Wickens, Banks, & Yeh, 1998).

Navy researchers investigated the dimensionality issue (2-D versus 3-D) as well, finding very similar trends. 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, Cowen, Smallman, & Oonk, 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, understanding the terrain itself, its general topography and possible high and low spots, is enhanced by 3-D views whereas 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). 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 above. Based on operator performance for both the antenna-placing task and the terrain correspondence test, the two superior options were the time morph and the overlay displays. The time morph allowed the observer to replace a 2-D topographic map with a 3-D representation for a two 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 both 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).

The above 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). While these cues do 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 using motion and stereoscopic cues need to be carefully assessed against possible costs. In particular, costs associated with 3-D in general and alarming reports of simulation sickness in particular need to be investigated more thoroughly before widespread adoption of these technologies 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 observer's actions and the 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 using 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.

RELATIONS AMONG SYMBOLS: DISPLAYING TACTICAL INFORMATION

The military situation map and the use of standard symbols has 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. 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 where the applications are limited and the symbol set 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 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 using 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 NATO standards (NATO STANAG, 1990) have resulted in adding more human friendly symbology and the adoption of color standards. This in turn has influenced the U.S. 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 above. The introduction of digitized displays on television monitors has introduced its own problems. Many of the display surfaces are small causing the symbols to cover too much surface area occluding neighboring symbols and giving the commander only an approximate location of a particular unit.

Searching for target symbols is among the most primitive tasks the commander performs in order to use the situation map, and yet human performance on 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 evolved 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 spot 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”). 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., scanning for Taliban strongholds and Northern Alliance defense structures at the same time). 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).

Besides cognitive processes, there are other well known properties of the human perceptual system that enhance the ability to quickly identify and understand symbolic relationships. Coding schemes such as color are used frequently both to generalize among like symbols and discriminate among different classes. 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 where 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 the color codes to search across another coding dimension. Color attracts the user's attention and it interferes with his or her ability to filter out 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 situation awareness for standard military situation displays (Nugent, Keating, & Campbell, 1995; Van Orden, Divita, & Shim, 1993).

Future situation displays will be multi-media based and combine knowledge sources from varied commercial and military sources. The U.S. Navy at the Space and Naval Warfare 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 situation awareness, permit continuous updating of the military situation, and enhance the senior staff's ability to interact with supporting information systems. The concepts are still being developed but the current plans involve a notional prototype that captures the variegated information sources and live multimedia possibilities of the actual implementation. Imagery intelligence, smart knowledge portals, media from anywhere in the world, video of on-going 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 issues 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

DISPLAYING ABSTRACT PROCESSES

Ferren (1999), a design consultant for Disney's Imagineering Division, attacked the notion that information overload was inevitable for battlespace visualization displays if the battle process was represented in detail.

He argued 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 indicating humans' process information using holistic strategies rather than feature extraction processes. For example, Pomerantz, Sager, and Stoever (1977) found what they refereed to as a configural superiority effect. Their subject's task was to find simple physical features that were part of a larger configuration versus attempting to identify the same features in isolation. Counter-intuitively, adding information (being part of a configuration) decreased rather increased processing time. Apparently, individual features that were part of a configuration were perceived as patterns that formed emergent cues enhancing discrimination performance in contrast to the same cues in isolation. A similar linguistic phenomenon was discovered that showed improved recognition of a letter embedded in 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).

Cognitive engineering has adapted these principles based on emergent cues to develop a family of display concepts referred to as configural displays. The basic concept is that emergent cues depict intuitively higher order processes and possible interactions whereas these processes must be inferred from more traditional symbolic displays. Bennett and his colleagues (Bennett & Flach, 1992; Bennett, Toms, & Woods, 1993) used these concepts 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 under 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 using an integrated configural representation. Empirical results (using 16 officers at Ft. Huachuca) indicated that configural representations resulted in more effective situation 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 for understanding 3-D databases using cone representations, mathematical proximity functions, and various navigational and browsing utilities (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 using psychometric scaling techniques (Minkowski r-metric). Pathfinder and similar proximity functions can be used to display various cognitive relationships among data sources using map metaphors – similar objects are mapped in close proximity (McDonald & Schvanaveldt, 1988). Such techniques are not without their drawbacks; there are no unique cognitive distance functions (for example, during the cold war, the US and the Soviet Union were perceived as being close in terms of military power but distant in terms of political philosophy) and these functions may vary a great deal among experts. However, the military is starting 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.

VISUALIZATION AND DECISION PROCESSES

In the opening sections, three types of decision processes were mentioned. Most of the traditional research has focused on the second type of paradigm that is concerned with how humans perform compared to normative models of decision-making under uncertainty. This research is mainly concerned with identifying biases human evince in traditional decisions paradigms (Wickens & Hollands, 2000). Because many military situations are inherently uncertain, displaying risk and associated concepts such as uncertainty and utility are important issues for future combat systems. 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 but rather visualize concrete examples and use frequency judgments to assign uncertainty values. Thus, many of the decision biases are a result of the heuristic processes humans use to visualize the problem space (Johnson-Laird, Legrenzi, Girotti, 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. They investigated the effects of different visualization techniques for displaying uncertainty. The researchers found that displaying uncertainty in terms of concrete concepts such as the expected frequency of missiles that would "leak" (not be shot down by our defensive missiles) increased the operator's situation awareness compared to displaying the same information in terms of traditional probabilities (cf., Gigerenzer & Hoffrage, 1999). However, contrary to theoretical predictions (Wickens & Hollands, 2000) there was no evidence that framing the information in terms of possible losses as opposed to possible gains effected the operators decision to use reserve missiles. More recent research suggests that using configural display principles to combine uncertainty and target information will lead to improved decision-making compared to presenting the same information as separate indices (Barnes, McDermott, Hutchins, Gillan, & Rothrock, 2003).

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 non-existent trends anchoring their decisions both to first or last piece of information they received indicating individual differences as well as effects caused by slight changes in experimental conditions (Adelman & Bresnick, 1992; Adelman, Bresnick, Black, Freeman, & Sak, 1996). The National Missile Defense finding showed the same idiosyncratic behaviors even though the operators were given some training to help them understand that the sequence of hits and misses were independent. It is important to note, that considering trend information is not a sign of human irrationality. If for example, the missiles are not working according to specifications, then the operators should expect to see an inordinate number of misses early in the event sequence. The most likely means to overcome these trend biases would be to use more rigorous training methods than were possible in the short experiments reported here. Because in the final analysis visualization is a cognitive process, training soldiers to understand what they are seeing and the consequences of making the incorrect decision is as important as developing design principles. Too often, human engineering and training are treated as separate processes. Humans "visualize" what they expect to see and what they are trained to understand.

NATURAL DECISION-MAKING AND MENTAL SIMULATIONS

Whereas the previous reported research focused on the negative aspects of human decision-making and their heuristics 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 on 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 (COA) 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 analytic 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 decision tree) before choosing 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 (1999), 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 situation 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 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 rather the warfighter's ability to visualize a solution that is highly dependent on past experience and situation understanding. Kobus, Proctor, Bank, and Holste (2000) investigated 52 marines making COA decisions in a dynamically changing military situation under 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 situation assessment but made COA decisions both more accurately and rapidly than inexperienced marines. The experienced marines also were less affected by the degrees of uncertainty concerning the validity of the intelligence information they received. The advantage of experience seems to be that it allowed the officers to visualize an effective COA rapidly once enough knowledge was digested 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 rather 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 programmers. Experts were more adept at combining UNIX commands to solve novel programming problems than were programmers with less than two 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 those solving new problems require more than RPD processes. Humans must not only retrieve past memories but also must mix and match them to the current problem until a new solution emerges. The thought processes themselves tend to be "imagery" based and dependent on investigating the more likely solutions rather than assessing all possible solutions (Johnson-Laird, Legrenzi, Girotti, Legrenzi, & Caverni, 1999). The research results suggest that training using visualization techniques and role-playing in various military vignettes may aid in developing 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 the knowledge presentation should tell a story because a narrative presentation involves observers in a mental dialogue with the presentation material allowing them to fill in the blanks (Gershon & Page, 2001). Commanders do not need to be overwhelmed with details but rather 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 situation awareness or decision-making more than well-designed information displays (or more precisely under 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 lack of controls. A more measured approach would be to combine the strengths of controlled experiments with the realism of fieldwork using a hybrid research program (Barnes & Beevis, 2002). 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 warfighter 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.

VISUALIZING COMPLEX BATTLESPACES

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 being able to make probabilistic predictions has been challenged. Chaos theory, for example, assumes that minor events can radically alter the outcome of non-linear 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 either 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 warfighting 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 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 to interpret the streams of data that can overwhelm military capacity during critical situations. University of Illinois researchers supporting ARL have developed a series of decision support systems using Bayesian belief nets that can be used either 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 the probability structure must be created to account for each new battle situation. The advantage to these systems is that they handle large data streams and show inferential networks to the trained analyst that 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 combining important characteristics ("genes") to examine hundreds of thousands of options with surprisingly little computer overhead. FOX-GA is a genetic algorithm crafted at the University of Illinois that has been developed to generate and evaluate solutions to tactical problems in conventional warfare environments. The algorithm combined with a display portraying the results assisted surrogate commanders from Fort Leavenworth, Kansas by aiding them in visualizing twice as many new COAs when compared to 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 algorithm. The empirical question is whether the added complexity aid or hinder the analyst's ability to understand the military environment. ARL is in the process of investigating this issue by redesigning the basic algorithms underlying both the co-evolutionary and genetic approaches and generating visualization for non-traditional multiplayer, volatile situation such as anti-terrorist campaigns in Afghanistan (Barnes & Hillis, 2003). The results will be evaluated using experienced analyst's both 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).

An unfortunate mistake in attempting 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 attempting to capture combat complexity, the temptation to skip steps leads to disastrous field experiences because promising technologies are introduced prematurely (Barnes & Beevis, 2003). 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 attempting 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 using various predictive and assessment aids to enhance the commander's ability to operate in non-conventional 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 using realistic military vignettes with active duty officers as test subjects. This should lead to only the most promising concepts being tested during field trials and also the many minor problems with evolving concepts should be ironed out before being tested in these environments.

DESIGN PRINCIPLES AND A CONCEPTUALIZATION OF A FUTURE BATTLESPACE VISUALIZATION ARCHITECTURE

Visualization is a problem-solving stratagem that uses both 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 understanding 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 mangers 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 portraying 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 using techniques that aid the commander in visualizing not only the current situation but also to predict the most effective responses and future COAs. The most important human related design issues are:

- Projecting a 3-D representation on 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 aid in understanding 3-D views.
- Tactical information is displayed more effectively using 2-D planar formats whereas understanding the topography is best visualized using 3-D formats.
- There is a cognitive cost in switching between dimensionality and slant range views. Software utilities that allow the observer to "morph" (i.e., gradually shift software views) between slant range and dimensionality views of the same terrain have proven effective in laboratory experiments.
- In the future, warfighters may be able to visualize their military situation using VE. However, currently there are many costs associated with VE that must be overcome before the technology becomes used widely: motion sickness, perceptual illusions, time lags, and observer disorientations.
- 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 situation understanding displays using military symbol sets.
- New visualization techniques that are based on human pattern recognition abilities such as configural displays, proximity functions, and narrative formats 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 Commander's Critical Information Requirements (CCIR).

Prediction is an important but controversial component of the visualization process. The literature on biases suggests that the use of heuristics results in humans visualizing only a limited portion of the underlying problem space leading to sub-optimal decisions. The literature on 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 in the decision process information was presented, type of feedback, and how uncertainty was presented can have positive effects on performance. In contrast, cognitive biases such as complacency, anchoring effects, 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 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 both conventional and contingency operations. Methods to evaluate these technologies were also reviewed.

- Measures of uncertainty based on frequency counts offers a promising method for displaying uncertainty.
- Because cognitive biases are often based on rational expectations of real world processes, training using realistic simulations is necessary to allow the operator to visualize the outcome of these processes.
- Results from the naturalistic decision-making (NDM) literature suggest that simulations, role-playing, and storytelling exercises should improve the novice's ability to visualize solutions to novel situations.
- Visualization systems must be designed to keep the operator actively engaged and knowledgeable concerning 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 situation understanding. The visualization will be knowledge rich but data-sparse focusing on the decision elements that allows 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 indicating 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. There also needs to be a variety of tools that address specific problems and planning requirements. This suggests that the visualization architecture will be collaborative with each component having both private and public visualization aids. The components will be widely disbursed and 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 suggesting the importance of filters and knowledge management protocols in future systems. Principles based on using 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.

Figure 2 depicts not only the advantages but also some of the problems with future visualization architectures. The central display will portray an integrated panoramic view of the battlespace to give the commander an overall visualization of the unfolding battle situation. However, the many components discussed above will have to interrupt and compete for the commander's attention if the battle scene is to remain current and fluid. The problem will be to develop protocols so that the most important information is accessed but the various information sources do not overwhelm the commander. In our example, the knowledge integration updates coming from the battle staff have precedence. The video and imagery updates surface only if they meet the commander's criteria for critical information requirements. These videos are also carefully placed to complement the topography of the battle scene. Also included is an example where an outside source, perhaps an Air Force intelligence cell, spotted information that interrupts the commander's attention by centering the information and accompanying imagery in the middle of the commander's display. This would occur only if unexpected or particularly critical new information is obtained. Also in the example, the artificial intelligence (AI) system annotates this information and gives it additional context. The AI system may inform the commander that his original plan will be severely jeopardized based on this new information and the system may suggest alternative solutions based on the planning the commander has done previously with his staff during the rehearsal process. Again, this example underscores the main concern with future architectures: information technology must be orchestrated and tailored to the cognitive demands of the user. Information technology by itself will confuse rather than enlighten unless the proper recipe for information pull and information push is an integral part of future visualization architectural designs.

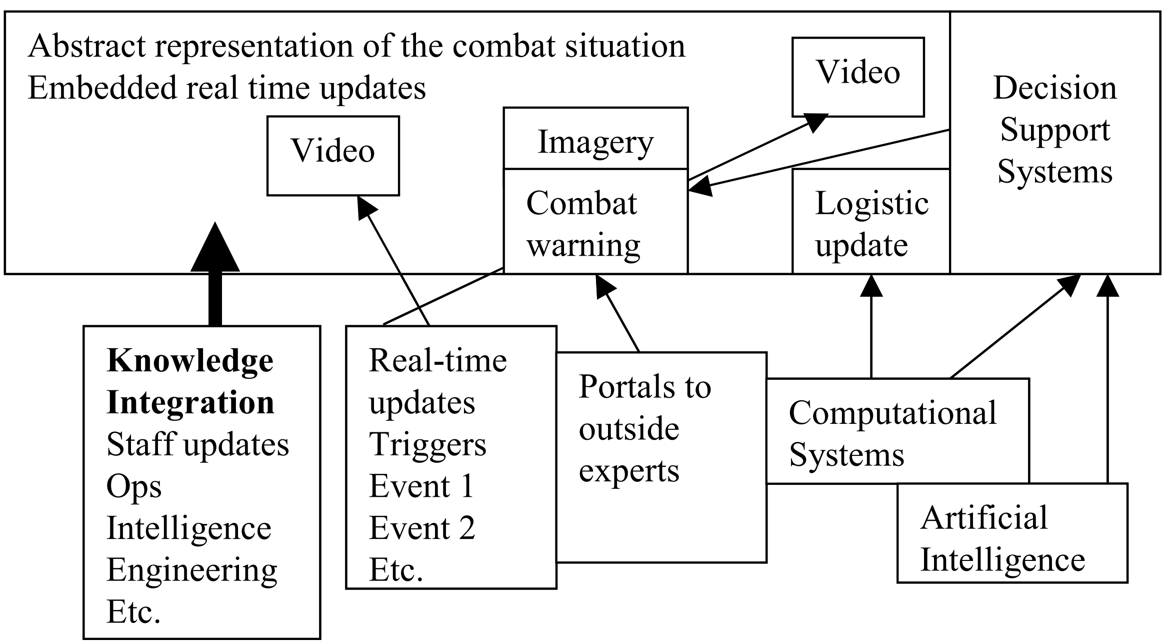

Figure 2: An Example of a Future Visualization Architecture Tailored to the Commander's Cognitive View of the Battlespace.

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