Seeing the Labyrinth: Visualizing a DoD Training Support System of Systems

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ABSTRACT

There is a necessity to model the Army Training Support System in order to improve its businesses practices and the overall decision-making process. Visualization has been chosen as a primary tool to represent the Training Support System of systems. The reasons for this approach are based on the complexity of the system. The TSS is so complex that it challenges the human capability to comprehend different interrelationships, activity flows and processes in an integrated way. New tools are needed in order to support the comprehension of such a complex system. The central idea is that, given the characteristics of human visual perception, human performance can be improved by providing displays that allow better use of the efficient processes of perception and pattern recognition. Additionally, the appropriate design of such tools will reduce the load of cognitively intensive processes of memory, integration and inference. Perception and cognition theories are used to provide a solid foundation in order to develop an effective visualization tool, which should minimize the perceptual processing load and free the mind for cognitive processes needed of managers and decision makers. Appropriate integration of concepts from complex systems, enterprise architecture, and human factors theories is being done to develop a methodology for building complex system visualization tools. This emerging methodology is based on the development of an integrated theoretical framework and the validation of such a framework by experimental findings.

ABOUT THE AUTHORS

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INTRODUCTION

The U.S. Army's Training Support System (TSS), as defined by the Army Training Support Center (ATSC), is a complex systems of systems that provides the networked, integrated, interoperable training support necessary to enable an operationally relevant training environment for warfighters. To accomplish its goal, the Army requires tools to support human understanding and decision making as part of the TSS. Among those needed tools, a visualization of the complex organization is proposed as a promising way to increase the awareness about the TSS enterprise. The development of such visualization tools leads us to pursue the understanding of what are complex organizational systems and their demands on human cognitive and perceptual processes, and why and how visualization can help coping with complexity. A methodology to build complex organizational visualization is intended to provide a framework for complex systems modeling and visualization.

THE PROBLEM

The ATSC is the Army's training support manager, planner, integrator, service provider, and researcher. The TSS as defined by the ATSC is a systems of systems that provides the Army with the networked, integrated, interoperable training support necessary to enable an operationally relevant training environment for war-fighters (Army Training Support Center, 2004). The TSS is composed by many training capabilities. Those capabilities are the different units that enable training to occur. Those capabilities have been organized in categories, under a hierarchical structure. However, the full interoperation and interdependencies are not clearly understood. Decisions made within one capability have impact over other capabilities but that impact cannot be evaluated since the interoperations and interdependencies are not clear. Those decisions determine and are determined by the called TSS business practices. These business practices involve management process and the planning, execution and assessment of training support practices. The knowledge of the effect produced by those business practices and the decision-making process within a capability is a necessity in order to improve the effectiveness of the whole system. A system with these characteristics can be considered a complex organizational enterprise. In general, enterprises that show this complexity demand the creation of new tools to help them dealing with the challenges that complex organizational systems generate.

HUMAN FACTORS CHALLENGES OF COMPLEX ENTERPRISES

The understanding of complex organizational enterprises by humans is bounded by available information as well as our cognitive and perceptual capabilities. Individuals dealing with complex organizations, such the TSS are required to work and make decisions based on their current understanding of organizational processes, components, interrelationships, and relevant situational information. Accordng to Heylighen (1991), due to such difficult challenges concerning understanding of organizational complexity, managers in these organizational environments require new tools and mechanisms to enable increased organizational awareness and management of emergent organizational behaviors on a higher, more abstract level.

One view of a complex organizational system is to view it as a higher-level metasystem. According to Keating et. al. (2002), the metasystem is itself a complex system that is comprised of multiple embedded autonomous complex systems. These systems are embedded because they are now within the boundaries of the higher level metasystem. Therefore, it follows that an enterprise's autonomy (freedom of decision, action and interpretation) is constrained by the perceived framework and views of the metasystem by enterprise participants.

The TSS is a very "large" system that involves many organizational units, architectures and standards, product lines, services and management processes. The ATSC has made significant progress toward determining components of the TSS and the hierarchical categorization of those components. Additionally the ATSC has determined the general pattern of operation and specified TSS operational capabilities. Even though this categorization provides understanding of the enterprise, an integrated metasystem view is needed.

However, enterprise metasystems can quickly become a confusing labyrinth when trying to understand dynamic interrelationships between embedded systems and components. Such understanding for the TSS, which is necessary to achieve future training support goals, is not clear, and has not been documented or formalized. As requirements for future force training support environments become more complex, and interoperable synthetic training environments become more sophisticated, the need to integrate the training event processes and functions within the TSS enterprise will become even more critical. This integration involves understanding interrelationships among components, and differentiating various types of interrelationships, (e.g., whether it is an activity precedence relationship, information flow, or decomposition). Individuals also need to identify the TSS organizational components and relationships related to a specific activity or process and what is the evolution of this network of interrelationships through time. Difficulties arise because of complex system dynamics including; intricate processes, a high numbers of activities, many different requirements, local and global objectives, many outcomes and outputs, and the interoperation of all components requiring harmonization of schedules and requirements.

Efforts to model the TSS have focused on enterprise architecture frameworks. However, the potential to communicate those models and to share a common understanding require an additional effort to effectively portray such models.

VISUALIZING THE LABYRINTH

A visualization approach shows great potential to help address the challenge of understanding enterprise metasystems. Woods stated that visualization can be a powerful aid to comprehension and conceptualization. (Woods, 1988). According to Woods, performance can be improved dramatically by the use of analogical representations. When studying, complex systems, including the relationships and connections among parts is important, since those relationships are what define the nature of a system. Grantham has stated that awareness of all the facts can be seen as knowledge, but seeing the connections between the facts (their relatedness) is understanding. He adds that constructing models is one thing, but visualizing them is another. According to Checkland (1981), "a diagram is an improvement of linear prose as a means of describing connections and relationships." Grantham (1993) refers to synthetic inquiry, which makes use of complex images presenting several people with the same image of reality, as one of the needs for complex systems understanding. Grantham emphasizes that "displaying critical information in visual form has cognitive impact beyond that of mere listing of numerical data." Visual images are very dense, because it is not only the elements themselves, but also their relationships of one another that are important. Visualization of organizational functioning is a very promising application of virtual reality technologies because it fits with how people cognitively process complex information. According to Bennett & Flach (1992), human performance can be improved by providing displays that allows the observer to utilize the more efficient processes of perception and pattern recognition instead of requiring the observer to utilize the cognitively intensive processes of memory, integration and inference.

METHODOLOGY CONSIDERATIONS

Even though visualization shows promise for enterprise representation, types of representations vary in their effect on information processing activities and problem solving performance. The perspective of representation design is important because there are many cases in the history of human-system interface where technology choices contained no intentional design approach relating to the form and the content of a representation. For this reason, a methodology to ensure the appropriate representation is a necessity. Currently, graphics displays related to enterprise and systems of systems architecture frameworks do not have strong foundations in psychological research of visual representations.

Because of this lack of scientific foundation, a methodology to organize visual display design and research for enterprise representations is needed. According to Dryer (1996), applied graphical syntax research investigates the interactive performance between user and graphical information display. This performance depends on efficiency of basic visual information processing afforded by the visual elements of the display (Cleveland & McGill, 1984; Kosslyn, 1989). Dryer stated that the level of basic psychophysical visual research transitions to, and directly influences, the applied graphical research level of information display design.

Additionally, according to Zhang and Norman, what is represented is relevant. The external representation of the domain in supporting artifacts affects performance by making certain information or manipulations of information more accessible at the expense of others. It is a fundamental scientific finding that how a problem is represented affects the cognitive work that is needed to solve the problem. This is referred to as the representation effect (Zhang and Norman, 1994). Matching the physical appearance of the display to meaning requires design processes with solid theoretical foundation. This theoretical foundation is summarized in the following paragraphs.

Syntax versus Semantics

The physical characteristics of graphic displays and how these characteristics interact with the perceptual capabilities of an observer are considered syntax (what do the parts look like, and how do they perceptually fit together). However, the display syntax must be considered in the context of what the display means. These are the semantics of the display relating to the underlying meaning of various display attributes. What the display represents in the context of problem solving is involved in its semantics. To address complex enterprise system understanding, we need to determine a visualization methodology with an effective integration of semantic and syntax approaches.

Semantic to Syntactic Mapping Concepts

The integration between visualization semantics and syntax relates to mapping of display concepts to representations. Woods & Roth (1998) state that, "in analogical representation the structure and behavior of the representation (symbol) relates to the structure and behavior of what is represented (referent). This means that perceptions about the form of representation correspond to judgments about the underlying semantics, for example, a relationship between two elements of the representation corresponds to a relational semantic property of the world."

The semantic mapping principle states that displays should be designed so that there is a one to one mapping between the invisible abstract properties of the process and the cues or signs provided by the interface. Bennett and Flach state that if the display produces highly salient emergent features and these emergent features directly reflect the critical data relationships and inherent constraints in the domain, then improved performance is likely to follow. They add that a good analogy is one in which the relational structure of the base domain (that which is understood) maps to critical structures in the target domain (that which is to be understood) (Bennett and Flach, 1992).

One of the strong forms of analogical representation is the use of integral displays or object graphic forms (Woods & Roth, 1998, Wickens, 1986). Integral displays have many potential advantages for improved user information extraction. However, Woods & Roth state that the real challenge is to map task-meaningful semantics to such integral displays. This is a more difficult challenge if the object we want to represent is a complex system consisting of many components with a high number of relationships.

Observation Process and Scale of Representation

Other key concepts for methodology consideration relate to the observation process, description, and scale of representation. According to Bar-Yam (1997), effective descriptions have consistent precision, so that all necessary information is present, but unnecessary information is minimized. The observation process is important because there is a finite complexity of any entity at a particular scale. One must choose a scale at which to observe a system. Scale refers to the level of detail, not the scope. The complexity of an entity is a function of the scale of observation. A key issue is identifying the scale of observation (i.e., the level of detail that can be seen by an observer) or the degree of distinction between possibilities.

Given these key concepts for methodology consideration, the question is how can we build graphic displays for complex organizational systems organizations?

THE PROPOSED APPROACH.

The development of the methodology is based on a theoretically and experimentally-derived foundation for visual display of complex systems that will facilitate the information decoding and comprehension of system components and interrelationship dynamics. This methodology is a modeling effort, which has shown promise in other domains. According to Fishwick (1995), modeling serves as a language for describing systems at some level of abstraction or, at multiples levels of abstraction. He adds that "models are used for the purpose of communicating with each other…models are a way to thinking and reasoning about systems". Adopting the terminology and methodology used by Dryer (1996) a roadmap of the research is described below. This roadmap contains four main components.

First component: Define the problem and domain semantics. This component implies the modeling of relevant semantics of the enterprise and the dynamics of the metasystem. Therefore, the first stage of the approach consists of capturing the relevant aspects of complex organizational systems. An architecture modeling approach is relevant to such systems. "An architecture is the fundamental organization of a system embodied in its components, their relationships to each other, and to the environment, and the principles guiding its design and evolution (IEEE Standard 147, 2000)." The U.S. Department of Defense (DoD) defines an architecture as the structure of components, their relationships, and the principles and guidelines governing their design and evolution over time, based on IEEE STD 610.12 (DoD Architecture Framework Working Group, 2003).

Concerning enterprise systems, various architecture frameworks have intended to present a structured high-level model, including enterprise information and business processes. The synthesis of such frameworks to enterprise metasystems is addressed and its relationship with complex systems theory is determined in this component.

After the enterprise semantic modeling process, the next step is to identify the information depicted by traditional graphical displays and the way those graphics represent the information

Second component: Mapping semantics to syntax. The second activity consists of deriving device display and task variables related to the problem domain, and the representation characteristics to support the tasks. The theoretical framework built for the first component will be used for this second component in order to define what are the considerations needed for the design. The focus of this component has been to study what is the information to be represented, how it should be portrayed, and whether or not improvements can be included. Also, new views of the system are considered.

Third component: Representation prototyping. A representation prototype is developed in this component for use in testing various representation treatments. This prototype needs to portray the range of promising features derived during the second activity. Critical problem domain semantic invariants shall be mapped to these promising displays features.

Fourth component: Usability testing. To measure the effectiveness of the visual display, the determination of the tasks needed to be performed by users is essential. In this activity, user evaluation and testing of the representation takes place. This can include formal experimental design and testing where promising feature combinations are structured as factors and treatments and empirically studied. The results from this experimental testing will be fed back into the feature and task mapping to provide enhanced information on effective relationships.

Carswell uses a three-way classification of decoding tasks requiring point-reading, local comparisons, or global comparisons (Carswell, 1992). These levels are discrimination, ranking, and rationing. Discrimination refers to determining if two values are equal or not equal. Ranking refers to deciding which of two values is greater than, less than, or equal. Rationing is a quantitative judgment of value proportions and differences. These task categories generally vary from involving focal attention to a single specifier (point reading) to those involving integration of many or all graphed values (estimations). Measures of task performance efficiency in these studies included response time and accuracy.

From the perceptual theory, the foundation of the methodology is based on providing a link between the relevant theory and the visual stimuli used in the visual representation.

ADOPTION OF PROMISING DISPLAY CHARACTERISTICS.

Promising display concepts, from perceptual theory and experimental studies are now described as considerations for mapping to enterprise semantics in the methodology's second component.
One of the concepts considered for the adoption of the configuration of display is based on the principle of

Proximity Compatibility (PPC). According to Wickens (1990), PPC depends critically on two dimensions of proximity or similarity: perceptual proximity and processing proximity. Perceptual proximity defines how close together two display channels conveying task-related information lie in the user's multidimensional perceptual space. Mental or processing proximity defines the extent to which one or more sources are used as part of the same task. The principle proposes a compatibility between these two dimensions. Additionally, we analyze here the Pomerantz classification of configural displays.

Display configurations can be classified into *separable*, *P-configural*, and *N-configural.* P-configural displays, according to Pomerantz, are those where perceptual properties emerge from the spatial positioning of discrete multivariate elements. P-configural displays exhibit Type P configuration properties, with elements acting as placeholders. Element positions define salient points on the configuration, similar to a constellation of stars (Pomerantz, 1981). N-configural displays occur when the nature of the elements, including position, orientation, and shape determine the configuration. The change of any single element in the display changes the overall configuration. (Pomerantz, 1981). The configural adaptation for the display depends on the characteristics of the configuration regarding emergent features, salience, preattentive perception and the possibility to attach semantic meaning to the configuration.

Grouping is also an important psychological concept relating to information display design. According to gestalt psychology, people group different visual elements together by certain patterns: proximity, similarity, continuity, and closure. Proximity states that objects that are spatially close will be perceived as being together (Zhou & Feiner, 1998).

Other considerations regarding complex systems visual tool design

Complex systems representations typically have the problem of a large number of data items. According to Ng (2000), if the number of elements is large it can compromise performance or even reach the limits of the viewing platform. Even if it is possible to layout and display all the elements, the issue of viewability or usability arises, because it will become impossible to discern between nodes and edges. In fact, usability becomes an issue even before the problem of discernability is reached. There is a tradeoff between displaying the whole structure of the system, and the display of detailed information. Limiting the number of visual elements to be displayed can improve the clarity and increase performance of layout and rendering. There is a balance between the amount of data represented in an display and the number of displays required to represent necessary complex system semantics.

The selection of promising configuration.

The selection of display configurations has a basis in the findings of Pomerantz on basic configurations and emergent features. This is done by analyzing existing graphic representations, adopting an evolving approach based on the identification information processing tasks, and proposing potential enhanced representations of that information.

One example of a systems modeling and visualization tool is CORE, from Vitech Corporation. CORE has diagrams to show different views of the system. In CORE, one diagram is the Enhanced Function Flow Block Diagram (EFFBD). As shown in Figure 1, the EFFBD from CORE has the classic features of logic structures and sequencing between functions and activities, as well as representing data triggers and flows (Long, 2002). An EFFBD has squares representing activities, boxes with rounded corners representing the data inputs and outputs, and arrows representing the relationships between activities to represent the flow of activities. Arrows also link the inputs and outputs to activities and triggers. EFFBD diagrams grow in complexity when there are several activities affected by the same input. The number of relationships can grow quickly when the input affects all the activities on the sequence process.

In initial analysis of the EFFBD, we have found the following information display problems:

1. Arrows are over used. There are multiple meanings for arrows with the same syntactic representation. Arrows are using to represent relationship between inputs and activities, outputs and activities, triggers and activities, between activities, and to represent the flow of activities.
2. To distinguish activity inputs and outputs is challenging, since there are many intersected lines and obscuration of arcs from boxes representing the inputs, outputs, triggers, and activities.

3. The use of space is not adequate. The use of opaque identification labels for numerous activity and information elements takes up a majority of display space and the location of those elements is random.
4. The representation of several sequences of activities requires a large visual space, and the computer screen is not enough. Scrolling is needed and the visualization of an integrated view is almost impossible.

The following are critical system elements needing representation:

- Inputs: differentiation among type of inputs and input destinations
- Outputs: differentiation among different type of outputs and output destinations
- Activities: determining type and logical sequencing of activities
- Triggers. Inputs with sequencing control over various activity processes
- Hierarchy: Decompositions of various entities

There are several particular data items within each set of elements. The representation requires differentiating between sets, and particular data items. With a coding system, the unique representation of each data item is possible, keeping a common representation for all the elements within the set, and varying one feature to represent each element. The coding has been developed using a grid filled with patterns and gaps. Varying the position of the gap in the grid produces the coding. If the grid has a size of 4 by 4, there are 16 possible locations for the gap. Therefore, 16 different data items can be codified with that grid. Combining different patterns, we can codify more sets of data items. One pattern can represent inputs and another pattern outputs.

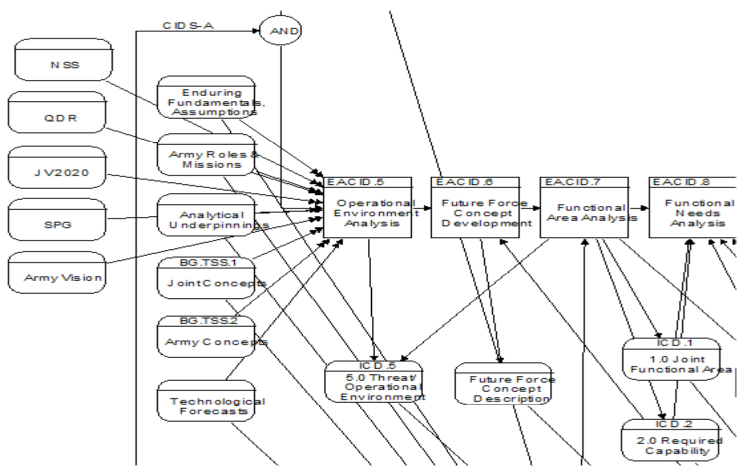

Figure 1. Example of traditional EFFBD view

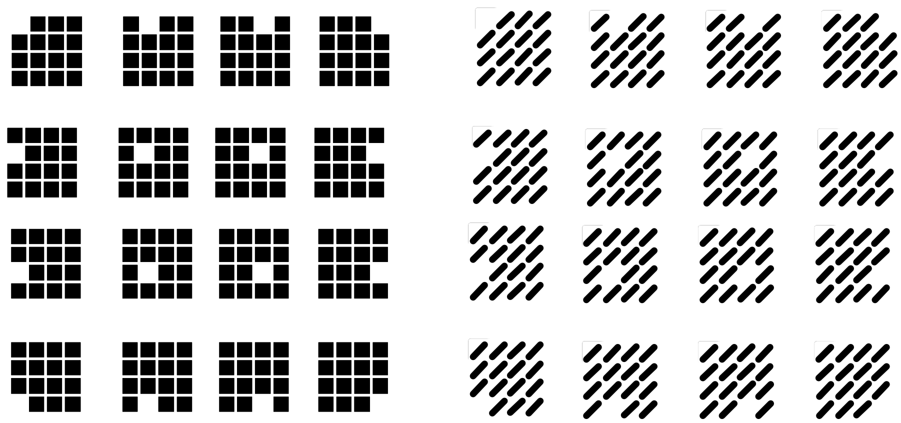

Figure 2. Example of codification using patterns

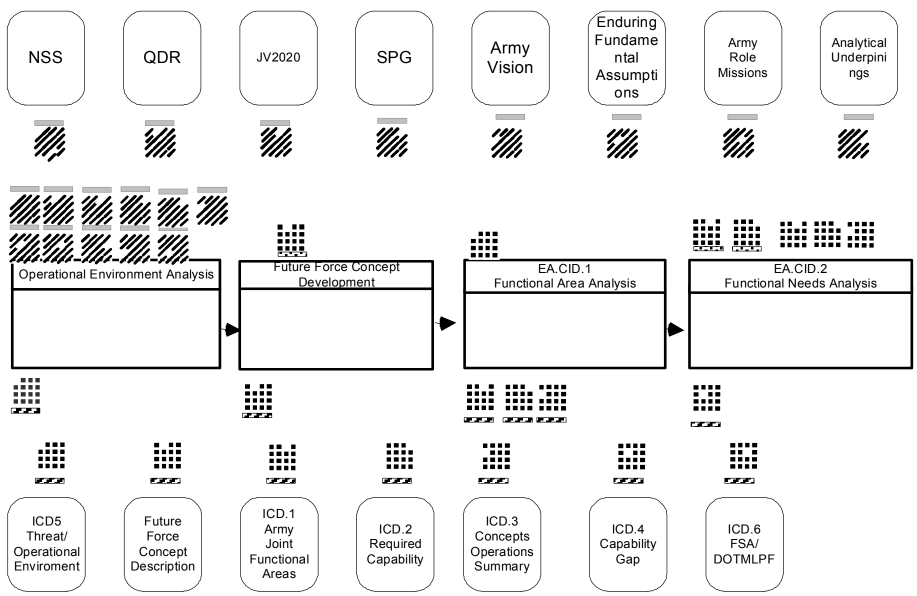

Figure 3. Example of visual representation of EFFBD using patterns to represent inputs and outputs

These patterns are used in the following way as shown in Figure 3. Each pattern represents one data item. For example, output labels and associated patterns are located on the bottom of the figure. Output patterns are then located below associated activities, using proximity to indicate the relationship, which avoids the use of arrows. Using this approach, emergent feature principles (according to Pomerantz) used for the design are:

Orientation. The slope of the line.

Proximity. A feature that emerges from the placement of two or more separate elements. (Pomerantz, 1989)

Similarity. A feature that emerges from the distance separating two or more primitives on some dimension such as color or size. (Pomerantz, 1989)

Lattices are used, combining these features, to create a set of symbols to represent sets of data items. Changes using squares, lines, and dots, can codify different information flow sets, such as inputs, outputs, and trigger flows. The impact of these configurations need to be evaluated according to visual sequence and composition. According to Zhou and Feiner (1998), if visual elements are organized in the right sequence, the resulting presentation will guide a viewer to process information efficiently.

With usability testing, we will determine the effectiveness of proposed codifications to represent the information related to activities. We also will determine the pre-emergent perceptual effect of proposed configurations.

Guidelines creating the design:

To this point in the methodology development, the following guidelines for creating complex system enterprise representations are emerging.

1. Innovation: The information needed to be represented can be presented in the visual display by using multiple emergent feature perceptual stimuli. New designs can break with the traditional mental model of the problem if the perceptual basis of the display is sound. It is expected that newly assigned visual representations could be adopted and accepted after the user gets familiar with the representation's semantic meaning. One example is the substitution of arrows to represent relationships. Mostly in systems diagrams, arrows connecting objects of different shapes has traditionally represented relationships and the set of arrows represent networks. However, the use of arrows when high number of relationships is present creates occlusion and the task of distinguish one relationship from another is hard or impossible. Several strategies to represent relationships and networks without arrows and using some emergent properties of stimuli such as proximity, closure etc., are being developed and tested.

2. The evaluation of the effectiveness of the visual display should be developed by experiments comparing the performance of users when using different display configurations. Representation performance will be evaluated with metrics based accuracy and response time. The task analysis gives more detail about the list of tasks the users have to perform.

3. The visualization of the TSS will be completed by the integration of different views of the system, not by one single view. The different views are based on the standard views given by the DoD architecture framework. In this case, the methodology is evolutionary instead of revolutionary, since the traditional views of systems are used as a starting point. The use of enterprise architecture views allows user testing concerning understanding of a common mental model. The base case for experiments evaluating the effectiveness of the display is given by current representations provided some enterprise software tools.

4. The representation of items of information from different views will use a similar coding approach, combining the use of traditional representation with lattices to enhance the use of space, and the cognitive and perceptual processes.

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