Ecological Interface Design for Military Command and Control

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Abstract: The authors use the cognitive systems engineering framework to design and evaluate an interface for military command and control. They discuss analytic tools and principles of this framework and provide concrete examples (e.g., work domain analyses for U.S. Army tactical operations at the battalion level). They also discuss principles of ecological interface design, including direct perception, direct manipulation, and the perception-action loop. The translation between work domain analyses and the specific characteristics of the interface are made explicit. The authors describe the potential for this interface to support effective decision making and problem solving, including links with naturalistic decision-making approaches. Evaluations of the interface have been positive and are described briefly. Actual or potential applications of this research include both specific interface design strategies for military command and control and general interface design principles for this category of work domain.

Introduction

The discipline of human factors and ergonomics emerged as a direct result of problems encountered in military systems during World War II. Advances in technology (e.g., radar and sonar) created new capabilities and opportunities. The benefits that these technologies produced were accompanied by occasional failures—some subtle, some spectacular. This brought the need to consider the higher-order "human-machine system" sharply into focus. Technology has advanced at an exponential rate since World War II; military contexts continue to be a breeding ground for technological innovation.

Cognitive systems engineering (CSE; Rasmussen, Pejtersen, & Goodstein, 1994) is a framework for system design that was originally conceived to deal with the demands presented by a different category of work domain: process control (e.g., power plants). CSE provides an overarching framework for design comprising concepts and analytic tools that can be used to guide system development and to leverage technology. The analytic tools (abstraction and aggregation hierarchies; decision ladder) provide templates for developing models of the domain constraints and decision-making activities within those constraints. The products of

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these analyses define the information content that is needed and the contexts in which this information will be used. The conceptual distinctions between skill-, rule-, and knowledge-based behaviors provide an efficient way to think about human constraints. These distinctions define the range of behaviors that need to be supported and the types of information that will be needed. Overall, CSE allows informed decisions to be made with regard to the interface resources (controls and displays) that are needed to support work in a domain.

A number of research programs applying the CSE approach to military systems have appeared in recent years (Burns, Bisantz, & Roth, 2004; Burns, Bryant, & Chalmers, 2005; Naikar, Moylan, & Pearce, 2006; Potter, Elm, Roth, Gualtieri, & Easter, 2002; Potter, Gualtieri, & Elm, 2003; Rasmussen, 1998). In this article, we describe another research program with that goal. The CSE approach was applied to the design of a command-and-control interface to support mobile Army decision makers during tactical operations. A virtual ecology was developed that allows Army decision makers to perceive critical situational factors directly (direct perception), as opposed to reasoning about them. This virtual ecology also allows Army decision makers to act directly on objects in the interface to execute control input (direct manipulation).

The overall goal was to transform the interaction requirements associated with decision making and problem solving during tactical operations from cognitive activities (requiring limited-capacity resources such as working memory) to perceptual-motor activities (using powerful and virtually unlimited perceptual resources). Concrete examples of the application of the CSE approach and the virtual ecology that it produced will be provided. We begin with a description of the work domain analyses that were performed.

Cognitive Systems Engineering

A fundamental premise of the CSE approach is that a detailed understanding of the work domain is crucial. A number of work domain analyses were conducted on Army tactical operations at the battalion level and below. These analyses were completed in cooperation with a large number of subject matter experts, including project investigators themselves (a colonel and two majors), active duty personnel (e.g., battalion commanders, intelligence officers, and Army ROTC cadre), and Army Research Laboratory personnel (participants in the Advanced Decision Architectures Collaborative Technology Alliance Consortium). Army publications were also consulted; commanders (brigade and battalion) were observed during large-scale field exercises. The overall results indicate that the scope, complexity, and severity of the challenges presented by this domain are staggering. This domain possesses all classical dimensions of complex, dynamic work domains, including complexity, inherent risk, dynamics, uncertainty, and more (e.g., an intelligent adversary). Specific findings will be organized in terms of the analytic tools of CSE: the abstraction hierarchy, the aggregation hierarchy, and the decision ladder.

Abstraction Hierarchy

The abstraction hierarchy is an analytic tool that is used to construct models of the work domain. It provides a template, typically with five levels, that can be used to categorize the critical characteristics (sometimes referred to as the *relational invariants, constraints, sources of regularity,* or *means-ends*) of a domain. The findings of our work domain analyses for military command and control during land-based tactical operations are listed in Figure 1.

Goals, Purposes, and Constraints. The top level of the abstraction hierarchy describes the goals, purposes, and constraints of the system. At this level, the system interacts with the external world. The description involves what the system is

Abstraction Hierarchy (Means-Ends Relations)	**Aggregation Hierarchy** (Whole-Part Relations)				
	High Grain of Resolution				Low Grain of Resolution
Goals, Purposes, and Constraints	Mission plans and objectives, collateral damage, public perception, etc.				
Priority Measures and Abstract Functions		Flow of resources, relative military force (force ratio), value of mission objectives vs. resource expenditure, probability of success / failure, etc.			
General Work Activities and Functions			Source, store, & sink. Tactical functions (command, control, maneuver, service support, air defense, intelligence, fire support, mobility & survivability), etc.		
Physical Activities in work, Physical Processes of Equipment				Number of vehicles (speed, maneuverability), weapons (power, range), and sensors (sensitivity, range); terrain (avenues of approach), etc.	
Appearance, Location, and Configuration of Material Objects					Physical location of units, physical characteristics of terrain and weather, etc.

Figure 1. Abstraction and aggregation hierarchies for Army tactical operations at the battalion echelon.

ultimately designed to accomplish (i.e., goals) and the usefulness of that system in terms of what it provides to the external world (i.e., purposes). It also describes restrictions on how the system may achieve those goals (i.e., constraints) that originate from the external world.

An Army battalion's purpose is to conduct tactical land-based warfare operations. General goals are set by the mission objectives that are obtained from the unit above (i.e., division/brigade). A commander and his or her staff will develop mission statements that further specify these goals; the mission statement is ultimately translated into more specific goals in the form of operation orders for lower-level units. An important component of these mission plans is the commander's intent (see more detailed description in the decision-making section that follows). Overall, the goal is to achieve mission objectives through efficient execution.

There are several outside, real-world constraints on the ways in which these goals should be accomplished. The resources of the battalion (e.g., equipment, personnel) are finite and valuable; their expenditure must be minimized. Tactical operations must comply with military laws (e.g., the Geneva Convention) that specify how these operations should be conducted (i.e., rules of engagement). Military personnel and the civil population must be protected to the extent possible; collateral damage should be minimized. Activities should comply with local laws and customs to the extent possible. Political and public opinion must be enhanced.

Priority Measures and Abstract Functions. The next level down in the hierarchy describes the intended proper functioning of the system. The description at this level involves the flow of resources (e.g., information, money, or resources) through the system in terms of a "general causal network" that is governed by physical or conventional laws. This can be thought of as a measure of internal consistency: When the system is functioning properly, domain resources do not just disappear inexplicably—they flow through the system in an orderly fashion.

The primary abstract function for tactical operations is the property of combat power (see also Potter et al., 2002). Combat power is the military "force" or potential that can be applied by a unit at a particular location and a particular point in time. Combat power is determined by a variety of factors, including tangible (e.g., the number and type of equipment, personnel, ammunition) and intangible (e.g., morale, leadership, initiative) resources. Combat power is a fluctuating commodity: Resources are continually flowing into (e.g., logistic reinforcements) and out of (e.g., expended in tactical engagements) the system.

The priority measures at this level include several important considerations and difficult trade-offs. How valuable or important is the strategic objective in terms of higher-order initiatives? How many of the finite resources must be expended to achieve that objective? What is the probability of success given the commitment of these resources?

General Work Activities and Functions. The middle level of the hierarchy provides a description of the general functions or activities that must be implemented by the system. These functions are independent of the physical mechanisms through which they are implemented. They are the fundamental defining aspects of the system; they are general descriptions of the capabilities of the system that allow it to do what it is supposed to do.

Descriptions at this level are extensive for a battalion, including maneuver (e.g., position forces, control terrain), fire support (field artillery, close air support, electronic warfare), air defense (protect from enemy aircraft and missile attacks), intelligence (collect information about enemy, weather, geography, etc.), mobility and survivability (eliminate obstacles impeding movement, establish protected fighting positions), and combat service support (arm, fuel, and fix equipment; logistics). Communication is a general function that cuts across all others. The work domain analyses reported here, however, focus on the general functions and activities of command and control. Command includes establishing commander intent, visualizing future battlefield states, formulating concepts of operations, assigning missions, ranking priorities, allocating resources, conducting risk assessments, monitoring current status, and anticipating change. Control includes computing requirements, defining limits, allocating means, monitoring status and performance, projecting change, and developing specific instructions from general guidance.

Physical Activities in Work, Physical Processes of Equipment. This is the highest level in the hierarchy that describes actual physical properties of the system. The description at this level comprises the physical characteristics or activities that are needed to implement the general functions of the system. At this level, control of the system is accomplished, measurement of system variables occurs, and physical functioning of the system is described (e.g., what is connected to what?).

The resources and activities of the battalion at this level are extensive. One critical type of information at this level includes the functional characteristics of the battlefield equipment. The primary vehicles for friendly forces are the Abrams tank and the Bradley fighting vehicle. Each of these two combat vehicles has functional specifications that include maximum speed, maximum traversable slope, cruising range, weapons (weapon type, number of weapons, destructive power, disruptive power, range), vulnerability/armor, radiation signatures, ammunition capacity, crew requirements, and so on. Other types of equipment include artillery, mortar, sensors, helicopters, communications, unmanned aerial vehicles (UAVs), and so forth. This equipment has important functional characteristics. The equipment of the enemy also possesses a similar set of functional characteristics; the differences between friendly and enemy forces in terms of these functional characteristics play an important role in tactical operations. Functional aspects of the terrain (e.g., avenues of approach) fall at this level.

Appearance, Location, and Configuration of Material Objects. The lowest level in the abstraction hierarchy provides information about the physical makeup of the system. What are the physical measurements of a system component? What is the color of a component? Where is the component located in space? What are the component's physical dimensions? The physical characteristics of the battlefield play an especially critical role in land-based tactical operations. A primary consideration is the battlefield terrain; this places a very stringent set of constraints on what can and cannot be done. For example, mountains and rivers are natural barriers inhibiting movement. Knowledge with regard to the physical location of friendly and enemy troops, equipment, weapons, and sensors is critical. Physical factors associated with the weather are also important (e.g., the presence of clouds can interfere with the provision of close air support).

Aggregation Hierarchy

A complementary analytic tool is the aggregation hierarchy, which is used to provide models of the "part-whole" structure of a domain: the different grains of resolution (from coarse to fine) that need to be considered. Unlike with the abstraction hierarchy, there is not a specific number of categories that are typically acceptable for the aggregation hierarchy. One dimension of aggregation in the battalion can be seen in Figure 1 (coarser levels on the left; finer levels on the right). A second dimension, not listed in Figure 1, is the hierarchical organizational structure of the battalion. A battalion is typically composed of three to six units that constitute lower-echelon levels (in this article, we assume four: Companies A, B, C, and D). Each company is further divided into three units at a lower echelon level (i.e., first, second, and third platoons). Finally, each platoon consists of a specific configuration of combat vehicles, resources, and personnel.

Summary. The abstraction and aggregation hierarchies provide templates for discovering the behavior-shaping constraints of a domain. The models that result provide alternative categories of information, relationships between categories, and alternative grains of resolution that a practitioner will need to consider when completing work in the domain. From a design perspective, these analytic tools provide a structured approach for a designer to determine the informational content that needs to be present in the displays.

Skill-, Rule-, and Knowledge-Based Behavior

The second fundamental set of system constraints is introduced by the cognitive agents who make decisions in the domain. Some of these constraints will arise from the specific skills and knowledge that characterize the targeted user population. For example, users of general information retrieval systems (e.g., the World Wide Web) will span the range of possible skills and knowledge. In contrast, commanders and leaders are reasonably homogeneous in terms of their specific knowledge: They are highly trained in the domain, the procedures to be followed, the tools at their disposal, and so forth. Another source of constraints includes general capabilities and limitations of the human cognitive agents. Rasmussen (1983) has characterized these general capabilities as three modes of behavior (or control): skill, rule, and knowledge based.

Skill-based behavior involves high-capacity sensory-motor activities that are executed without conscious control. Rule-based behavior involves the recognition of stereotypical situations and the execution of effective procedures that are based on prior experience. Knowledge-based behavior occurs when the agent is faced with situations that have not been encountered previously (i.e., problem solving). An interface needs to provide support for all three behavioral modes. However, the order of preference is skill-, then rule-, and finally knowledge-based behavior: Whenever possible, the goal is to allow the user to exercise powerful perception-action skills to the fullest extent possible. These points will be revisited specifically for the RAPTOR interface in later sections.

Military Decision-Making Process (or Analytic Process)

Classic explanations of decision making have viewed it as a highly analytic and cognitively intensive activity. Goals are reasonably well defined, and alternatives are carefully weighed and deliberately prioritized in terms of the probability of success. The work domain analyses indicated that this conceptualization corresponds very closely to the initial stages of planning for Army tactical operations. The Army refers to this as the military decision-making process (MDMP), and it has been the traditional focus within the military.

The MDMP will be described using the decision ladder, a CSE analytic tool that provides a template to model critical aspects of decision making in complex, dynamic domains (see Figure 2). The rectangular boxes in this diagram represent various types of activities, the circles represent states of knowledge that arise from these activities, and the solid arrows represent the transitions between activities and states of knowledge. As its name implies, the MDMP is a fairly lengthy process that occurs prior to the actual onset of a tactical engagement. Figure 2 provides a summary of the MDMP. The traditional labels for states and activities in the decision ladder (e.g., Rasmussen et al., 1994) have been refined to reflect the military domain (see Rasmussen, 1998). Note also that the dashed arrows in this figure do not represent transitions. Instead, they (and the associated text) provide more detailed annotations of the activities or states of knowledge in the decision ladder.

Situation Analysis. Decision making formally begins with a mission statement received from a higher echelon. An enormous amount of information is gathered before and during a tactical operation. The activities and products of the situation analysis phase (i.e., the left leg of the decision ladder in Figure 2) provide a necessary foundation for both effective initial planning and subsequent execution. The raw data available are staggering. For example, extremely detailed information about friendly combat resources (e.g., the inner temperature of an individual artillery gun's bore or the gallons of gas in an individual vehicle) can be obtained in near real time.

As has been noted previously (Woods, 1991), a fundamental problem is to convert these raw data into meaningful information. A partial listing of information products that are routinely prepared by Army personnel during data analysis/conditioning is shown in Figure 2. These products include the essential elements of friendly information (EEFI; how to prevent the enemy from seeing me); the friendly forces information requirements (FFIR; how I see myself); the

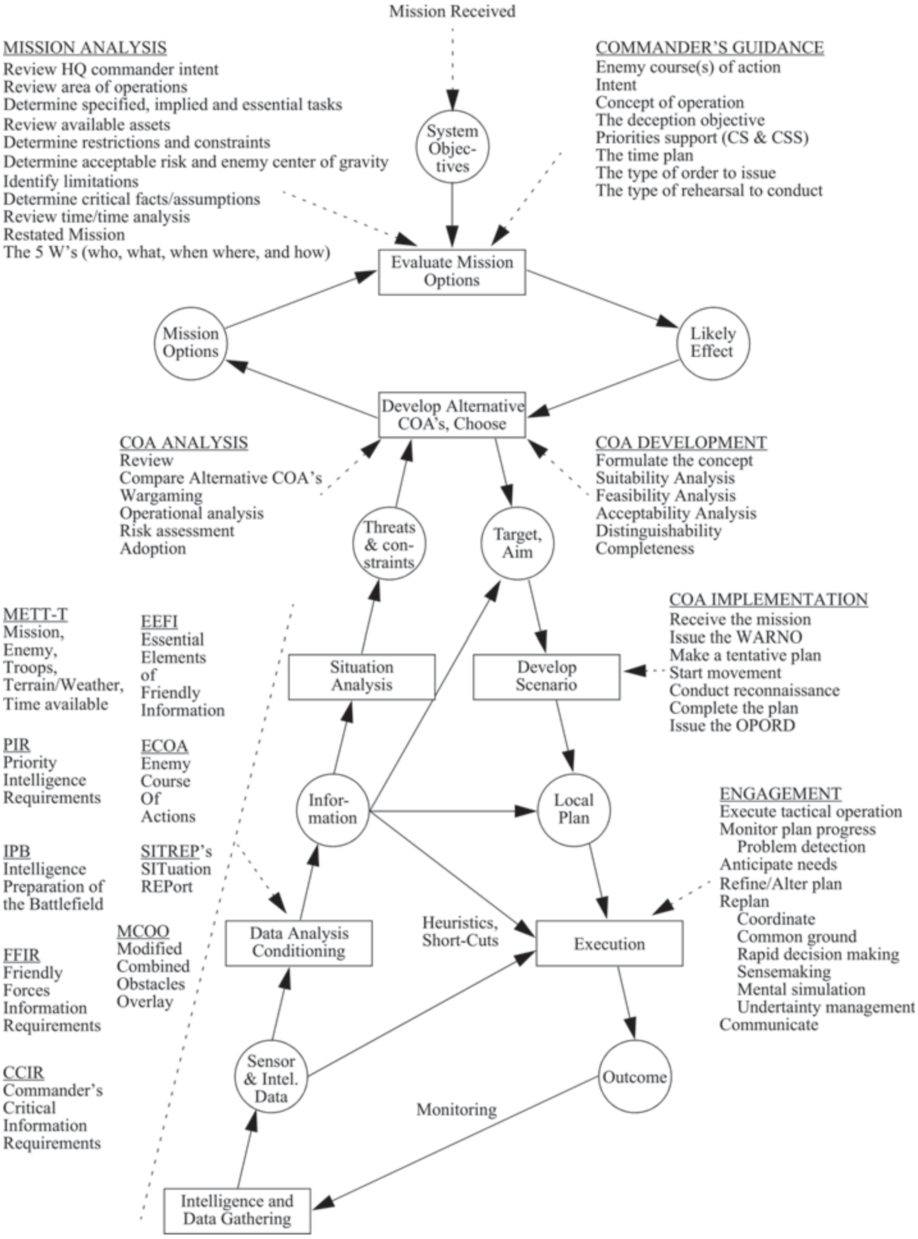


Figure 2. Decision ladder for Army tactical operations at the battalion echelon.

priority intelligence requirements (PIR; how I see the enemy); the commander's critical information requirements (CCIR; mission-related information needed by the commander to make decisions); the mission, enemy, troops, terrain/weather, and time available (METT-T; fundamental information about the engagement); the modified combined obstacles overlay (MCOO; terrain analysis); and intelligence preparation of the battlefield (IPB; a thorough analysis of enemy and terrain).

Develop Courses of Action. The commander and his or her staff consider these and many other factors in developing, evaluating, and choosing between alternative courses of action (COAs). The four primary activities (mission analysis, commander's guidance, COA development, and COA analysis) are illustrated at the top of the decision ladder in Figure 2. As the annotations suggest, these activities are quite extensive. Although they are listed in loose chronological order (early activities in the upper left and clockwise around to later activities), there will be multiple iterations in this loop when COAs are developed for a battalion.

It is important to emphasize that the MDMP is a deliberate and exhaustive exercise that closely mirrors classical explanations of decision making. The commander and his or her staff are making value judgments regarding the ultimate worth of the objective, the probability of success or failure, and the associated costs. They are working with incomplete and potentially misleading information. They must consider a number of factors (e.g., descriptions of the size of the force to be encountered, the various phases of the battle, objectives to be taken, movement across physical terrain, resources to be expended, and a final state to be achieved). Typically not one but several alternative COAs will be devised, accepted, and prioritized. Each COA can be fairly complex and has several preplanned variations (branches and sequels). Descriptions of the potential courses of action that could be taken by the enemy will also be developed, including the most likely and the most dangerous courses of action. In a very real sense, the goal of this overall activity is to consider all factors and available options and then to determine the COA that has the highest probability of success.

An important component of the mission statement is a section referred to as the "commander's intent" statement. The U.S. Army (1997) defines commander's intent in the following fashion:

> A clear, concise statement of what the force must do to succeed with respect to the enemy and the terrain and to the desired end state. It provides the link between the mission and the concept of operations by stating the key tasks that, along with the mission, are the basis for subordinates to exercise initiative when unanticipated opportunities arise or when the original concept of operations no longer applies. (pp. 1–34)

Klein (1994) collected and analyzed a total of 35 mission statements from Army training exercises at the brigade/battalion level. His analysis provides a script for effective commander's intent statements. There are seven categories of information in the script: (a) purpose of the mission (higher-level goals), (b) mission objective (image of the desired outcome), (c) plan sequence, (d) rationale for the plan, (e) key decisions, (f) antigoals, and (g) constraints and considerations.

Planning/Execution. The planning/execution phase of an engagement is initiated when the battalion commander and his or her staff issue a mission statement that is conveyed to lower-echelon leaders. This represents movement down the right leg of the decision ladder in Figure 2. The mission statement is complete in the sense that critical information is specified (see previous section). However, this mission statement (and the associated COA) should not be confused with a plan for the engagement. The guidance it contains is fairly general in nature and quite short (76–200 words; Klein, 1993). It is the responsibility of the lower-echelon commanders (in this case, the company commanders) to determine the details of how the mission gets accomplished. The lower-level commanders interpret the higher-level commander's intent and generate the specific details that are required to fill in the mission plan. This division of responsibility and authority provides an interesting contrast to that in military organizations where plans are implemented primarily in a top-down manner (i.e., the former Soviet Union).

Thus, the primary goal of the next stage of activity (develop scenario) is to implement the COA through the development of a mission plan. The resulting mission plans can be quite detailed and complex. Each course of action might include mission goals, detailed plans for lower-level units (e.g., routes of ingress and egress, activities, synchronization points), levels of enemy resistance expected, and acceptable levels of resource expenditures. The mission plan is then communicated to lower-level units (i.e., companies and platoons) for execution through an operation order (OPORD; see Figure 2).

Intuitive Decision Making (or Naturalistic Decision Making)

The next activity is to execute the plan (see the bottom of the right leg in Figure 2). There is a need, obviously, for decision making and problem solving at this stage. However, the deliberate, analytic processes used prior to an engagement (i.e., MDMP) are too time-consuming for use during the actual engagement. This is primarily due to the combination of extreme time pressure and uncertainty that occur (i.e., the "fog" of war). The Army recently has recognized a second category of decision making. Although initially referred to as the combat decision-making process, it is now referred to as "intuitive" decision making (U.S. Army, 2003).

This distinction parallels recent developments in the decision-making literature, generally referred to as naturalistic decision making. An excellent example is recognition primed decisions (RPDs; Klein, 1989a). In the first stage of RPD, experts are believed to use perceptual cues, in conjunction with their prior experience, to determine how prototypical a particular case is (e.g., how is this case similar, or dissimilar, to those that I have encountered before?). Thus, the emphasis is on recognition (as opposed to analytic decomposition). This is followed by a "situational assessment" phase that involves establishing goals, looking for critical perceptual cues, developing expectancies about how upcoming events should unfold, and identifying typical actions that have proved successful for similar situations in the past.

Contrary to the classical view of decision making, RPD views experts as satisficing, not optimizing. Experts do not generate and evaluate all possible solutions. Essentially, viable alternatives are considered in a serial fashion until one that has the potential to work is found. Before implementing a potential solution, experts will normally engage in a form of "mental simulation" where each step in the potential solution is checked for its potential to succeed or fail. Thus, experts generate and evaluate only a few "good" alternative solutions and are looking for the first solution that has a good chance of working.

The goal at the onset of a tactical engagement will be to complete the mission according to the plan (or set of plans) that was developed. During the execution phase, the primary locus of control shifts from higher-level commanders to lower-level leaders and troops who are fighting the battle. Ultimately, lower-level leaders will base their actions on their understanding of the current battlefield situation and the commander's intent, as expressed in the mission's operation order. Plans often need to be revised, especially when there is an intelligent adversary. In fact, changes to a mission plan are probably the norm rather than the exception. A change may be as simple as a minor modification of the current COA. A minor modification is defined as one in which the alterations to the plan involve no changes in goal priorities and no additional changes in coordination between units. These minor modifications will occur spontaneously.

In other cases, entirely new mission plans must be developed. We will refer to this as *replanning*. Under these circumstances, leaders might well be trying to determine what the appropriate goal should be, given the current context. In essence, commanders are forced to reenter the problem-solving activities at the top of the decision ladder, where values and priorities must be considered and traded off and new courses of action must be determined. As mentioned previously, it is very likely that commanders will not be searching for an optimal solution but rather will be considering a very small number of potential solutions that could work.

It is also important to note that replanning efforts may not always be needed as a result of the failure of a current plan or the lack of appropriate branches or sequels. In fact, replanning might be needed because the plan is succeeding far better than expected: New opportunities are recognized, but substantial changes in the original plans are needed to seize them. A Warfighter exercise at Ft. Drum provided a particularly interesting example along these lines: A new COA was needed for friendly forces because the original plan was working too well (enemy resistance was far less than expected) as opposed to failing. In this case, the original mission goals and plans were changed to seize an opportunity that was presented. The new COA maximized their combat power, took advantage of their earlier successes, and allowed them to take an alternative objective quickly.

The final observation regarding replanning is that this is a course of events that commanders do not undertake lightly. If replanning is required, that means that the initial understanding of the ways in which the tactical engagement would unfold was incorrect. A commander and his or her staff now need to "go back to the drawing board" to try to do a better job than the first time around. This will be somewhat more difficult because there will be greater time pressure. A decision to issue new operations orders also entails a great deal of overhead activity (e.g., communicating new mission plans to all units).

Ecological Interface Design

The work domain analyses described in the previous section form the foundation for effective interface design. *Ecological interface design* (EID; Rasmussen & Vicente, 1990; Vicente & Rasmussen, 1990) is a term that has been used to describe the translation of these findings into specific designs. As its name implies, EID is inspired by Gibson's (e.g., Gibson, 1966) work. Rasmussen et al. (1994) state that "in Gibson's terms, the designer must create a virtual ecology, which maps the relational invariants [i.e., the behavior-shaping constraints] of the work system onto the interface in such a way that the user can read the relevant affordances for actions" (p. 129). This will be referred to as *direct perception.*

Gibson (e.g., 1966) also emphasized that successful interaction with the natural environment depends on a dynamic and continuous "perception-action loop." This translates into an additional component of ecological interfaces: Resources should be provided that allow users to utilize "high-capacity sensori-motor" skills (Rasmussen, 1986, p. 112) to execute actions. This corresponds to the familiar concept of *direct manipulation.*

Direct perception, direct manipulation, and an intact perception-action loop are principles that form the foundation of effective interface design. The implementation of these three principles (i.e., the design strategy) will depend on the general characteristics of the underlying work domain. Rasmussen and his colleagues (1994) have developed a continuum for categorizing domains. At one end of a continuum are domains in which the unfolding events arise from the physical structure and functionality of the system itself (e.g., process control). In these "law-driven" domains, highly trained and frequent users respond to demands that are created by the domain. At the opposite end of the continuum are "intent-driven" domains, where the unfolding events arise from the user's intentions, goals, and needs (e.g., information search and retrieval). Users typically interact with these systems on a more casual basis, and their skills, training, and knowledge are more heterogeneous.

The interface design strategy that will be successful for a particular domain is determined by the domain's location on this continuum. The CSE literature has provided excellent examples of design strategies for domains that fall at either end of the continuum. The most effective design strategy for law-driven domains is to develop analogical, geometrical forms that reflect the constraints of the domain (e.g., Vicente, 1991). The most effective design strategy for intent-driven domains is to develop spatial metaphors (e.g., the desktop metaphor) that relate interaction requirements to more familiar concepts and activities (e.g., Pejtersen, 1992). The design strategy (or perhaps strategies) appropriate for domains that fall in the middle of this continuum is less clear. These domains (e.g., hospitals, offices, manufacturing plants; Rasmussen et al., 1994) are characterized by the presence of both law-driven constraints and intent-driven constraints.

Military command and control is a good example of this domain category. Law-driven constraints arise from an extensive technological core (e.g., weaponry, sensors, communications). However, there are also intent-driven constraints. The difference in intentions between friendly and enemy forces is by far the most obvious example. However, intent also plays a substantial role within a military organization. For example, during tactical engagements, lower-level leaders base their actions on an interpretation of the commander's intent statement in mission orders (e.g., Klein, 1994). The RAPTOR (representation aiding portrayal of tactical operations resources) interface represents one solution to the challenges presented by this category of domain. An overview of this interface is provided in Figure 3. The discussion of this interface will be organized according to the principles of direct perception and direct manipulation.

Direct Perception

The fundamental goal in achieving direct perception is to develop graphical representations that provide effective mappings between the constraints of the work domain and the constraints of the perceiver. One dimension of this mapping is the extent to which information from all levels of the abstraction hierarchy are represented in the displays (i.e., does the virtual ecology provide the information that is needed to make effective decisions?). A second dimension of this mapping is the extent to which the displays encode this information using a visual currency (e.g., emergent features or metaphors) that can be used effectively (i.e., can the agent pick up the information that has been encoded into the representation?).

Creating effective graphical representations for a domain is a substantial design challenge that requires consideration of visual forms, domain constraints, processing capabilities, and limitations of the human visual system, creativity, and art. The major displays in the RAPTOR interface will be described now, beginning with additional details of the work domain analysis that are relevant to its design.

Friendly Combat Resources Display

The work domain analyses indicated that one of the primary requirements for effective tactical decision making is to monitor the current level of friendly combat resources. A unit's primary resources are its tanks and Bradleys, as well as the ammunition, fuel, and personnel that are required to operate them. A single graphical format was developed to represent these resources at each echelon level. A primary consideration in the design of this format is that the individual combat parameters are essentially independent: Changes in their values can be correlated (e.g., fuel and ammunition expenditures in an offensive scenario) but do not necessarily have to be (e.g., ammunition, but not fuel, in a defensive scenario). Thus, independent graphical representations of each parameter (e.g., bar graphs) are the proper design choice, as opposed to a combined representation (e.g., a single geometric form for all five variables). See Bennett and Flach (1992), Bennett and Fritz (2005), and Bennett, Nagy, and Flach (2006) for a more detailed discussion of these and related issues.

The graphical format for friendly combat resources is illustrated at the company level in Figure 4. The primary representational format consists of horizontal, analogical bar graphs (one for each combat resource). The base of each bar graph is located

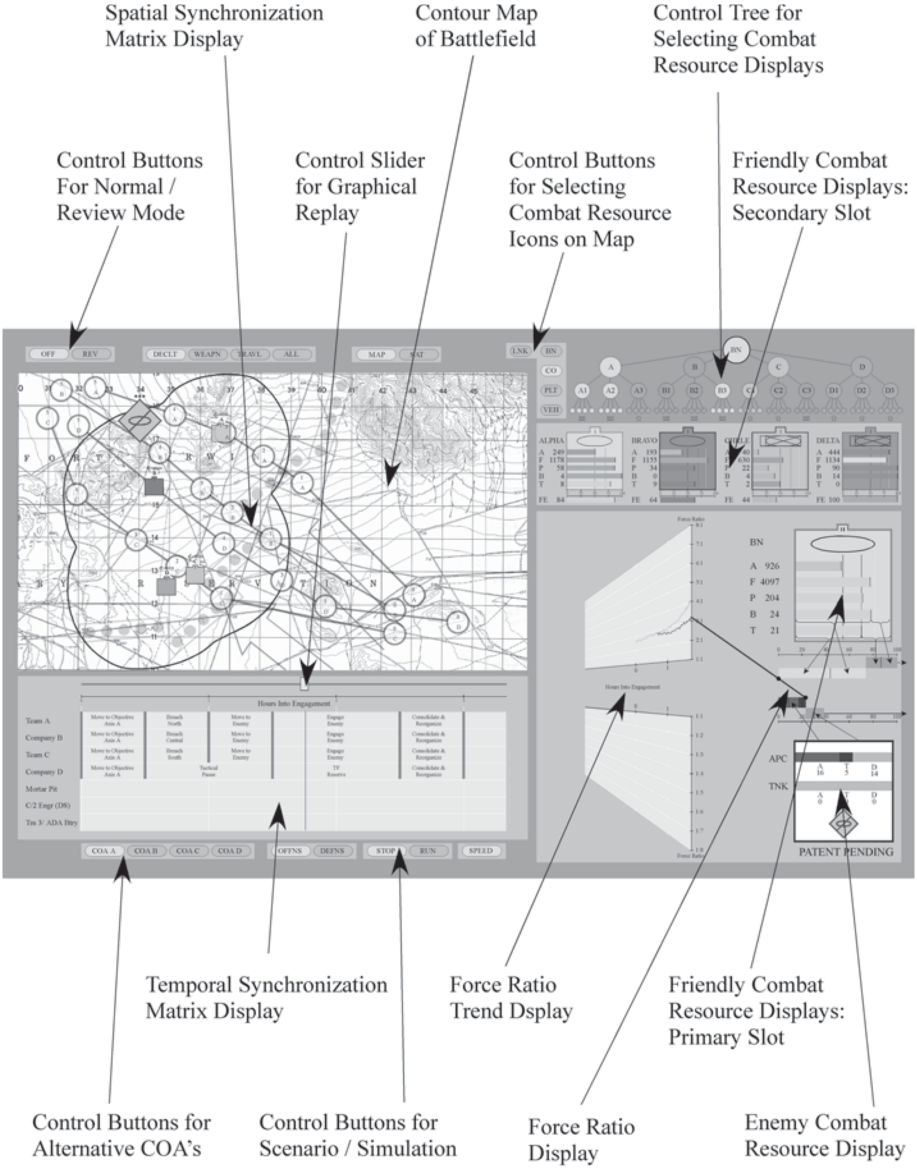


Figure 3. Overview of the RAPTOR interface.

on the left edge (0%); the horizontal extent of the bar graph (emphasized by a short vertical line—the analog percentage indicator) provides an analog indication of the percentage for that resource (100% is located on the right edge). These bar graphs are also color coded (green, amber, red, and black) to represent the categorical status of the associated resource. Each color corresponds to a category of resource percentages (100%–85%, 84%–70%, 69%–50%, and ≤49%, respectively) that are defined

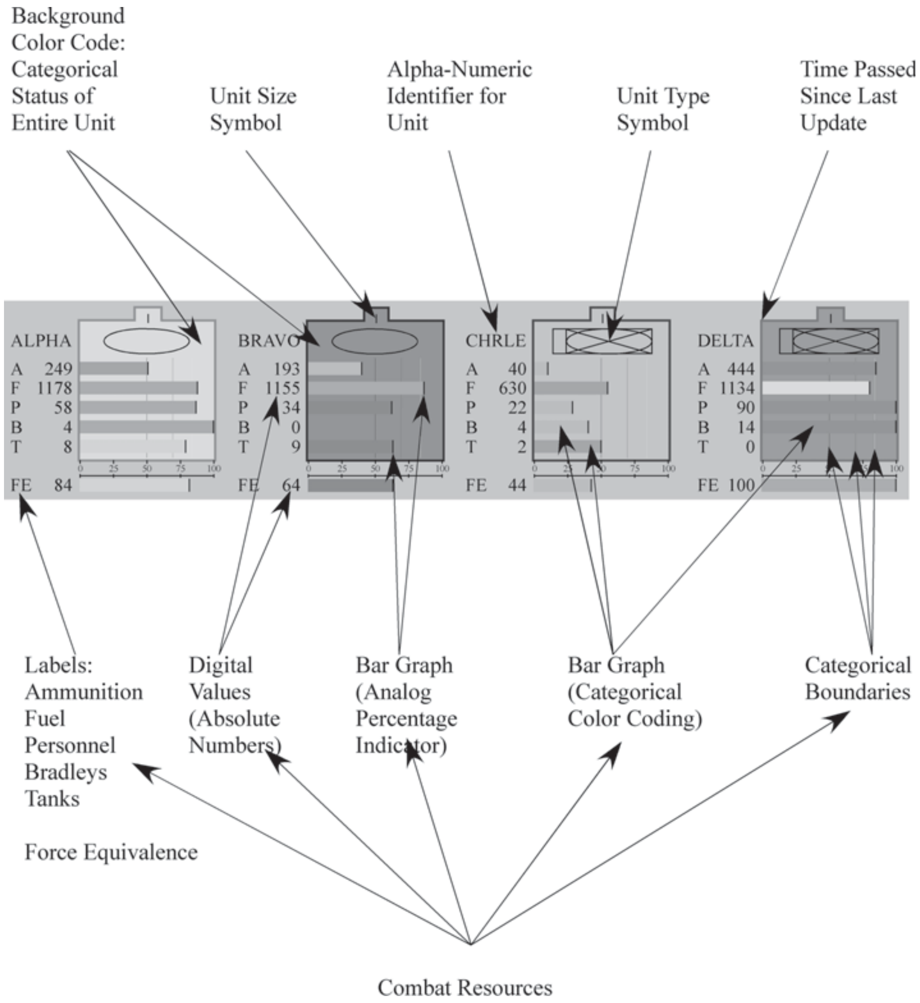


Figure 4. Friendly combat resources display.

by Army convention. Note that analog graphical representations of the boundaries between these categories are also represented in the display. For example, the boundary between red and black categorical status is represented by the thin vertical line located at 50% and extending behind the bar graphs.

Several other representational conventions were also used in the display. The categorical status of the unit as a whole is represented by the background color code of the entire display (e.g., amber for Company A in Figure 4). Alpha-numeric representations were used to present exact values for combat resources. These are the single-character labels (e.g., "T" for tanks) and the digital values that appear on the left side of the display. The digital values provide absolute numbers, not percentages. Additional information regarding the unit's name, size, type, and the amount of time since the last update of information in the display is also incorporated.

In summary, three kinds of encoding conventions are used in this display: categorical, analog, and alphanumeric. Together, these representations provide commanders and leaders with support for a variety of informational needs. The categorical color coding is probably the most salient information in the display; it supports commanders in "spot-checking" or loosely monitoring the overall status of the unit or a combat parameter. The analog bar graphs provide more precise representations of each combat resource. More important, they provide analog graphical representations that are particularly useful in determining patterns and relationships (e.g., the value of parameters relative to each other or to boundaries). Finally, the digital values provide support when precise values are needed (e.g., when providing other personnel with "slant" summary reports).

Enemy Combat Resources Display

The domain analyses revealed that estimates of enemy combat resources are also needed. These estimates are obtained from a variety of sources (e.g., satellite imagery, UAVs/surveillance aircraft, spotters, battlefield reports, intelligence estimates). There is, of course, a higher degree of uncertainty in these estimates, relative to those for friendly combat resources. Army intelligence officers were consulted to determine exactly what kind and what resolution of information should be incorporated into an enemy combat resources display. They indicated that the primary concern was the status of enemy combat vehicles (i.e., tanks and personnel carriers). Furthermore, the grain of resolution was fairly coarse, involving three different categories of information. The first category comprises enemy vehicles that have been observed and verified as being alive (A) and dangerous. The second category comprises enemy vehicles that have been engaged and disabled (D). The third category comprises template (T) enemy vehicles: those that are likely to be in the area of engagement (based on intelligence analyses) but have not yet been observed.

The enemy combat resources display represents this information using the same general kinds of representations as in the friendly combat resources display: analogical, categorical, and digital values. The primary representation format is a horizontal contribution (or stacked) bar graph (see Figure 5). Each segment of a bar graph represents a portion of the combined resources. Consider the top contribution bar graph, which represents information regarding enemy personnel carriers. The left, middle, and right bar graph segments provide an analog representation of the percentage of vehicles that are alive, template, and disabled, respectively. They are also color coded (bright red, dull red, and gray, respectively). The analog graphics are also annotated with digital values that provide exact values of the number of vehicles in each category (and assorted other information). The bottom contribution bar graph represents tanks. The lack of red segments indicates that all tanks have been disabled.

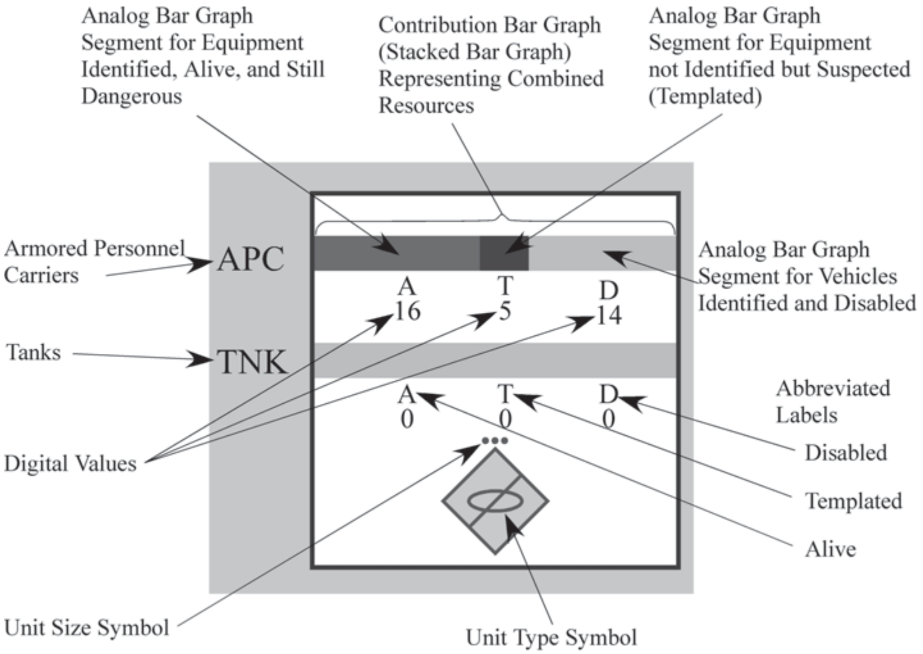


Figure 5. Enemy combat resources display.

Force Ratio Display

The domain analyses revealed that a fundamental consideration in tactical operations is *force ratio*: the relative amount of combat power that exists between two opposing forces at any point in time. Force ratio is considered throughout a tactical operation. It is a primary consideration during the planning stages. For example, Army doctrine dictates that a force ratio of six to one or better is needed for a friendly unit considering an offensive attack against a well-fortified and dug-in enemy. Force ratio is also a primary consideration during a tactical engagement. Commanders and their staff develop detailed estimates of how force ratio should change during the course of an engagement. Commanders monitor force ratio to assess progress (or a lack of progress) toward tactical goals during an engagement. Thus, force ratio is a critical piece of information that testifies with regard to decisions to initiate, continue, alter (e.g., choose another course of action), or abort a mission.

A simplified estimate of force ratio was devised in concert with Army subject matter experts. As described earlier, combat power is broadly defined and includes both tangible and intangible factors. The primary tangible contributors to combat power (tanks and armored personnel carriers) were used to compute estimates of force and force ratio. Numerical estimates of the military force of individual friendly and enemy combat vehicles were obtained (U.S. Army, 1999a). Military force for a unit was estimated by taking the number of operable vehicles, multiplying by the appropriate constant, and summing across the two vehicle types. This numerical estimate will be referred to as force equivalence, primarily to retain the distinction between it and the broader concept of power. An estimate of the force ratio between two opposing forces was obtained by dividing the larger of the two force equivalences by the smaller. A future goal is to devise more comprehensive estimations of force equivalence (including, for example, artillery, aviation, and morale).

The force ratio display is illustrated in Figure 6, on the right. The primary graphical format is the contribution bar graph. There are two of these, aligned on

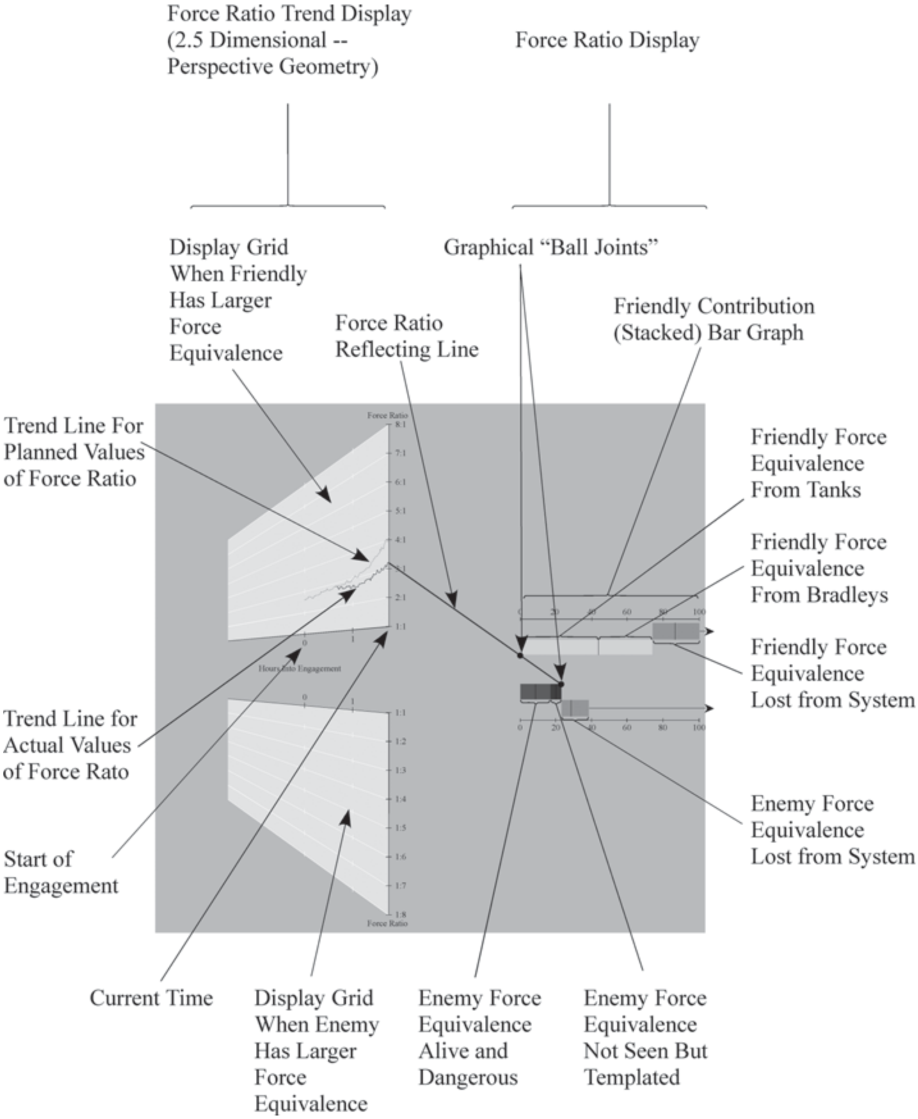


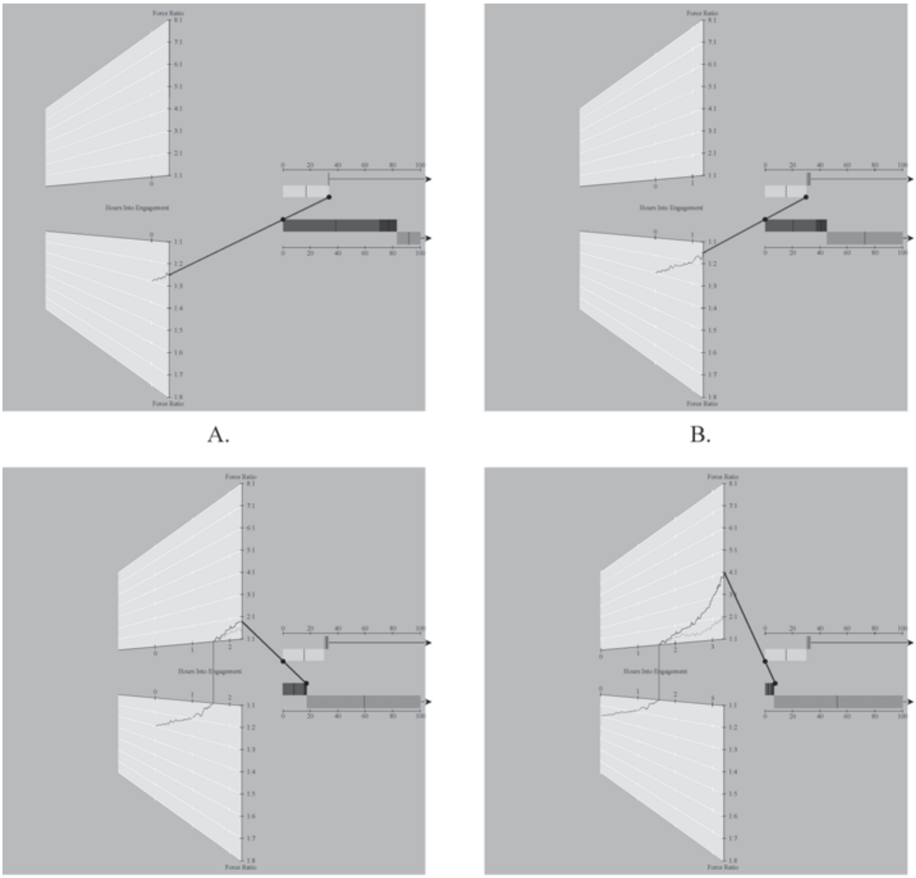
Figure 6. Force ratio and force ratio trend displays.

the left-hand side with the origin of the axes; one is for friendly force equivalence (top), and one is for enemy force equivalence (bottom). The friendly contribution bar graph contains two segments on the left (tanks and Bradleys, respectively). These segments represent the force equivalence of current, available resources and are color coded according to the resource's categorical status. The two segments on the right (offset vertically and upward) represent disabled tanks and Bradleys (i.e., the military force has exited the system). The enemy contribution bar graph has four segments on the left: enemy tanks and personnel carriers that are alive (left two segments) and enemy tanks and personnel carriers that are in the template (right two segments). The two segments on the right (lower, offset) represent disabled vehicles.

Unlike the two previous displays (friendly and enemy resources), the two variables (force equivalence) being represented in this display interact in a lawful fashion to define a higher-order property (force ratio). This relationship is emphasized by the force ratio reflecting line, which connects the force ratio and the force ratio trend displays in Figure 6. This line is connected to the two bar graphs, as emphasized by the graphical "ball joints" (Vicente, 1991). The reflecting line intersects the scale of the force ratio trend display at the exact spot that corresponds to the current value of the force ratio. This is ensured by the following geometrical properties. Changes in the horizontal extent of the smaller bar graph (the enemy bar graph in Figure 6) push (or pull) the endpoint of the line, thereby changing its orientation. Changes in the horizontal extent of the larger bar graph (the friendly bar graph in Figure 6) push (or pull) the force ratio trend display (the left graph in Figure 6) toward the force ratio display.

This is an example of a "configural" display that produces "emergent features." Emergent features are higher-order visual properties that arise from the interaction of lower-level graphical elements (Bennett & Flach, 1992; Bennett & Fritz, 2005; Bennett et al., 2006). The most salient emergent feature produced by the force ratio display is the orientation of the force ratio connecting line (see Figure 6), which dynamically changes as a function of the relationship between friendly and enemy force equivalence. Emergent features can be very salient to the observer; they can provide very powerful decision support when mapped properly into the domain's semantics. This is the appropriate design choice when variables interact in a lawful fashion, as is the case for the force ratio display.

An example of the dynamic behavior of this display over time is provided in Figure 7. A fundamentally different configuration is illustrated. The enemy force equivalence is initially greater than the friendly force equivalence (see Figure 7a). Therefore, the force reflecting line is now anchored at the bottom right corner of the friendly bar graph and the upper left corner of the enemy bar graph; the distance from the force ratio and the trend display is equivalent to the length of the enemy bar graph (alive and template segments). Figure 7b illustrates the effect of substantial losses incurred by the enemy approximately 1 hr later. The enemy force ratio is substantially smaller but still greater than the friendly force ratio; the force ratio trend display has been drawn successively closer as a result.



A.

B.

C.

D.

Figure 7. Force ratio and force ratio trend displays over time.

The enemy losses continue to be substantial over the next hour, as illustrated in Figure 7c. The force ratio has tipped toward the friendly side. This is reflected in the orientation of the connection line: It is now anchored on the upper right of the enemy bar graph and passes through the lower left of the friendly bar graph. The distance from the force ratio trend display to the force ratio display is determined by the length of the friendly bar graph. The enemy losses continue in Figure 7d; the diminishing length of the enemy force equivalence bar graph pulls the orientation of the connecting line upward.

Force Ratio Trend Display

The force ratio trend display (left side of Figures 6 and 7) illustrates the actual and planned values of the force ratio over time, as illustrated in the previous example. A few additional points are in order. The display is scaled using the laws of perspective geometry (toward a vanishing point to the left). This is a variation of the time tunnel design technique (Bennett, Payne, & Walters, 2005; Bennett & Zimmerman, 2001; Hansen, 1995) that produces substantial savings in display real estate. Trend lines for both actual value and planned values of the force ratio can be plotted on the display grids. These trend lines provide several emergent features that should be useful to commanders. The trend lines are an analog representation of the values of the planned and actual force ratios over time. This historical trace specifies both the direction and the rate of change for the force ratio across the engagement. The degree of spatial separation between the planned and actual trend lines provides an analog property that visually specifies discrepancy from the plan (an important consideration identified in the domain analyses). This visual property could serve as an early warning that alternative courses of action need to be considered or replanning needs to be initiated.

Spatial Synchronization Matrix Display

The domain analyses revealed that there are substantial requirements to coordinate and synchronize the activities of the various units. The land-based nature of Army tactical operations places a premium on spatial considerations: The physical characteristics of the terrain (e.g., mountains) place critical constraints on what can and cannot be done. The location of friendly and enemy forces with respect to critical features of the battlefield terrain is an extremely important consideration. Was the enemy initially found in the physical location that intelligence sources had indicated? Are friendly forces in appropriate physical locations relative to the enemy? Are friendly forces arrayed in appropriate physical locations relative to one another? What potential actions are supported by terrain features? What potential actions are limited by terrain features?

The spatial synchronization matrix display illustrates a number of spatial constraints (see Figure 8) that are critical to land-based tactical operations. The primary component is a contour map providing an analog spatial representation of the physical characteristics of the battlefield terrain (i.e., the contour lines representing changes in elevation). Although not pictured, the capability to view this terrain via satellite imagery (and to toggle between views) also has been incorporated, along with explicit representations of key spatial synchronization requirements. A synchronization point is a location in space (i.e., a physical location on the battlefield) that a friendly unit must occupy (usually at a particular point in time; see the complementary discussion that follows).

A synchronization point is represented in the display by a labeled circle. The letter inside the circle indicates the unit; the number refers to successive synchronization points for that unit. The planned spatial route for each unit in the mission is represented by the activity segments (lines) that connect the synchronization points. Thus, the spatial synchronization requirements are situated in the context of the battlefield using analog graphical representations. Additional spatial information in the display includes transparent icons representing friendly unit locations and arcs representing primary weapons envelopes, obstacles, and enemy units and fortifications.

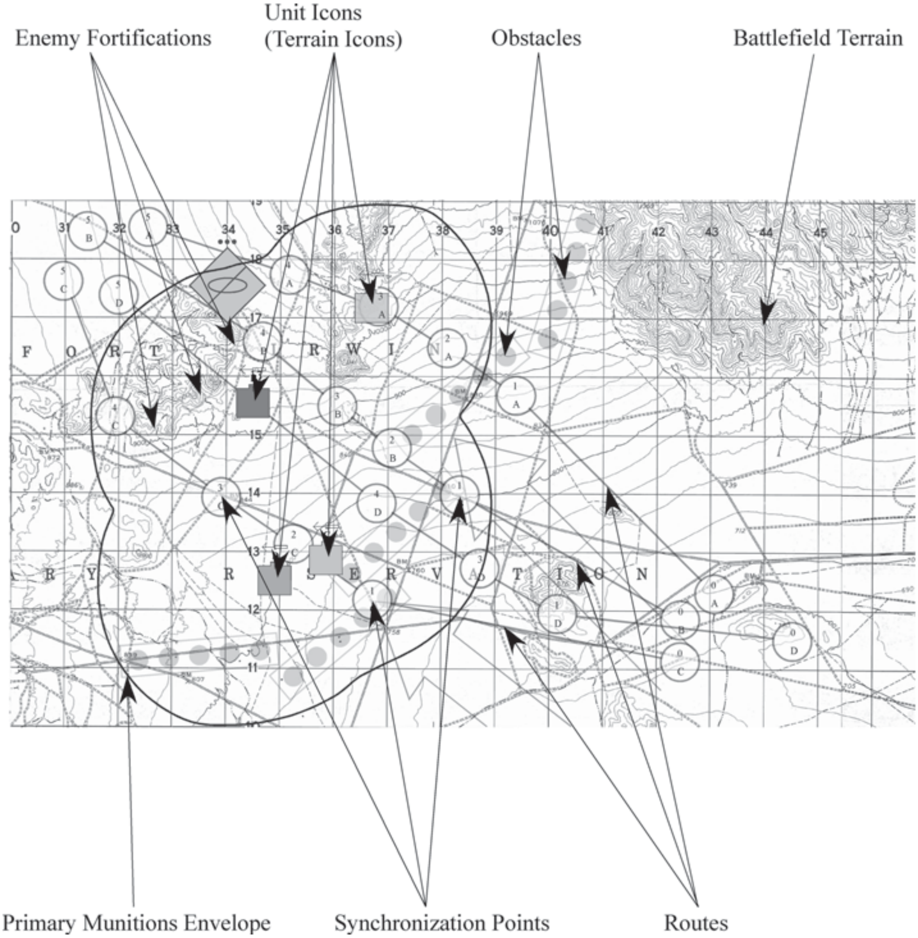


Figure 8. Spatial synchronization matrix display.

Temporal Synchronization Matrix Display

There is also a need to coordinate the activities of the various units across time. These activities will have different initiation times and will require different amounts of time for their completion. A number of critical temporal synchronization points (e.g., movement to a geographical point by a specific time; completion of a coordinated set of activities by multiple units at a specific point in time) are typically included in a plan. These temporal considerations become extremely important when critical events require that these activities culminate simultaneously (e.g., breaching fortifications or obstacles).

The temporal synchronization display explicitly illustrates some of the temporal synchronization requirements that were identified (see Figure 9a). Time is

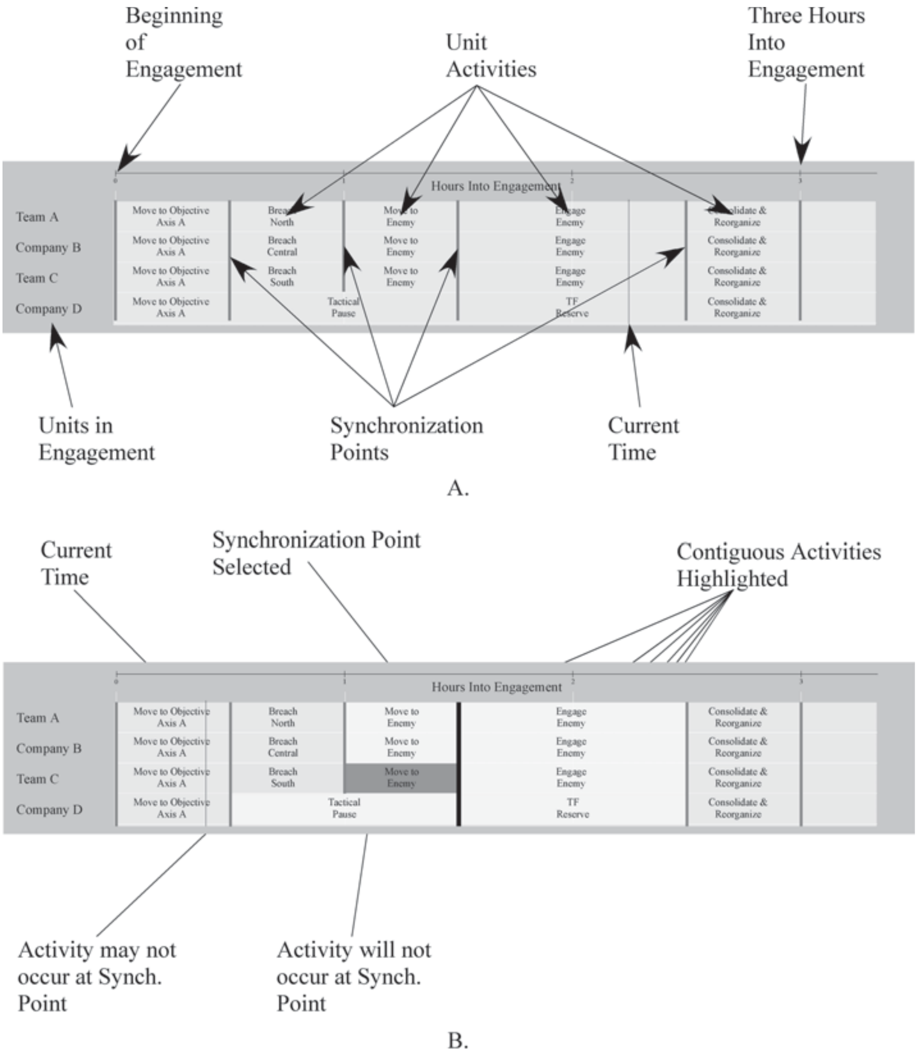


Figure 9. Temporal synchronization matrix display.

represented in the *x*-axis of the matrix, ranging from the initiation of the engagement (0) to a point 3 hr later (3). The various units involved in the tactical operation are represented along the *y*-axis of the matrix (e.g., Company B). A row in the matrix graphically illustrates the sequence of activities that are planned for each unit (e.g., Breach North) and an analog representation of the amount of time that each activity should take (the horizontal size of the cell). In addition, temporal synchronization points (i.e., the points in time where there is a requirement to coordinate the activities of these units) are illustrated graphically by the thick gray lines that run vertically through the display. The present time in the engagement is illustrated by the thin vertical line.

Visual changes in the display indicate the status of various activities with regard to their associated temporal synchronization requirements. For example, in Figure 9b, Team C's activity of "Breach South" has been highlighted by a change of color (yellow in the actual display). This indicates that this unit is in danger of not completing the activity on time. Similarly, the next activity for the same unit ("Move to Enemy") has also been highlighted (red in the actual display). This indicates that the unit will not complete the activity on time (e.g., the unit cannot travel fast enough to reach the destination by the designated time).

Summary. Synchronization requirements are currently represented by an alphanumeric table in the operations order for a mission, which is clearly not a particularly effective representation. The spatial and temporal matrices provide analog graphical representations of the constraints that are related to these synchronization requirements. Although these two displays have been described separately, critical events often need to be synchronized in both space and time simultaneously. Therefore, these two displays have been designed to work together in a complementary fashion. For example, positioning the cursor over one of the two displays will produce visual rollover effects in the associated symbol in the other display: If the leader places the cursor over a synchronization point in the temporal synchronization matrix, then the corresponding visual information is highlighted in the spatial synchronization display.

Plan Review Mode and Displays

The work domain analyses included the observation of Army commanders who were participating in large-scale training exercises. Prior to these observations, it was fully expected that commanders and leaders would monitor the progress of a mission. What came as a surprise was the extent to which that was true. In practical terms, commanders were often observed to ask the same fundamental question—"Where am I relative to plan?"—in a variety of different ways and with respect to a variety of different resources. Thus, commanders monitored not just the actual status of combat resources but the actual status within the context of planned mission activities and resource expenditures. Commanders and leaders need to monitor planned and actual progress in terms of space, time, objectives, resources, goals, intentions, and courses of action for both friendly and enemy forces to make informed command-and-control decisions. At the present time, there is very little computerized support to assist leaders in this regard.

A "Plan Review" interface mode was developed to meet this need. This mode can be toggled on and off by pointing and clicking on the "REV" button (upper left corner in Figure 3). Two primary changes occur (see Figure 10). The first change involves the spatial synchronization matrix display. A plan icon will appear for any actual unit icon that is on the map (see the icons with a black "X" in Figure 10a). Each plan icon represents the planned physical location and the planned categorical strength of combat power (indicated by color coding) for a unit. Deviations

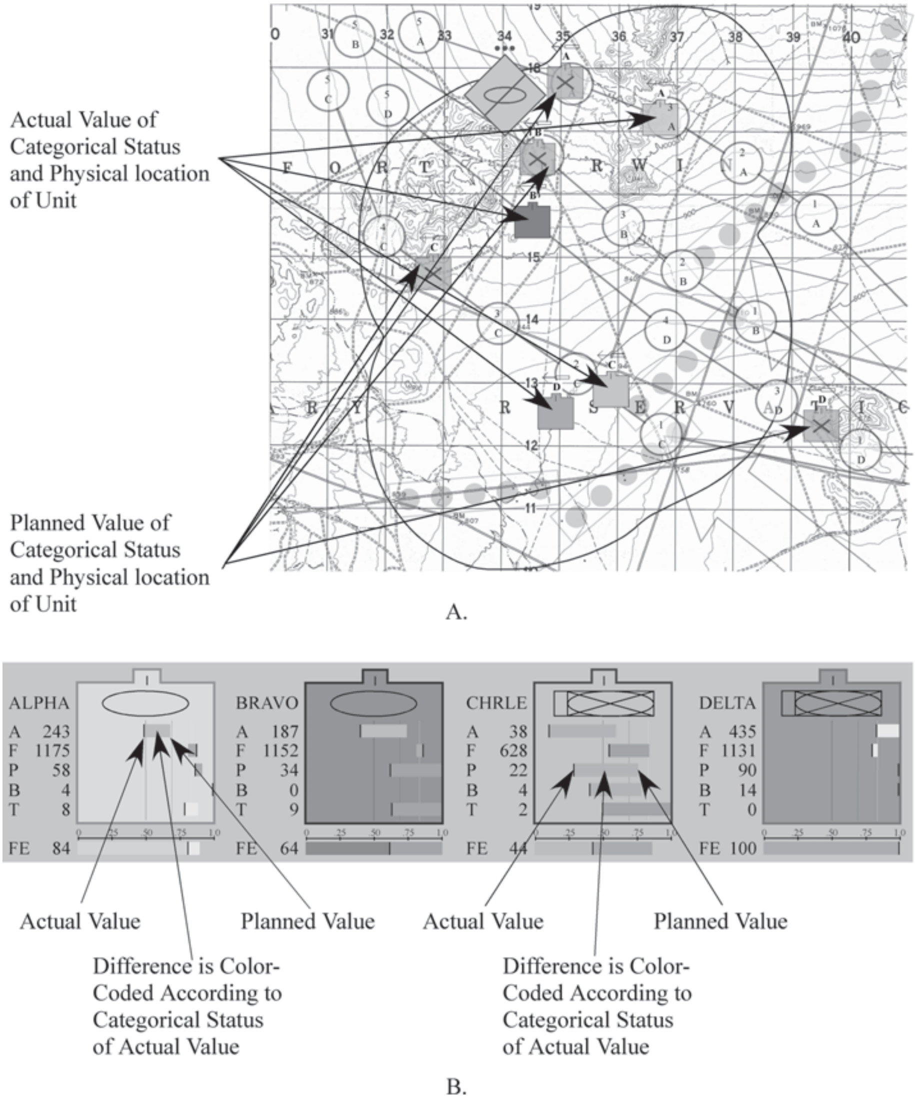


Figure 10. Plan review mode.

from plan are specified by differences in spatial location or color between the planned and actual icons for a unit.

The second change involves the format of the friendly combat resource displays. A "floating bar graph segment" appears for each combat resource (see Figure 10b). This floating segment specifies a range of values that corresponds to the difference between the planned and the actual values for a parameter. Thus, the width of this segment specifies the degree of discrepancy. Furthermore, the color of the segment specifies the direction of the discrepancy by assuming the categorical color code of the actual value. This results in a direct specification of both the amount and the direction of deviation from plan for all combat parameters. For example, the presence of large black and red floating segments in Figure 10b is a very clear and prominent indication that Company C has deviated substantially from plan and in a negative fashion. Conversely, large yellow or green floating segments would specify that the current operations are going better than planned.

Representing deviations between planned and actual values will facilitate a leader's capability to recognize that a discrepancy requires alternative preplanned courses of action or replanning. Leaders will be alerted to the fact that the battle is deviating from plan earlier in the engagement and therefore will be more proactive in adapting plans to meet the particular needs of the present context.

Alternative Course of Action Display

The domain analyses revealed that commanders usually develop multiple COAs during the analytic planning stage prior to a tactical engagement. One COA will be chosen as the single best alternative; other COAs reflect the ways in which the actual battle is most likely to deviate from that plan. Adopting an alternative COA can be dictated by battlefield events. For example, the CCIR and mission statements often contain a description of specific events that will trigger a preplanned response (a branch or sequel in the original plan). This corresponds to the heuristics (shortcuts) on the decision ladder: A particular knowledge state (situation analysis leg) can mandate a preplanned or well-known response (the solid arrows pointing to the planning/execution leg). Several interface resources were provided to support the commander in these very important decisions.

The graphical replay slider (see Figure 3) allows the commander the opportunity to review the status of the current COA. The leader can point, click, and drag the slider along the horizontal extent of the track to provide either a historical "replay" of the tactical operation as it unfolded across time or a "pre-play" of future events as they are envisioned in the current COA. The displayed information changes to review mode when the slider is selected (i.e., both planned and actual mission information is displayed). Dragging the slider to the left (from current time to initiation) provides a continuously updated "rewind" of all displayed information regarding the engagement. Dragging the slider to the right (from the initiation time) provides a continuously updated "replay" of the engagement.

The displayed information changes when the slider continues past the current time in an engagement: Only planned information is then displayed because there is no corresponding actual information. There are no limits on the number of rewinds, replays, or pre-plays. The slider springs back to the location corresponding to current time when it is released. Thus, the graphical replay slider allows the leader to review past, present, and future battlefield activities with regard to a number of critical factors, including planned versus actual spatial synchronization, temporal synchronization, and expenditure of combat resources.

The commander also may review the alternative COAs and their fit with the current context. An alternative COA can be made visible temporarily in both the temporal and spatial matrix displays by positioning the cursor over the appropriate button at the bottom of the interface (see Figure 3). Graphical representations of the new COA replace those of the old COA; elements of the new COA that are different from the old COA will be highlighted in red. This allows the leader to review an alternative COA in light of current spatial, temporal, and resource constraints. Moving the cursor away from the button results in the reappearance of the original COA. If a leader decides that an alternative course of action is more appropriate, then this decision can be implemented by clicking on the button (and then verifying that choice). This will initiate the process of communicating this change in plan to lower-level units.

Direct Manipulation

Direct manipulation has been discussed extensively in the human-computer interaction literature. Hutchins, Hollan, and Norman (1986) provided an early and influential analysis. Their explanation of direct manipulation was, to a large degree, couched in terms of technology:

> There is a feeling of involvement directly with a world of objects rather than of communicating with an intermediary. . . . Actions apply to the objects, observations are made directly upon those objects. . . . Input and output languages of the interface . . . [are] interreferential, allowing an input expression to incorporate or make use of a previous output expression. This is essential for creating the illusion that one is directly manipulating the objects of concern. . . . It is because an input expression can contain a previous output expression that the user feels the output expression is the thing itself and that the operation is applied directly to the thing itself. This is exactly the concept of "interreferential I/O." . . . From this perspective direct manipulation will occur when the display interface and the control interface have been merged together. (pp. 114–115)

Consider a simple example of direct manipulation: dragging an icon into the trash bin. The object in the task domain (a computer file) is represented by "output" in the interface (its icon). The desired command input (deleting the file) is achieved through direct manipulation of the output icon (i.e., point, click, drag, release). Compare this with deleting a file through a command line interface (e.g., "del unwantedfile.doc [return]"). This command is a request for action that is forwarded to an intermediary (the computer). The object of interest is not being acted upon directly; the manipulation is quite indirect. Similarly, it is important to note that interaction via a pull-down menu does not constitute direct manipulation: The menu, not the object, is being manipulated, and it remains a request for action to be completed by an intermediary.

CSE and EID provide a complementary interpretation of direct manipulation relative to that proposed by Hutchins et al. (1986). This perspective draws on the original insights of Gibson (e.g., 1966). Human interaction with the real world is characterized by powerful perception-action skills. Consider the manipulation of real-world objects. An observer sees an object of interest in the real world and reaches for it (i.e., initiates an action). The observer continuously monitors the progress of the hand/arm toward the object (perception) and continuously corrects the trajectory of the hand (action) so that it eventually intercepts the target. This is an example of an open-loop system that relies critically on a feedback loop. In the case of human interaction with the world, this feedback loop is referred to as the perception-action loop (or cycle). Successful completion (grasping the object) depends on continuous space-time signals that keep the perception-action loop intact.

From this perspective, the goal of interface design is to build a virtual ecology that maintains an intact perception-action loop. Thus, dragging an icon into the trash can involves continuous space-time signals (graphical representations of both object and target that are physically located in the display space), skill-based behaviors (e.g., visual perception and action), and an intact perception-action loop (user monitors progress toward goal and adjusts movements based on discrepancies from goal). In contrast, the continuous space-time signals are missing with a command line or a pull-down menu; the perception-action loop is broken, not intact. The interface resources that were designed to support direct manipulation (i.e., provide an intact perception-action loop) in RAPTOR will now be described.

Synchronization Points

The spatial and temporal synchronization matrix displays provide simple examples of direct manipulation. The visual representations of the synchronization points in the temporal matrix (i.e., the bold vertical lines in Figure 9a) can be manipulated directly to adjust the timing of activities. For example, if one unit is lagging behind and is clearly not going to make a synchronization point on time (as illustrated in Figure 9b), the leader can point, click, and drag the appropriate vertical line to the right, thereby establishing a later synchronization time. Similarly, a leader can point, click, and drag the graphical representations of the spatial synchronization points (i.e., the circles in Figure 8) to alter the point in space to which a unit maneuvers. These actions constitute the minor modification of an existing plan. Ultimately, these modifications could be made visible in shared displays to facilitate communication and thereby the synchronization of activities across various units.

Levels of Aggregation. As previously mentioned, a critical requirement in tactical operations is to track the status of friendly combat resources. These data are numerous and complex: Five combat resources (tanks, Bradleys, fuel, ammunition, personnel) exist at a number of different levels, ranging from battalion (1), companies (4), and platoons (12), all the way down to individual vehicles and soldiers. The simultaneous display of this information is simply not an option, and interface resources that allow a leader to selectively focus at different levels had to be devised. A related design consideration places additional constraints on the presentation of this information. We initially reasoned that the best option would be to present combat resources on the battlefield itself (i.e., present resource levels in the context of terrain features that further restrict potential activities). However, our initial attempts at doing so were rejected by Army subject matter experts because critical terrain information was obstructed. Thus, the requirement to track friendly combat resources introduced a number of trade-offs and compromises; direct manipulation played an important role in the design solution.

Tree Control

The design solution involved two spatially dedicated areas for the display of detailed friendly combat resources that were located off the contour map and control mechanisms to change their level of aggregation. As illustrated in Figure 3, one large friendly resource display is presented in a primary slot, and several smaller resource displays are presented in a secondary slot. The primary control mechanism for changing the level of aggregation in these displays is the tree control (see top right portion of Figure 3). The visual appearance of this control mirrors the hierarchical structure of friendly units, ranging from the battalion at the top (BN) to individual tanks and Bradleys at the bottom (the symbols at the bottom are standard Army representations for tanks and Bradleys; U.S. Army, 1999b). The nodes of the tree are color coded to reflect the categorical status of the unit or vehicle.

The tree control works in the following manner. Pointing and clicking on a node in the tree replaces all current displays (both primary and secondary slots) with the set of displays associated with that node. Consider the configuration illustrated in Figure 3 (battalion display in the primary slot and company displays in the secondary slot). If the leader pointed and clicked on a company node, then the company-level resource display would appear in the primary slot and the platoon-level resource displays would appear in the secondary slot. If the leader had clicked on a node at the bottom of the tree, then the resources for an individual vehicle would have occupied the primary slot and information regarding the soldiers in that vehicle (e.g., hydration level, core temperature, sidearm ammunition) would have occupied the secondary slot. Thus, with one mouse click, the leader can change the level of aggregation for the detailed display of friendly resources from the battalion level to the level of an individual soldier or anywhere in between.

Terrain Icon Controls

The design solution outlined in the previous section does not address an important consideration: the physical location of units, vehicles, and personnel on the battlefield terrain. Small transparent “terrain” icons were developed to meet this need; they are placed unobtrusively on the terrain map (see Figures 3 and 8). The lower left corner of an icon corresponds to the physical location of a soldier, vehicle, or unit. These terrain icons also provide some additional information (e.g., alphanumeric label, unit size indicator, and color coding for overall categorical status of the unit).

Avoiding clutter was a primary goal because Army personnel often mentioned that the presence of too many unit/vehicle icons on electronic battlefield maps is a primary drawback of existing systems. Therefore, control mechanisms were devised to allow commanders to change levels of aggregation. The default configuration has the four company icons on the contour map (see Figure 3). Pointing and clicking on any combat resource display in the primary or secondary slots would place that unit's terrain icon on the map and remove all others. Sets of terrain icons at a particular level of aggregation can be implemented via the control buttons located next to the tree control (see Figure 3). For example, pointing and clicking on the "PLT" button places the 12 platoon icons on the map and removes all other terrain icons.

Nodes of the tree control structure can also be selected and manipulated to place more selective sets of terrain icons on the map. Finally, a leader can "drill down" within any terrain icon currently on the terrain map: Pointing and clicking on an icon replaces it with all icons at the next level down in the tree structure. For example, clicking on a company terrain icon replaces it with the three platoon icons for that company. All other terrain icons are not altered (i.e., they remain present). Finally, the simultaneous change of both the terrain icons and the combat resource displays can be achieved by pressing the "LNK" control button. This setting produces simultaneous changes in both the resource displays and the terrain icons (i.e., the resource displays in the primary and secondary slots are always present on the map). These interface resources allow almost any desired configuration of displayed information to be achieved within a mouse click or two.

Summary. RAPTOR embraces direct manipulation to the fullest extent. There is no command line; there are no pull-down menus. All potential actions by the commander are executed directly on objects in the interface. Normally, this will involve the direct manipulation of the objects of interest in the interface. Button presses may supersede direct manipulation but only under circumstances where direct manipulation would impose cumbersome interaction requirements. Thus, the virtual ecology merges displays and controls, provides continuous space-time signals, and ensures an intact perception-action loop.

Support for Skill-, Rule-, and Knowledge-Based Behaviors

A fundamental assertion of CSE and EID is that interface resources should be provided to support skill-, rule-, and knowledge-based modes of behavior. The resources, provided by the RAPTOR interface that supports each mode, will be summarized in this section. Although each category will be discussed separately, it is important to note that the same interface resource (e.g., a display) can provide support for all three modes of behavior. Rasmussen (1983) makes this clear: "The distinction between the perception of information as signals/signs/symbols [i.e., skill-/rule-/knowledge-based behavior] is generally not dependent on the form in which the information is presented but rather on the context in which it is perceived, i.e., upon the intentions and expectations of the perceiver" (p. 260).

Skill-Based Behavior

The fundamental goal of interface design is to leverage powerful and natural human skills of perception (e.g., obtaining visual information) and action (e.g., manipulating objects). Stated alternatively, the interface should be designed so that domain practitioners are required to use limited-capacity mental capabilities (e.g., mental calculations that require working memory) only when it is absolutely necessary. The previous sections describing the RAPTOR interface in terms of direct perception, direct manipulation, and the perception-action loop provide a detailed account of the resources that were designed to support these skill-based behaviors.

Rule-Based Behavior

Effective displays should also provide graphical representations that produce a rich set of signs to support rule-based behavior. A properly designed interface will convey the current state of a domain directly to the practitioner through its spatiotemporal behavior, thus providing support for the recognition of prototypical system states. In turn, a properly designed interface will suggest the actions that are appropriate (i.e., shortcuts on the decision ladder), at least to expert agents who have learned the actions and the associated perceptual cues (Rasmussen, 1983).

Consider one example involving the enemy combat resource display (see Figure 5). Imagine that the display indicates that a large percentage of enemy vehicles have remained in the template category late into the course of an engagement. The critical display feature (i.e., the middle segment remaining large) serves as an explicit sign specifying a dangerous possibility: The enemy may well be engaged in a feint maneuver (i.e., the larger enemy unit that is supposed to be here is actually poised to wreak havoc elsewhere). An experienced commander would see the perceptual cues provided by the display and realize that a sequence of activities to test that possibility would need to be performed. Other examples of visual cues providing support for rule-based behavior include the following discrepancies between planned and actual values: force ratio over time (force ratio trend display; see Figures 6 and 7), physical locations of units (spatial synchronization matrix in review mode; see Figure 10), timing of activities and events (temporal synchronization matrix; see Figure 9), resource levels (friendly combat resources displays in review mode; see Figure 10), and general progress (alternative COA displays).

Thus, the displays in RAPTOR provide a rich set of signs that facilitate a leader's ability to recognize prototypical situations and that suggest appropriate actions (e.g., further investigations to clarify the situation, the adoption of preplanned branches or sequels, or the need for more extensive replanning). Leaders will be alerted to the fact that the battle is deviating from plan earlier in the engagement and will therefore be more proactive in their reactions to meet the particular needs of the present context.

Knowledge-Based Behavior

When plans fail or need to be revised substantially, as is often the case with an intelligent adversary, commanders and leaders are faced with novel situations (i.e., circumstances outside of those considered prior to the engagement) and will therefore be engaged in problem solving. Lewis et al. (2004) summarize observations on knowledge-based behaviors in tactical operations:

> Replanning [problem solving] draws on a variety of cognitive activities that emerge in naturalistic settings. . . . It draws on problem detection (to determine that a plan needs to be modified), coordination (to ensure the teamwork needed in modifying the plan), common ground (to ensure that the units involved do not hold conflicting views of the situation), rapid decision making (to judge whether, when and how to revise the plan), sensemaking (to appraise the affordances of friendly forces in a dynamic setting), mental simulation (to gauge if the revised plan is likely to be effective), and uncertainty management (to handle the confusion of modifying a plan in progress). (p. 7)

To support these activities, the displays should provide symbolic representations of critical information at all levels in the abstraction hierarchy. These displays will serve as external models that allow critical constraints and relationships to be perceived directly, thereby providing the graphical explanations that are necessary for effective problem solving. This symbolic content at each level of the abstraction hierarchy will be briefly described for the RAPTOR interface. These are graphical representations of the information listed in Figure 1. The tangible information at the level of goals, purposes, and constraints (highest level in the hierarchy) are mission plans and objectives.

The spatial matrix, temporal matrix, and alternative COA displays contain explicit representations of plans; all other displays contain implicit representations in terms of planned versus actual progress. The primary representations at the level of abstract function and priority measures are the force ratio and the force ratio trend displays. These displays show the ebb and flow of military force (as estimated by force equivalence) for friendly and enemy forces. The level of general functions and activities, to some degree, is implicitly represented in all aspects of the interface because the overall goal is to support the general functions of command and control (primarily). There are numerous representations of information at the level of physical processes and activities. The friendly and enemy combat resource displays represent measured values of combat parameters (e.g., tanks, Bradleys, ammunition, fuel, and personnel). Other information at this level includes the weapons envelope for the primary munitions of both friendly and enemy vehicles and a variety of unit-related information (i.e., identification, type, and size symbols). Information at the lowest level of the abstraction hierarchy (physical form and configuration) includes the physical characteristics of the battlefield terrain and the physical location of a unit on this terrain.

It should be noted, however, that the RAPTOR interface does not contain many sources of information that would be critical to a commander and his or her troops during tactical engagements. Critical elements of the terrain could be represented more effectively (e.g., its impact on routes of travel). The weather exerts a tremendous effect on tactical operations, and it is simply not addressed in RAPTOR. Similarly, information required to support major battle operations systems outside of command and control (i.e., maneuver, fire support, air defense, intelligence, mobility and survivability, and combat service support) are not provided.

Evaluation

Several formal evaluations of the RAPTOR interface have been conducted using qualitative simulations of tactical engagements and Army personnel. For example, Talcott, Bennett, Martinez, Shattuck, and Stansifer (2007) compared two interfaces (an early version of RAPTOR and a laboratory version of an existing Army interface) for their capability to support leaders in obtaining information regarding friendly combat resources. Fifteen statistical comparisons between these two interfaces (main effects or simple main effects) were significant, and all of them favored the RAPTOR interface. Several similar controlled laboratory experiments have also provided empirical results indicating that the RAPTOR interface is more effective than existing interfaces.

Another experiment was conducted to investigate the impact of RAPTOR displays on more complicated aspects of decision making. Sixteen officers from the United States Military Academy participated in the study. Fifteen of these participants had previous experience with battalion-level tactical operation centers. Two versions of RAPTOR were developed: an enhanced version and a baseline version (without the force ratio, force ratio trend, and review mode). Participants assumed the role of battalion commander and viewed a dynamic, authentic scenario (either offensive or defensive) using one of the two interfaces. The scenario was paused at six different points that coincided with critical events. During each pause, the participants were required to complete two questions. The participants were first requested to "Please verbally describe the situation as you understand it." The participants were then asked, "What actions, if any, would you take at this time?"

It was found that participants who used the enhanced RAPTOR interface exhibited a greater tendency to produce references to plans and operations orders. Twice as many references to mission plans were made by those participants using the enhanced interface (52) than those using the baseline interface (26). Substantially more references to the mission operations order were also made by participants using the enhanced version (24 vs. 15). The participants offered enthusiastic support for both versions of RAPTOR, as indicated by the selected quotes listed as follows:

> "From a visual standpoint very helpful."
>
> "I could see that my reserve was falling behind from where they were supposed to be. That spatial relationship helped a lot."

> "It was very clear watching the battle . . . where I needed to change my priorities of fire . . . where we were having success and where they were having success."
>
> "I could see that decision . . . the display made that decision abundantly clear to me."
>
> "Much more useful than some of the other interfaces I've . . . used . . . in Iraq."

Conclusions

There is a tremendous need for the interface to provide effective decision support for military command and control during tactical operations. Military personnel are subjected to work conditions that can have a serious impact on their capability to perform in an effective manner. They experience sleep deprivation and extreme physical fatigue. They also experience high degrees of stress, where the stakes can involve life or death. It is under these conditions that the benefits of the CSE and EID approach (the leveraging of powerful perception-action skills during decision making and problem solving) are likely to be magnified. Klein (1989b) reiterates these sentiments for command-and-control interfaces from the perspective of naturalistic decision making:

> We must insist that the designers of these systems have appropriate respect for the expertise of proficient operators and ensure that their systems and interfaces do not compromise this expertise. We must find ways to present operators with displays that will make situation assessment easier and more accurate. We also want displays that will make it easier for operators to assess options in order to discover potential problems. In other words, we want to build decision support systems that enhance recognitional as well as analytical decision strategies. (p. 64)

We believe that the RAPTOR interface, developed from the CSE and EID design framework, represents a good start toward meeting these requirements. The principles of direct perception, direct manipulation, and the perception-action loop have been applied to the development of an interface that should contribute to lifting the "fog of war" by allowing leaders literally to "see" constraints, opportunities, and solutions directly in the interface and to act upon them. Leaders are likely to have better understandings of the dynamic and stressful conditions arising in the battlefield and should therefore make faster and more effective decisions. Efforts to assess these potential benefits are ongoing. Dynamic scenarios and intelligent adversaries are being developed using a commercial simulator. The goal is to obtain more objective and domain-defined measures of performance (e.g., lives and resources saved).

The interface design strategies used in RAPTOR are directly relevant for researchers developing military decision support. The general approach and the principles of design that have emerged are useful for all application domains that fall within this general category (i.e., both intent- and law-driven sources of constraints). For example, see Talcott et al. (2007) for a brief discussion of these principles applied to flexible manufacturing. A patent application has been filed for the RAPTOR interface.

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