

Perception-Action Icons: An Interface Design Strategy for Intermediate Domains

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Objective: A prototype interface was developed to support decision making during tactical operations; a laboratory experiment was conducted to evaluate the capability of this interface to support a critical activity (i.e., obtaining the status of friendly combat resources). **Background:** Effective interface design strategies have been developed for domains that have primarily law-driven (e.g., process control) or intent-driven (e.g., information retrieval) constraints. However, design strategies for intermediate domains in which both types of constraints are equally critical, such as military command and control, have not been explored as extensively. The principles of direct perception, direct manipulation, and perception-action loops were used to develop a hybrid interface design strategy (“perception-action icons”) that was incorporated into the prototype interface. **Methods:** A qualitative tactical simulation and an alternative interface (an experimental version of an existing U.S. Army interface) were developed. Participants used both interfaces to provide estimates of friendly combat resources for three different categories of information at three different echelon levels. **Results:** The results were unequivocal, indicating that the interface with perception-action icons produced significantly better performance. **Conclusion:** The perception-action icon design strategy was very effective in this experimental context. The potential for this design strategy to be useful for other intermediate domains is explored. **Application:** Actual or potential applications of this research include both specific interface design strategies for military command and control and general interface design principles for intermediate work domains.

INTRODUCTION

Cognitive systems engineering (Rasmussen, Pejtersen, & Goodstein, 1994) provides a general framework for the development of effective computerized decision support. The foundation of this approach is that an analysis and description of domain constraints (i.e., the regularity in a domain or, alternatively, the nature of the work to be done) is essential in developing effective interfaces. Rasmussen et al. (1994) have developed a continuum to categorize different domains in terms of their constraints. At one end of the 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 in which 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 far 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 cognitive systems engineering literature has provided excellent examples of design strategies for domains that fall at either of the two ends of the continuum. The most effective design strategy for law-driven

domains is to develop analogical visual displays that utilize geometrical forms to directly reflect domain constraints (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) that is appropriate for domains that fall in the middle of this continuum is less clear. These domains are characterized by the presence of both law-driven constraints and intent-driven constraints that are roughly equivalent in terms of their importance in shaping overall system behavior. The term *intermediate* will be used to describe this general category of domains. A good example of an intermediate domain is military command and control. There are law-driven constraints that arise from an extensive technological core (weaponry, sensors, communication, etc.). However, there are also intent-driven constraints. The difference in intentions between friendly and enemy forces is one obvious factor, but intent also plays a substantial role within a military organization. For example, during tactical engagements lower-level leaders base their actions upon an interpretation of the commander's intent statement in mission orders (e.g., Klein, 1994). One solution to the design challenges presented by this category of domains was implemented in a prototype interface for U.S. Army commanders. This solution will be described in the context of the principles of cognitive systems engineering and ecological interface design that guided its development.

Perception-Action Icons for Military Command and Control

Gibson's (1966) theoretical work in experimental psychology has provided valuable insights for interface design. The simple example of navigation through the natural environment will be used to illustrate some of these concepts. The *ambient optical array* is specified by (and corresponds to) the structure of the natural environment. The actions performed by an agent (i.e., reorientation of the eyes, turning of the head, ambulation) produce systematic transformations of the optical array that are referred to as *optical invariants* (e.g., optical flow). The brain "resonates" to this information; the information is "obtained" or "picked up." This,

in turn, provides *affordances* or possibilities for action by the agent. The agent coordinates and adjusts his or her actions based on feedback obtained from the continuous space-time signals that arise from (and are specific to) the combination of structure in the environment and observer action. Thus, successful interaction with the natural environment depends upon a dynamic and continuous perception-action loop that draws upon highly efficient skill-based behaviors (Rasmussen, 1983).

The implication for interface design is that the displays and controls in an interface should be designed to maintain an intact perception-action loop, thereby facilitating interaction. The Representation Aiding Portrayal of Tactical Operations Resources (RAPTOR) interface achieves this goal through "perception-action" icons that provide integrated display (direct perception) and control (direct manipulation) design components that preserve the loop's integrity. Each component will be described in greater detail.

Direct perception. In describing direct perception, Rasmussen et al. (1994) observed, "In Gibson's terms, the designer must create a virtual ecology, which maps the relational invariants of the work system onto the interface in such a way that the user can read the relevant affordances for actions" (p. 129). The abstraction (means-ends) and aggregation (part-whole) hierarchies are analytical tools that have been developed to discover the constraints (i.e., the relational invariants) of a work domain. An analysis of U.S. Army tactical operations at the battalion level was conducted using these tools (Martinez, Bennett, Talcott, Stansifer, & Shattuck, 2001); a partial listing is provided in the left section of Table 1. Achieving direct perception requires at least two different sets of mappings. One set of mappings involves the relationship between the constraints of the work domain and the informational content encoded into the graphical representations (i.e., are appropriate categories of domain information and relations available in the interface?). This will be referred to as *content mapping*. A second set of mappings involves the relationship between the visual properties of the graphical representations and the perceptual capabilities and limitations of the observer (i.e., have the domain constraints been encoded or represented in the interface so that they can be easily obtained?). This will be referred to as *form mapping*. The quality of these mappings will determine the extent to which the affordances

TABLE 1: Abstraction Hierarchy Analysis of Army Battalion During Tactical Operations and Corresponding Visual Indicators in RAPTOR Interface

Abstraction Hierarchy	Military Tactical Operations	RAPTOR Icon
Goals, purposes, and constraints	Mission objectives, collateral damage, public perception, etc.	
Abstract functions and priority measures	Combat power, value of mission objectives vs. resource expenditure, probability of success/failure, etc.	Categorical combat power indicator for unit
General functions and activities	Command and control, maneuver, combat service support, air defense, intelligence, fire support, mobility and survivability, etc.	Activity symbol indicating role in battle
Physical processes and activities	Vehicles (speed, maneuverability), weapons (power, range), sensors (sensitivity, range), terrain (avenues of approach), etc.	Quantitative indicators for combat parameters; range fan for primary munition
Physical form and configuration	Physical location of units, physical characteristics of terrain and weather, etc.	Terrain map, position of graphical form

of the domain, and therefore the potential for appropriate control actions to be executed, will be available for pickup by the observer.

The first set of mappings (i.e., content) for the RAPTOR interface is summarized in the right-hand side of Table 1; an example of the graphical format (a unit at the battalion echelon level) and associated “roll-over” behaviors is illustrated in Figure 1. The combat power of a unit (i.e., its military force) is a fluctuating commodity that ebbs and flows according to resources expended during battle and resources gained during reinforcement. The categorical status of a unit’s combat power is represented by the background color code (i.e., green: 100%–85%; amber: 84%–70%; red: 69%–50%; and black: <49%) of the unit’s icon. This information resides at the level of abstract functions and priority measures. The tangible contributions to a unit’s combat power are determined by the values of five combat parameters (tanks, Bradley personnel carriers, ammunition, fuel, and personnel). The percentage of each parameter is represented by the vertical position of an analog marker relative to the bottom (0%) and top (100%) of the combat parameter mats and by digital values (see Figure 1); the categorical status of each parameter is represented by the color of this mat. This information corresponds to the level of physical processes and activities in the abstraction hierarchy.

Other information at this level includes the range arc specifying the weapons envelope (Figure 1b) for the unit’s primary munition and the

unit’s identification, type, and size symbols. The unit’s role in the current tactical operation is indicated through standard U.S. Army activity symbols (i.e., the graphic marked as “unit activity symbol” in Figure 1b). This information corresponds to the level of general functions and activities. Information at the level of physical form and configuration includes the physical characteristics of the battlefield terrain and the physical location of the unit on this terrain.

The second set of mappings (i.e., form) involves the relationship between the visual properties of the display and the observer’s perceptual capabilities and limitations. In tactical operations the combat power of a unit is perhaps the most critical information to be presented; the tangible contributions to a unit’s combat power consist of the five combat parameters. At least two categories of graphical formats could be used: (a) a display in which the combat parameters are mapped into a single geometrical form and (b) a display in which each combat parameter has its own unique representation. Both of these formats can produce emergent features and therefore can qualify as “configural” displays; however, to facilitate discussion the former will be referred to as *configural displays* and the latter will be referred to as *separable displays*.

The proper choice between these two formats depends upon the inherent relationships between the domain variables to be presented (Bennett & Flach, 1992). A configural display is the appropriate

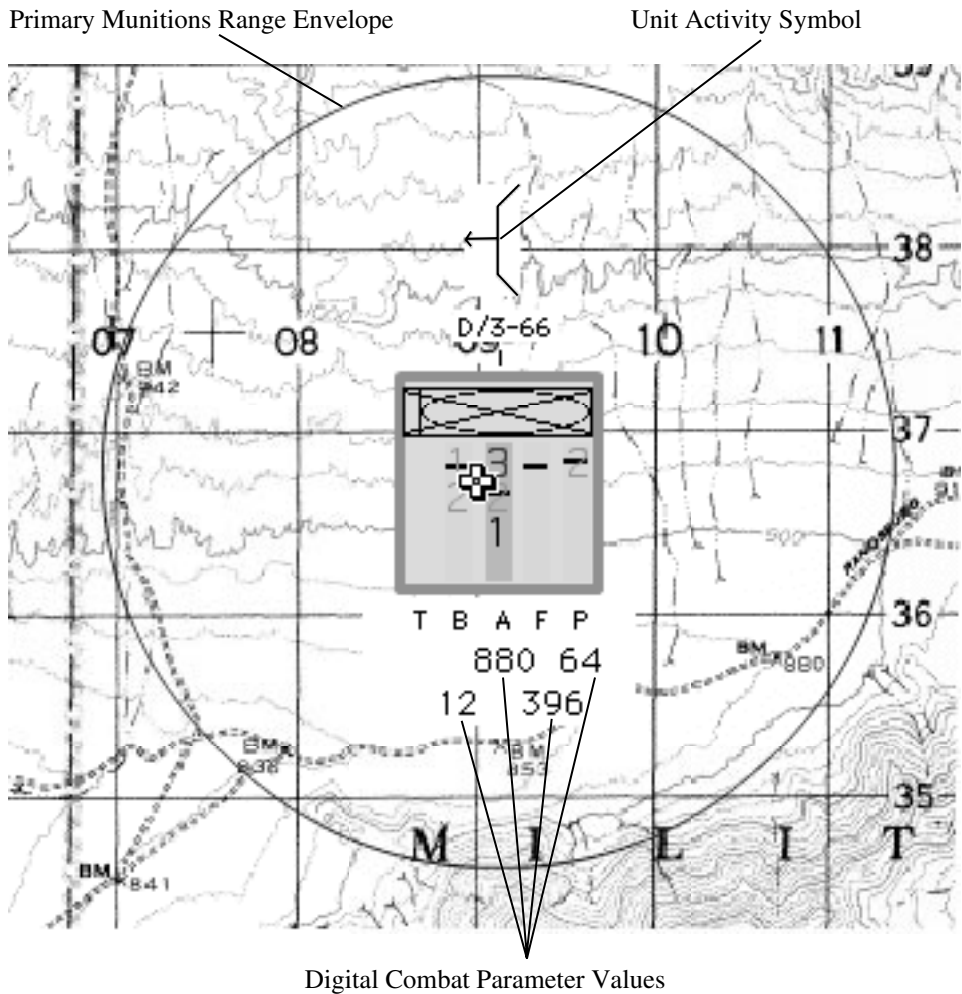
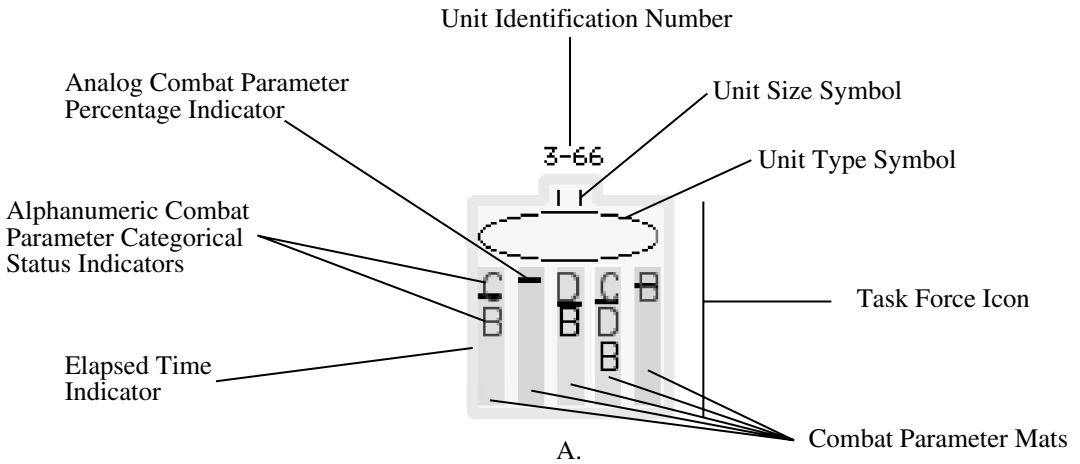


Figure 1. Direct perception in the RAPTOR interface. (a) Key elements of the perception-action icons in the RAPTOR interface (illustrated at the battalion level). (b) Additional “rollover” information that appears when the mouse is positioned over a unit icon (illustrated at the company level).

choice when the individual variables are tightly coupled (i.e., interactions between individual variables produce higher order domain properties). Under these circumstances a properly designed configural display will produce salient, higher level visual properties (i.e., emergent features) that correspond to these higher order domain properties. However, when the individual variables are loosely coupled (they do not necessarily interact to produce well-defined higher level domain properties), a configural display will produce salient visual properties (i.e., emergent features) that are meaningless yet at the same time quite difficult to ignore. See Bennett and Flach (1992) and Bennett and Fritz (2005) for more detailed discussions of these and related issues.

The domain analyses revealed that the five combat parameters are not tightly coupled: the relationship between them can vary substantially across different contexts (e.g., offensive vs. defensive missions). Thus, the proper design choice for the RAPTOR interface was to incorporate unique representations for each of the combat parameters (see Figure 1). Note that the pattern of relative heights for the analog indicators can produce a limited form of configurality (Sanderson, Flach, Buttigieg, & Casey, 1989) that matches the loosely coupled relationships that characterize the combat parameters.

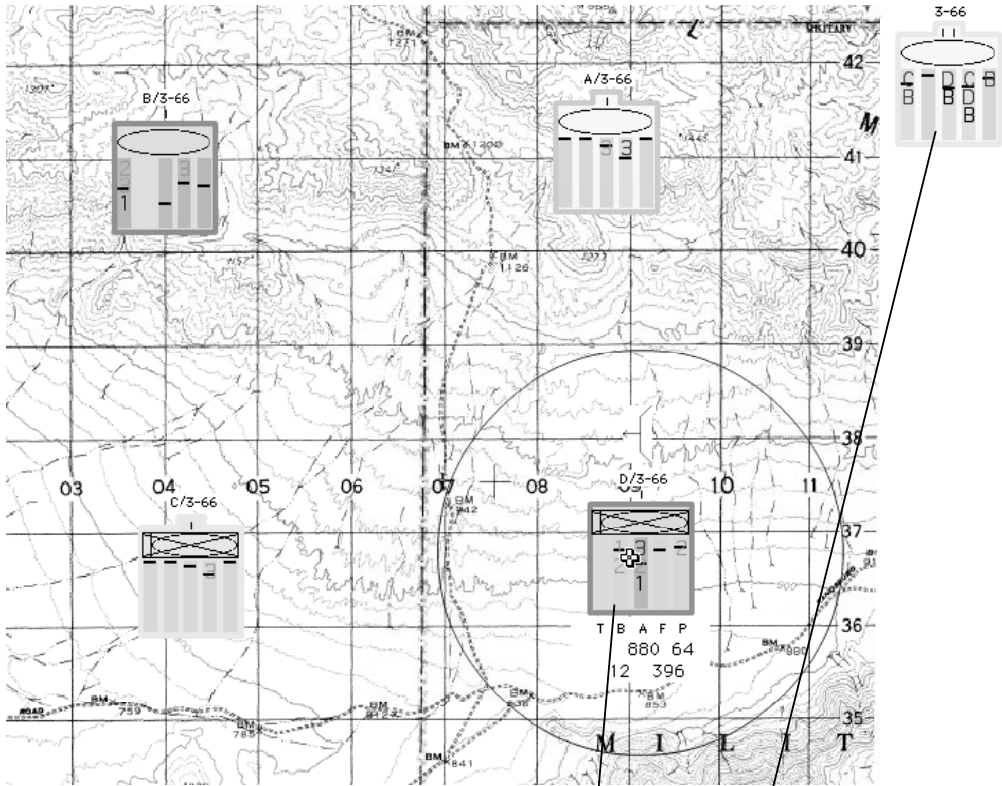
A second set of considerations in form mapping involves more specific characteristics of the display. The constraints in complex, dynamic domains will be hierarchically structured and nested; there is a corresponding need to visually segregate the information that appears in the interface (see Tufte, 1990). The challenge is to provide visual information that reflects the inherent structure and the relative importance of the corresponding domain information. Effective mappings at this level were devised for the RAPTOR interface. For example, the most critical piece of information (combat power of a unit) is represented by the most salient visual feature in the graphical format (the background color code of the unit's icon). Information at an intermediate level of importance (individual combat parameters, their values, and their relationships) was presented through visual features (background parameter mats, analog percentage indicators) at an intermediate level of salience. Basic information (e.g., unit's identification, type, and size symbols) was presented at the lowest level of visual salience. Finally, some information

(munition envelope, activity symbol, digital values of combat parameters) was available only when the mouse rolled over an icon, thereby providing access to this information but avoiding clutter.

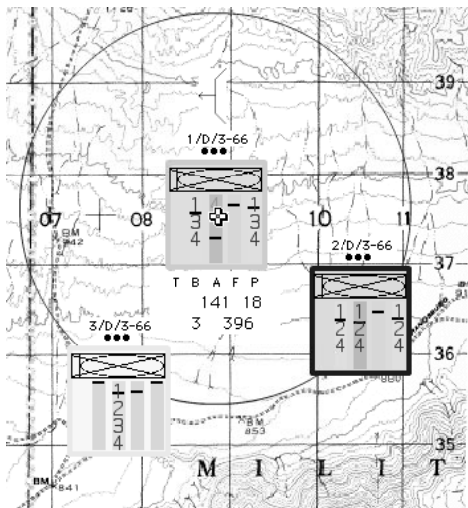
Direct manipulation. The concept of direct manipulation has a long history in the human-computer interaction literature. For example, more than 20 years ago Hutchins, Hollan, and Norman (1986) provided an extensive analysis. It has since become a platitude that the interface should be designed so that objects can be manipulated directly. In reality, this goal is rarely achieved. For example, pull-down menus have become universal in today's application software. Although they are a clear improvement over command line interfaces, they do not constitute direct manipulation: The objects of interest are really *not* being manipulated directly. Recently, Burns and Hajdukiewicz (2004) emphasized this point by referring to direct manipulation – “where users feel as if they are working directly with the object and not with the interface” – as “the ‘holy grail’ of interface design” (p. 2).

A description of decision-making requirements during tactical operations is needed to appreciate how the icons in the RAPTOR interface were designed to achieve the design goal of direct manipulation. Units at each echelon level can pursue collective or individual mission objectives. Therefore, an essential requirement is to consider the combat resources and activities at each echelon level. This imposes substantial demands on the commander and his or her staff. There are at least 17 echelon levels that a commander needs to consider: 1 at the battalion level, 4 at the company level (A, B, C, and D) and 12 at the platoon level (1, 2, and 3 for each company). To complicate matters further, the commander is required to track the five combat resources for each of these units and may need to consider these resources in the context of the battlefield terrain, given that it has a substantial impact on a variety of factors relevant to tactical operations.

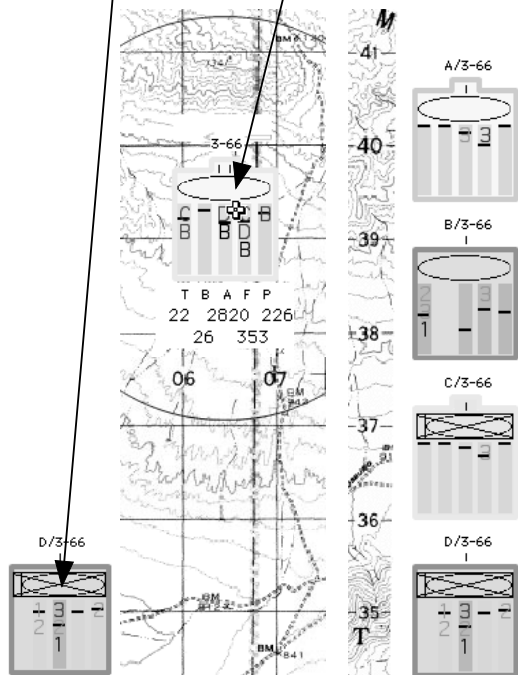
Direct manipulation of the graphical icons (i.e., pointing at and clicking on them) in the RAPTOR interfaces allows an individual to execute critical control functions regarding echelon level. The default configuration of the RAPTOR interface presents the four company icons on the contour map and the battalion icon off the map (Figure 2a). Clicking an icon on the contour map provided a finer grain of resolution. For example, a click on



A.



B.



C.

Figure 2. Direct manipulation in the RAPTOR interface. (a) Default configuration of RAPTOR with company icons located on the contour map and battalion icon located in the holding area. (b) Manipulation of an icon on the contour map produces view of combat resources at a finer grain of resolution. (c) Manipulation of an icon in the holding area produces a view of combat resources at a coarser grain of resolution.

the D company icon circled in Figure 2a would move this icon off the map to the location indicated by the left arrow and place the three associated platoon icons on the contour map (Figure 2b). Conversely, clicking an icon located off the contour map, such as the battalion icon in Figure 2a, would move it onto the contour map as indicated by the right arrow and place the four associated company icons off the contour map (Figure 2c). Thus, the objects of interest (icons representing units of action) are manipulated directly to change the resolution and the context in which information about friendly combat resources was displayed.

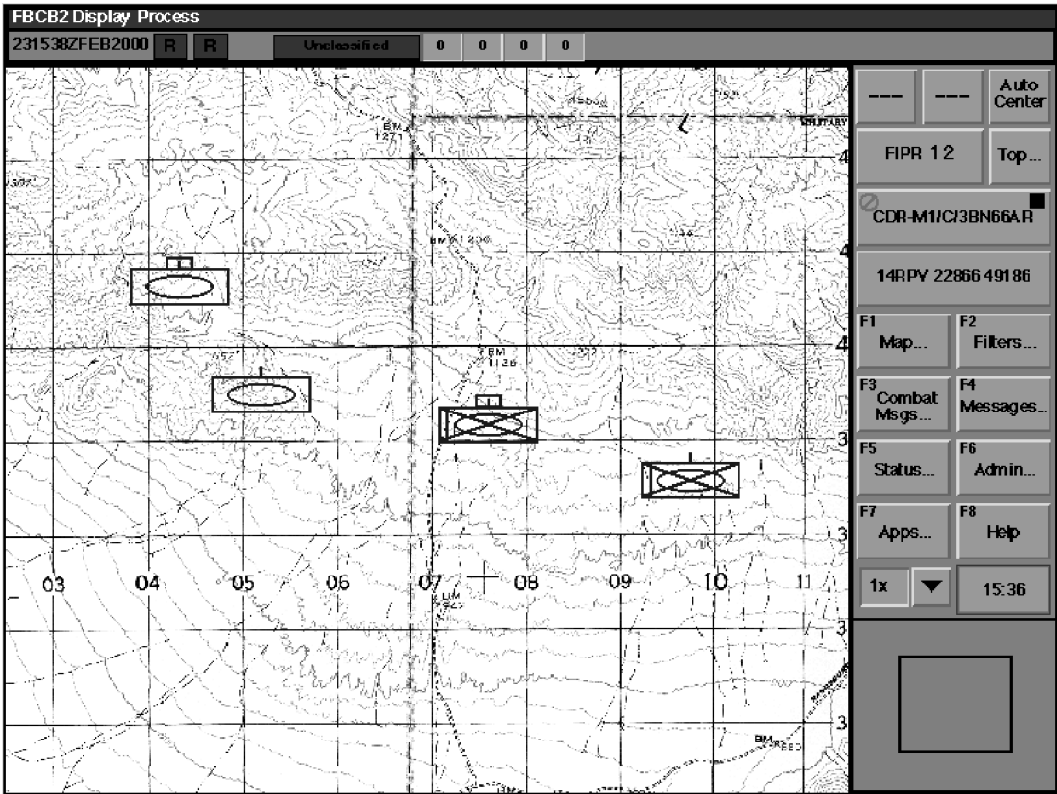
The instantiation of the perception-action icons design strategy in RAPTOR produced an interface that stands in sharp contrast to an existing, and partially fielded, U.S. Army interface: the Force XXI Battle Command Brigade and Below (FBCB2) interface. An experimental version of this interface was developed, and the features that are relevant for obtaining friendly forces information will be described. Figure 3 illustrates the main screen of the FBCB2 interface; symbols for the four companies of a battalion are present on the contour map (Figure 3a). The “F3 Combat Msgs” button is clicked to access company-level information regarding combat resources. The “combat messages” screen (Figure 3b) appears and presents a matrix with rows corresponding to the four companies (e.g., “D/3-66”) and columns corresponding to combat readiness parameters (e.g., “fuel”). The matrix cells present a categorical estimate of each company’s combat parameter strength through color coding and a letter indicator (e.g., “B” for black). More detailed data can be obtained by activating the company’s button in the left-most “Unit” column (e.g., “D/3-66”), which produces a “long form message” screen containing an alphanumeric data sheet (see Figure 4a). The “FIPR 12” (Figure 3a, top right corner) button is clicked to access platoon-level information. The “FIPR” screen (Figure 4b, “Flash-0” tab activated) then provides access to a military “E-mail inbox” with platoon information (e.g., “1/A/3-66AR”). Clicking the buttons in the “Time,” “Msg Type,” or “Source Originator” columns provides a detailed alphanumeric data sheet similar to that in Figure 4a.

Field studies of the FBCB2 interface (Center for Army Lessons Learned, 1997; Prevou, 1995) indicate that commanders and their staffs were inundated by the amount of data presented and the amount of effort required to interpret these data,

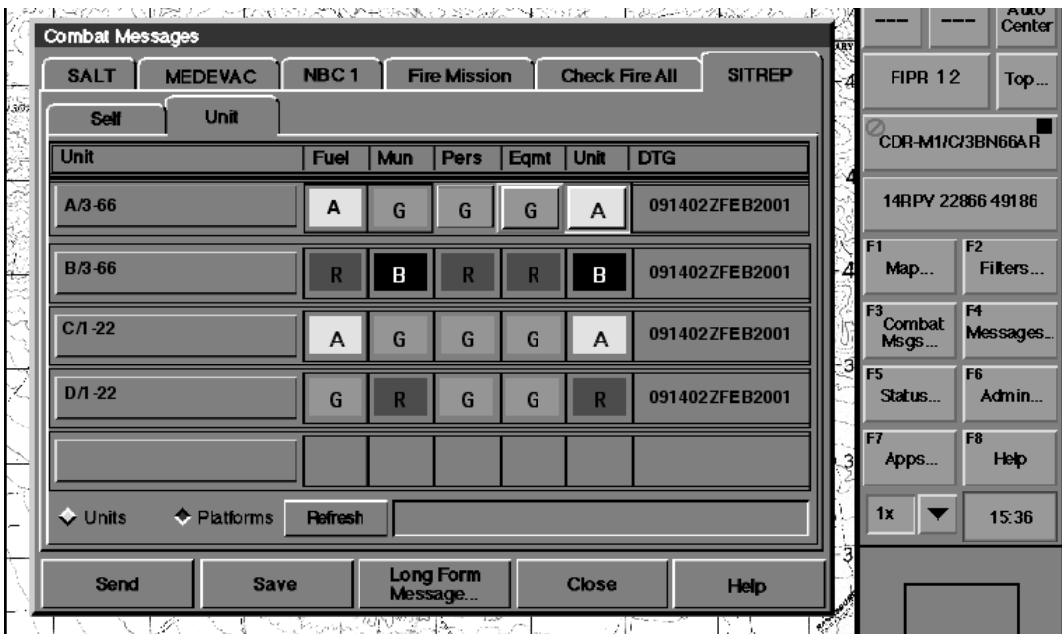
particularly during combat situations when high stress and heavy workloads were imposed. A concrete example of these difficulties is illustrated by the activity sequence required to obtain the value of a combat resource (e.g., number of tanks) at the battalion level. The “F3 Combat Msgs” button is activated from the main screen (Figure 3a). A company button (e.g., “D/3-66”) is then activated in the combat messages screen (Figure 3b), and the corresponding long form message screen appears (Figure 4a). The parameter value must be located in the alphanumeric data and remembered. The entire process must be repeated for three more companies, followed by the computation of the final parameter value (either mentally or manually).

The RAPTOR interface, designed specifically to support direct perception and direct manipulation, provides far better interface resources for the completion of this task. The user simply needs to activate (i.e., click on) the battalion icon and mouse over it (after it appears on the contour map) to view the computed parameter value (assuming the default configuration of the RAPTOR interface illustrated in Figure 2a). Although space limitations do not permit a thorough description, similar advantages are present with RAPTOR for different informational needs (e.g., the categorical status of tanks) and different echelon levels.

The previous discussion suggests that the RAPTOR interface will be more effective than the FBCB2 interface in obtaining friendly forces information. This hypothesis was tested in a controlled laboratory setting. A qualitative simulation was developed to portray realistic changes in combat resources at three time periods during an offensive tactical scenario. Active U.S. Army officers served as participants and were required to perform well-constrained but critical tasks. Three types of assessments were administered with regard to the combat readiness of friendly forces: quantitative (e.g., “What is the numerical value of tanks in Company C?”), categorical (e.g., “What is the color-code status of fuel in the Battalion?”), and needs (e.g., “What platoon in Company B needs Bradleys?”). Participants were also required to consider friendly forces at three different echelon levels (battalion, company, platoon). These assessments are typical of the information-seeking activities that U.S. Army commanders would perform repeatedly during the course of tactical operations. It was predicted that the RAPTOR interface would improve performance.

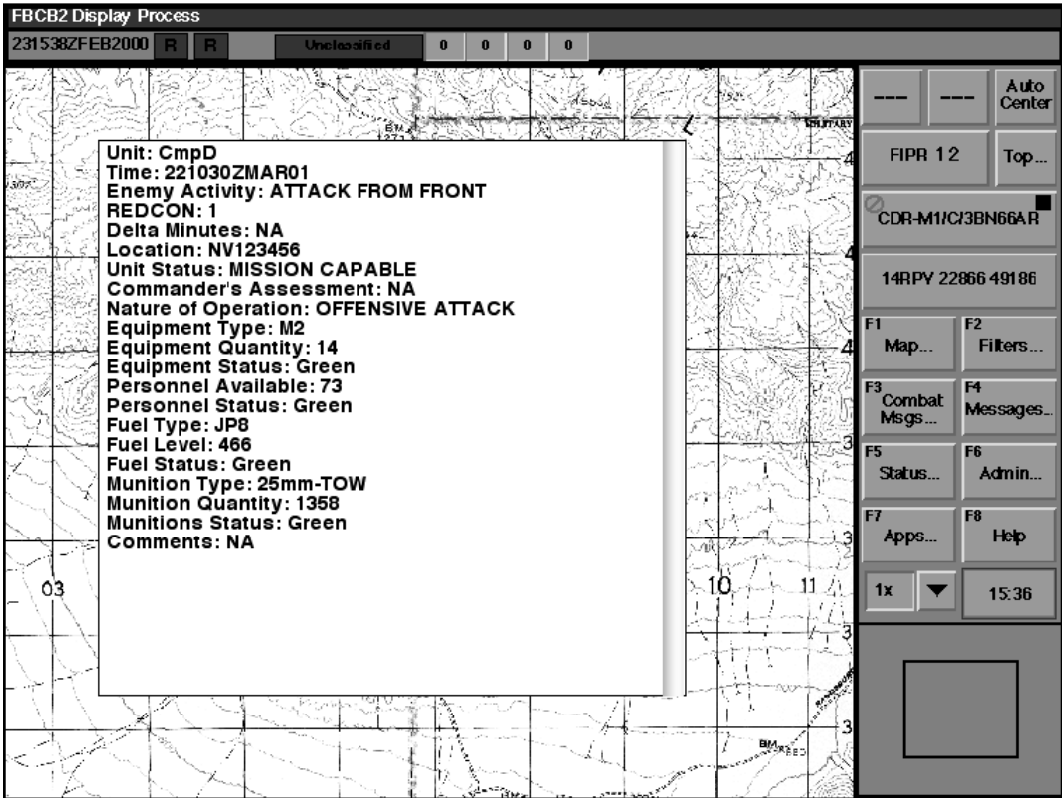


A.

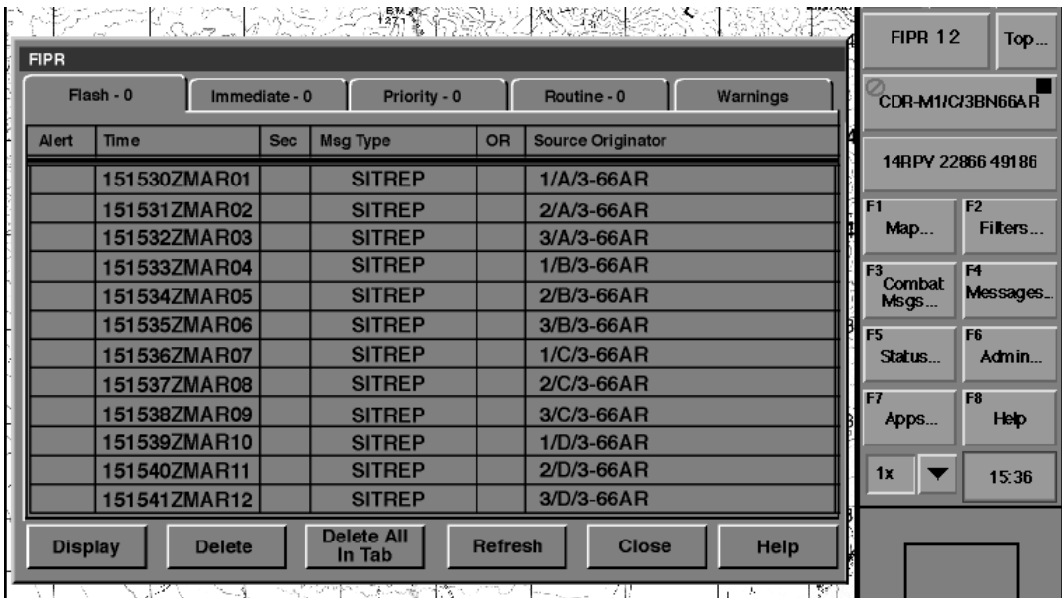


B.

Figure 3. FBCB2 Interface 1. (a) Default configuration of FBCB2 interface (main screen). (b) Activating the “F3” button in default configuration (Figure 3a) produces a pop-up window with a categorical summary of combat resources at the company level (“Combat Messages”).



A.



B.

Figure 4. FBCB2 Interface 2. (a) Activating the company button (e.g., “D/1-22”) in the combat messages screen (Figure 3b) produces pop-up window with alphanumeric descriptions of combat resources at the company level (“long form message”). (b) Activating the “FIPR 12” button in default configuration (Figure 3a) produces a pop-up window with a list of buttons corresponding to platoons (and long form messages upon their activation).

METHOD

Participants

Twelve male U.S. Army officers (6 captains, 6 sergeants first class) volunteered to participate. Their military specialties were engineer, artillery, or armor (8–20 years of active-duty service), and they ranged from 30 to 41 years of age. No participants had previous experience with either interface. All participants had normal or corrected-normal visual acuity and color perception.

Apparatus

All experimental events were controlled by identical computers (Apple Computer, Inc., Cupertino, CA, G3-300 MHz), with identical color monitors (Dell Computer, Round Rock, TX, Trinitron, 40.64 cm, 1024 × 768 resolution, Model D1025TM) and standard keyboards. Participants were also provided with notepaper, a pen, and a calculator.

Simulation Model

A simulated offensive tactical scenario was developed, based on exercises conducted at the U.S. Army's National Training Center. The battalion's mission was to traverse a predefined route, engage the enemy, defeat the enemy, establish a defensive position, and prepare for a counterattack. There were four companies in the battalion: Companies A (10 tanks and 4 Bradleys), B (14 tanks), C (4 tanks and 14 Bradleys), and D (14 Bradleys). There were three platoons (Platoons 1, 2, and 3) in each company (each with 4 tactical vehicles – either all tanks or all Bradleys). The combat resources for each echelon level (battalion, company, platoon) were considered at three different points in time: H-hour (onset of initial engagement), H + 3 (3 hr later), and H + 12 (12 hr later). The combat resources consisted of five combat readiness parameters: tanks, Bradleys, ammunition, fuel, and personnel. Three of these parameters (tanks, Bradleys, personnel) were computed as a simple percentage of the full complement. Ammunition was computed as the number of potential armored vehicle kills (all 120-mm rounds + all antitank missile rounds + the 25-mm rounds/10). Fuel was computed as the unit range in kilometers (using the fuel economy of the M1 Tank).

Interfaces

The Introduction section provides details re-

garding the two interfaces, and only minor qualifications will be provided here. Two of the authors (Talcott, Martinez) completed an abbreviated U.S. Army course on the actual FBCB2 interface. The experimental FBCB2 interface was designed to replicate the visual appearance and selected functionality of this interface as it appeared in December 2000. The experimental interface differed from the actual interface in three respects. First, tank and Bradley resources were separated. Second, fuel and ammunition were calculated as range and potential kills (instead of gallons and rounds, as described previously). Third, platoon-level data were simplified (only platoon status E-mail messages appeared) and more organized (listed in order of company or platoon, not in the order they were received). These changes were introduced to provide equivalent information, thereby making comparisons with the RAPTOR interface more meaningful.

Procedure

Participants completed four sessions on successive days. In the training session (2 hr) all participants received both written and oral descriptions of the simulation, interfaces, and experimental tasks and completed a practice session using both interfaces. Participants then completed one experimental session (1 hr) on each of 3 successive days. Each experimental session contained six blocks of trials formed by a factorial combination of the two interfaces and the three combat phases. The order of these six blocks was randomized.

Three types of questions were administered. A “quantitative assessment” question asked for the quantitative value of a combat readiness parameter (tanks, Bradleys, ammo, fuel, personnel) for a particular unit (e.g., “What is the numerical value of tanks in Company C?”). A “categorical assessment” question asked for the categorical code (e.g., black, red, amber, or green) of a parameter for a particular unit (e.g., “What is the color-code status of fuel in the Battalion?”). A “needs assessment” question asked which of the various units at a particular level needed a particular resource (e.g., “What platoon in Company B needs Bradleys?”). The participants were instructed to respond as accurately and as quickly as possible; no discussion of specific strategies was provided.

A total of 18 trials were completed during a block of trials; each block consisted of two sets of 9 trials (a factorial combination of the three

echelon levels and the three question types). The presentation order of the trials within a subblock were randomized. The specific company (one of four) or platoon (1 of 12) and combat readiness parameter (one of five) that appeared in a question was chosen at random. Participants pointed and clicked on buttons (see Figure 3a) to indicate their response. After each trial the participant was provided feedback on accuracy of his or her responses. Thus, participants completed 324 trials (18 trials in each of six blocks during three experimental sessions).

RESULTS

Accuracy scores were computed as correct or incorrect. Latency was measured from the appearance of a question until the initial response (1/20-s

accuracy). Latency outliers were identified using the test described in Lovie (1986, pp. 55–56): $T_1 = (x_{(n)} - x)/s$, in which $x_{(n)}$ is a particular observation (one of n observations), x is the mean of those observations, and s is the standard deviation of those observations. Accuracy scores associated with latency outliers were also not considered. The percentage of outlier scores was 2.24%, 1.62%, and 1.77% for the quantitative, categorical, and needs assessments, respectively. Nonparametric tests were conducted to assess the distribution of outliers across experimental conditions; none was significant. Remaining scores were averaged across battle phase, session, and repetition; a set of five preplanned orthogonal contrasts were performed (see Figure 5a). The results of the preplanned contrasts involving interface are listed in Figure 5b. Additional contrasts were performed to assess the

Contrast #	Verbal description:	Interface, Echelon:					
		RAPTOR, Battalion	RAPTOR, Company	RAPTOR, Platoon	FBCB2, Battalion	FBCB2, Company	FBCB2, Platoon
1.	Main effect – interface	1	1	1	-1	-1	-1
2.	Main effect – echelon: battalion (B) vs. company (C) / platoon (P)	2	-1	-1	2	-1	-1
3.	Main effect – echelon: C vs. P	0	1	-1	0	1	-1
4.	Interaction effect – interface × echelon: B vs. C/P	2	-1	-1	-2	1	1
5.	Interaction effect – interface × echelon: C vs. P	0	1	-1	0	-1	1

A.

Contrast #	Quantitative				Categorical				Needs			
	Accuracy		Latency		Accuracy		Latency		Accuracy		Latency	
	F	p <	F	p <	F	p <	F	p <	F	p <	F	p <
1. Interface	<i>ns</i>		231.39	.01	10.49	.01	79.52	.01	13.15	.01	51.36	.01
4. Interface × B vs. C/P	9.61	.02	179.41	.01	11.14	.01	62.98	.01	15.28	.01	<i>ns</i>	
4a. Interface at B	8.92	.02	207.08	.01	21.24	.01	70.76	.01	<i>ns</i>			
4b. Interface at C/P	<i>ns</i>		145.25	.01	<i>ns</i>		34.38	.01	16.18	.01		
5. Interface × C vs. P	<i>ns</i>		<i>ns</i>		<i>ns</i>		18.42	.01	<i>ns</i>		113.36	.01
5a. Interface at C							59.34	.01			112.00	.01
5b. Interface at P							10.10	.01			<i>ns</i>	

B.

Figure 5. Preplanned contrasts and empirical results. 5a. Preplanned, orthogonal contrasts conducted for interface and echelon level, including contrast weights. 5b. F-values and significance levels for the preplanned contrasts involving interface and for the tests of the simple main effects of interface (following a significant interaction). A shaded cell signifies performance advantages favoring the RAPTOR interface; *ns* signifies that a contrast was conducted but the results were not significant at the .05 level. B = battalion, C = company, P = platoon.

simple main effects of interface when significant interface by echelon interaction contrasts (Contrasts 4 and 5) were obtained; the results are also listed in Figure 5b. The interface and echelon interaction means for each of the three assessments are illustrated in Figure 6.

DISCUSSION

The pattern of results was clear and unequivocal, indicating that the RAPTOR interface was more effective than the FFCB2 interface. Five of the six contrasts testing the main effect of interface were significant (Contrast 1, Figure 5b); there were seven significant interaction contrasts (Contrasts 4 and 5, Figure 5b) and 10 significant contrasts for the simple main effects of interface (Contrasts 4a, 4b, 5a, and 5b). Each statistical comparison between interfaces that was significant indicated that performance with the RAPTOR interface was better than performance with the FFCB2 interface (these contrasts are highlighted with grayscale shading in Figure 5b; see also Figure 6). The superior performance of the RAPTOR interface was present in all assessment categories (quantitative, categorical, and needs), dependent variables (accuracy, latency), and echelon levels (battalion, company, platoon).

These results clearly indicate that the RAPTOR interface provided better support for obtaining friendly combat resources than did the FFCB2 interface. They will be interpreted from the cognitive systems engineering perspective (Rasmussen et al., 1994) alluded to in the Introduction (see Bennett & Walters, 2001, for a focused discussion in the context of display design). Specifically, overall performance will be determined by the quality of mapping between three sources of constraints: those constraints contributed by the domain (the demands to be met), the agents (capabilities/limitations), and the interface (requirements introduced through design). The discussion will be organized around the principles of direct perception and manipulation.

Direct Perception

The RAPTOR interface was specifically designed to support direct perception, as discussed in the Introduction section. The content mappings (domain constraints ↔ interface constraints) were effective: information from the various categories of the abstraction hierarchy were present in the

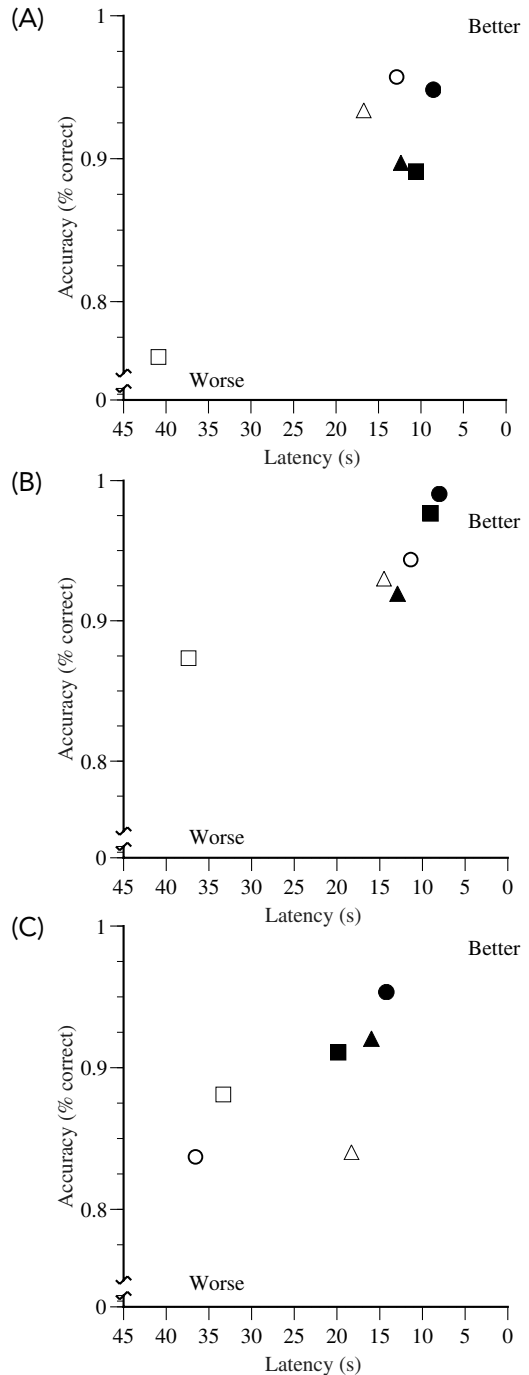


Figure 6. Mean levels of performance for all interface and echelon combinations. Accuracy is plotted on the y axis; latency is plotted on the x axis (note that better performance is located in the upper right portion of the graph). Filled and unfilled symbols identify means obtained with the RAPTOR and the FFCB2 interface, respectively. Squares, circles, and triangles identify means obtained for the battalion, company, and platoon echelon levels, respectively. (A) Quantitative assessment. (B) Categorical assessment. (C) Needs assessment.

interface, as were consistent summaries of combat resources at all relevant echelon levels. The format mappings (display constraints ↔ agent constraints) were also effective. The graphical representations were carefully designed to reflect the inherent constraints of the domain information being represented (e.g., unique representations for each combat parameter) and to support information pickup (e.g., categorical, analogical, and alphanumeric visual information corresponding to assessment requirements). The constraints introduced by the RAPTOR interface allowed skill-based interaction: It decreased the amount of cognitive resources and mental effort required and allowed the agent to use powerful visual perceptual skills to obtain information regarding friendly combat resources.

In contrast, the FBCB2 interface did not support direct perception effectively. The quality of the content mappings was poor. There was little regard for the categories of information that should be present in the interface (i.e., levels of the abstraction hierarchy). In addition, data regarding friendly combat resources were presented in piecemeal fashion (e.g., no summarization or integration across lower echelon levels). The quality of format mappings was equally ineffective. The primary form used to represent combat resources was alphanumeric (i.e., the long-form messages) as opposed to graphical. This forces the agent to use limited cognitive resources (i.e., working memory) to derive information mentally. (For more detailed discussions of similar considerations, see Bennett & Flach, 1992; Bennett, Nagy, & Flach, 1997; and Bennett & Walters, 2001.) As a result, acquiring information with the FBCB2 interface requires extensive search (i.e., navigation through multiple screens to locate all of the relevant data) and extensive cognitive processing (maintaining and manipulating these data in limited-capacity working memory). In summary, although the FBCB2 interface provides an abundance of low-level alphanumeric data, there is actually very little graphical information about domain resources to be perceived directly.

Direct Manipulation

The RAPTOR interface provides resources that support direct manipulation. Consider the quote by Norman (1986), who described direct manipulation as “the qualitative feeling of control that can develop when one perceives that manipulation is

directly operating upon the objects of concern to the user. The actions and the results occur instantaneously upon the same object” (p. 53). A critical control function for a commander engaged in tactical operations is to change his or her span of attention to monitor progress and coordinate activities across the organizational hierarchy (i.e., battalion, company, platoon). The commander needs to control the grain of resolution at which friendly forces are considered and to see these units in the context of the battlefield terrain. The RAPTOR interface supports this need by providing icons that represent these real-life objects of interest (i.e., the 17 units of action) and their resources directly. These icons can be manipulated directly to change both the resolution (i.e., the various units of action) and the context (whether the icons appear on the battlefield terrain) of combat resource information.

The surface appearance of the FBCB2 interface suggests that direct manipulation is present: the tabs, buttons, and fields are graphical objects that can be pointed at and clicked on. However, this surface appearance is misleading. The graphical representations of the real-life objects of interest (i.e., the unit symbols on the contour map) cannot be manipulated directly: Obtaining combat resource information involves indirect manipulation of the tabs, buttons, and fields. The lack of direct manipulation resources in the interface imposes inefficient action sequences. Changing the resolution of combat resource information (e.g., viewing the resources of a lower level unit) involves repeating the basic action sequence from scratch, as opposed to the context-conditioned shortcuts enabled by RAPTOR (e.g., pointing and clicking a company icon on the map). Direct manipulation cannot be used to view combat resources in the battlefield context: The map is covered by the large display windows (see Figures 3 and 4). In summary, the FBCB2 interface may well qualify as a “graphical user interface”; however, the manipulation that it supports is far from direct.

GENERAL DISCUSSION

These results indicate that the perception-action icons design strategy provides an effective solution for a critical challenge posed by one intermediate domain, military command and control. Early theoretical perspectives of human-computer interaction (Hutchins et al., 1986) emphasized the role of direct manipulation, to some degree at the expense

of direct perception. In contrast, theoretical perspectives on interface design for law-driven domains tend to emphasize the role of direct perception, in part because direct manipulation of higher-order properties is not feasible, given the many-to-many mappings and conflicting goals that characterize these domains. Insights from ecological psychology (e.g., Gibson, 1966) suggest that direct perception and direct manipulation have a far closer and much more symbiotic relationship. More specifically, this work suggests that the incorporation of an intact perception-action loop should be considered as a higher-order goal in interface design. The perception-action icons in the RAPTOR interface achieve this goal: The agent uses highly efficient perceptual-motor skills to pick up the affordances presented in the space-time signals in the interface (direct perception of the icons) and to coordinate and synchronize execution of critical control functions for controlling the span of attention (direct manipulation of the icons).

The potential for the perception-action icons design strategy to generalize beyond the context of military command and control will now be entertained. This strategy is a hybrid solution that adapts and draws selectively from general strategies developed for domains located at the ends of the continuum. The perception-action icons design strategy will be compared and contrasted with these general strategies so that its defining characteristics are clear. The factors that contribute to the success of this design strategy for the current intermediate domain (i.e., military command and control) will be described. Another intermediate domain and the potential utility of the perception-action design strategy will then be considered.

The constraints in law-driven domains have a high degree of regularity that facilitates analysis and modeling; the critical design activity involves the mapping of domain constraints into analog geometric representations that provide concrete spatial analogies. Configural displays can be particularly useful in this role, at least when designed properly (e.g., Bennett & Flach, 1992): They will produce higher level visual features (e.g., closure, symmetry, parallelism) and dynamic behaviors that accurately reflect domain constraints. The interface constraints that are imposed by this design strategy are well mapped to powerful skill-based behaviors of the human agent (e.g., the pickup of visual information). The human agent can “see” system states and potential solutions,

rather than deducing them. Note that the domain constraints are inherently complex; therefore, the visual analogies will also be rich and complex. Thus, the success of this design strategy relies upon a knowledgeable and experienced human agent.

In intent-driven domains there is less regularity in the constraints of the domain, and therefore the agents’ intentions and goals play a larger role in the unfolding interaction. These users will typically have far more diverse sets of knowledge about the domain, more diverse sets of computer skills, and less extensive experience with the decision support system. The use of spatial metaphors in the interface can relate the requirements for interaction to more familiar objects and activities, thereby leveraging preexisting concepts and knowledge. For example, the BookHouse system (Pejtersen, 1992) uses spatial metaphors extensively to assist agents in locating a book of fiction. The interaction requirements are related to familiar activities: The agent navigates through an overarching spatial metaphor (i.e., a virtual library) to select subsets of books (i.e., enter a different wing of the library) and to execute different search strategies (i.e., enter a different room). Similarly, specific search terms are specified through the direct manipulation of icons with spatial metaphors that “suggest” the search term through an associative link to preexisting concepts in semantic memory. Thus, the icons provide affordances and serve as signs that represent the various actions that can be executed.

The perception-action icons design strategy draws selectively from these two categories, adapting the details to the context presented by military command and control. First, the overlap with the design strategy for intent-driven domains will be considered. The extensive use of icons to facilitate interaction is a key feature of both design strategies. In both cases the icons present affordances and serve as signs for actions that can be taken; the icons can be manipulated directly to execute these control inputs. A key difference lies in the visual representations that are used in these icons. The icons for intent-driven domains (e.g., the BookHouse) use metaphorical representations that relate interaction requirements to more familiar concepts and activities. In contrast, the RAPTOR icons contain a variety of representations (geometrical, categorical, symbolic, alphanumeric) that are designed to convey specific and detailed information about the domain. Herein lies

the overlap with successful design strategies for law-driven domains. A unit's combat resources are the tangible contributors to the overall combat power of the unit; the value of these continuous variables must be conveyed directly, not metaphorically.

More fundamentally, the need for the perception-action icons design strategy appears to arise from the defining characteristics of the objects of interest in the domain of military command and control. First, consider the objects of interest at the two end points of the continuum: The objects for intent-driven domains are essentially independent and loosely coupled (e.g., books of fiction); the objects for law-driven domains are highly dependent and tightly coupled (e.g., mass balance, energy balance). The objects of interest in military command and control (in this case, the various units of action) possess both of these qualities. The units are clearly dependent and coupled (e.g., organizational structure, coordinated mission goals), unlike the objects of interest in intent-driven domains. At the same time, they also possess a potentially high degree of independence (e.g., independent resources, independent mission roles), unlike the objects in law-driven domains. The perception-action icons design strategy is successful because it supports these dual needs. Information regarding combat resources can be obtained collectively or individually through the direct perception of the icons that correspond to the 17 units of action constituting the organizational structure of the battalion. Direct manipulation of these icons allows the combat resources to be considered at the proper grain of resolution and context for assessing progress toward collective or individual mission goals.

The perception-action icons design strategy is likely to be successful for other intermediate domains to the extent that the objects of interest in these domains share the defining characteristics outlined previously. Another intermediate domain will be examined in greater detail to explore this possibility. Flexible manufacturing qualifies as an intermediate domain, primarily because of the incorporation of "just-in-time" production strategies (Rasmussen et al., 1994) that require substantial discretion on the part of the operator. A representative example is described by Dunkler, Mitchell, Govindaraj, and Ammons (1988). Several categories of products are manufactured; each category is associated with a different set of man-

ufacturing constraints. These constraints include the number and type of machining operations, the temporal sequencing of these operations, and the amount of time that is required. There are a limited number of configurable machining cells that can be used to perform the various operations. There is also an automated scheduler. However, the automated scheduler is not always capable of producing an acceptable solution, given the complex space of manufacturing possibilities (including inventory). Therefore operator intervention is often required. In summary, there are collective system goals with regard to both the category and the number of products that need to be produced within a particular time frame. Meeting these goals, however, requires the consideration of individual products: the number, type, and sequencing of the machining operations that need to be accomplished if the product is to be completed on schedule.

Although the surface details are different, the defining characteristics of the objects of interest are reasonably similar to those in military command and control, and it appears that perception-action icons would provide a very effective interface design strategy for this domain. Direct perception could be achieved by designing an icon that graphically represents the manufacturing goals and constraints associated with an individual product (e.g., machining operations and scheduled completion times relative to production goals). The direct perception of these constraints would clearly specify instances in which the operator needs to override the automated scheduler to expedite the processing of a product that is late. In turn, the operator could execute this control input through the direct manipulation of these icons (i.e., dragging and dropping an icon on the graphical representation of a machining center or processing buffer). In summary, the results of the present evaluation and an analysis of the potential for generalization suggest that perception-action icons constitute an interface design strategy that will prove successful for other intermediate domains.

ACKNOWLEDGMENTS

We would like to thank the officers of the 4th Brigade, 85th Division (Training Support), who volunteered to participate in this experiment. We would also like to thank the numerous U.S. Army officers who provided their valuable input and feedback during the design of the RAPTOR interface. This

work was supported through participation in the Advanced Decision Architectures Collaborative Technology Alliance sponsored by the U.S. Army Research Laboratory under Cooperative Agreement DAAD19-01-2-0009. The study reported in this article was completed in partial fulfillment of the requirements for the master of science degree for Christopher Talcott.

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Date received: June 20, 2002

Date accepted: December 22, 2005