Work Domain Analysis for Ecological Interface Design of Tangible Interfaces

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ABSTRACT

This research developed a Work Domain Analysis (WDA) to help in guiding the design of a user interface for the Augmented REality Sandtable (ARES). ARES combines the traditional military sandtable used in sandtable exercises with projected topography. It leverages commercial off the shelf software in an effort to provide affordable simulation technology. In order to create an interface that is usable, valid, representative of the environment, and free from unnecessary elements, there is a need to perform a top to bottom domain analysis that can be validated by experts. This assists in deciding interface grouping, visual mapping, and ease of learning in the operational environment. WDA takes the relationships that exist between interface components and translates those into tangible interface design specifications. WDA, a foundation for ecological interface design (EID), will be leveraged in future usability experiments as well as the incorporation of a tutor to ARES. The WDA uncovered common functionality and unexpected relationships between the interface components to better support the tasks of land navigation, and military tactics training to support mission needs. Detailed breakdown of these domains can help to serve as guidance for other projects looking for a structured basis for interface design.

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INTRODUCTION

Cognitive Work Analysis (CWA) is a framework used to analyze complex socio-technical systems. It has an emphasis of analyzing a system in terms of its constraints (Vicente, 1999). It has been applied across several domains including, fighter aircraft cockpits, air traffic control, nuclear power generation, military command & control, and healthcare information systems. CWA is composed of five phases: Work Domain Analysis (WDA), control task analysis, strategies analysis, organizational analysis, and competencies analysis, each used to analyze different levels of constraint specificity (Vicente, 1999).

This paper uses a process defined in Naikar (2013) to use WDA to assist in mapping out domain requirements to support development of Ecological Interface Design (EID) (Rasmussen & Vicente, 1989). The Augmented REality Sandtable (ARES) will serve as an applied use case for this process. ARES is a research proof-of-concept that was developed from the concept of a military sand table (McNab, 2012), and uses a commercial off-the-shelf projector integrated with a Microsoft Kinect™ to display content on manually-contoured sand that the user can interact with, as shown in Figure 1. The goal is to demonstrate the applicability of WDA for simulation interface requirements definition across domains.

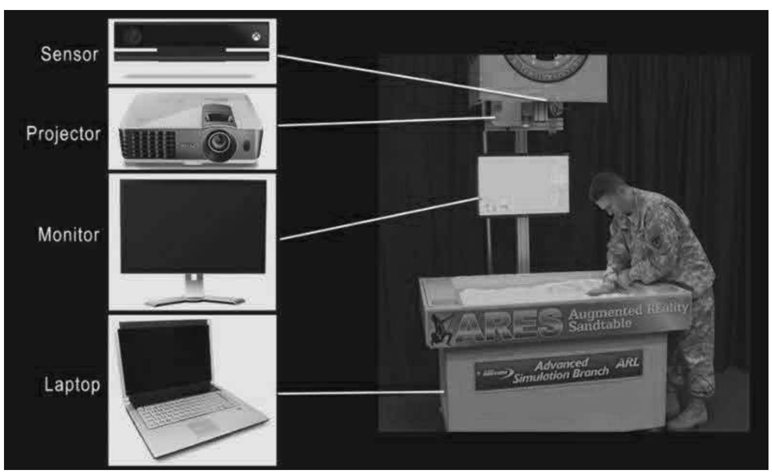

Figure 1: The Augmented REality Sandtable

Work Domain Analysis (WDA)

WDA is a functional model of user constraints during interaction with the system (Naikar, 2013). WDA takes a systems approach, understanding the social and technical limitations of the domain. WDA addresses systems in relation to a range of user roles, mental models, and situation understanding based on the information provided. Developing the model using constraints can identify those pieces of information that are most often needed, as well as providing the flexibility to adapt to unexpected situations (Naikar, 2013). According to Vicente (2002), this ability is the added value of WDA as opposed to one of the other human factors engineering tools, such as task analysis. While a task is defined into a series of actions (something you "do," verb) to produce a goal, a work domain is independent of any person, technology or interface (something you "act on," noun). If you do not know what the task is, modeling it is not possible, but the domain has characteristics that can be applied across situations (Vicente, 2002).

The visual representation of the WDA, the Abstraction-Decomposition Space (ADS), is a table which has two dimensions. The abstraction dimension consists of an Abstraction Hierarchy (Rasmussen, 1985) which is a diagram constructed through means-end chain analysis. Means-end analysis (Gutman, 1982) is created such that each lower level provides a "means" to get the next higher level task done, and each higher level within the diagram is an "end" or result that occurs from activity at the lower levels. Using means-end analysis it is possible to make structural relationships according to different levels of constraints. The five levels of the hierarchy and a short description about each are shown in Figure 2.

Functional Purpose	• Describes the overall purpose of the system
Abstract Function	• Describes the laws that the system must hold
Generalized Function	• Describes processes to achieve the purpose
Physical Function	• Descibes the system components
Physical Form	• Describes the characteristics of each component

Figure 2. Levels of the Abstraction Hierarchy

The abstraction dimension, also developed by Rasmussen (1985) breaks a system down into multiple levels of detail according to differing levels of resolution. The most common breakdown consists of whole system constraints, followed by subsystem constraints, followed by component constraints. It provides an avenue for individuals who look at the system from different perspectives (i.e. management versus individual performers) to understand how different resolution levels can map to differing levels of functional constraints. Although the number of system decompositions is typically three, there can be more or less decompositions as well, depending on the nature of the domain.

WDA is an analytical tool and as such it needs to be combined with the design strategy, which is the reason why it is often paired with EID (Lintern, 2006). WDA can be used as a starting point to identify information that should appear on the EID display, as well as to determine the form various display elements should take. Naikar (2013) explains that WDAs make it possible to identify interface specific requirements for a range of tasks.

Additionally, WDA can be combined with an intelligent tutoring system (ITS) to provide tailored and customized learning for individuals and teams (Sottilare & Holden, 2013; Goldberg & Cannon-Bowers, 2013). WDA is especially relevant to ITSs, which seek to provide tailored instruction based on domain competency (prior knowledge), current performance, and learner states (e.g., engagement level). In order to assess what the individual knows about the domain, the designer must first ask questions based on the relationships between system components. Incorporating WDA processes early on in system design can inform model representations used to guide ITS practices. Understanding the form and function of a system can assist an ITS developer in establishing assessment practices that adhere to the various abstraction levels of a domain structure.

Ecological Interface Design (EID)

EID is a theoretical framework composed of ecologically valid cues which seeks to reduce human error by creating interfaces that do not require a higher level of cognitive activity than are required for completing the user's objective (McIlroy & Stanton, 2015). Burns & Hajdukiewicz (2004) relate EID to WDA by describing how an ecological environment reflects the relationship between the constraints of the domain and what is perceptually available to the viewer. The foundation for EID comes from Knowledge Representation, a field of artificial intelligence which Rasmussen used to create his information process model. In the model, called the SRK taxonomy, Rasmussen defines three types of processing: skill-based; rule-based; and knowledge-based (McIlroy & Stanton, 2015). Skill-based processing occurs when the human can perceive the environment without any intervention, which is the foundation of ecological psychology. Rule-based processing is based around cultural / social conventions or rules where the user applies that rule to understand the situation. Knowledge-based reasoning takes it a step further, where the user needs to be capable of deriving meaning based on current information.

It was from this taxonomy that Rasmussen & Vicente developed the primary principles of EID:

- Allow the operator to act directly on the display so that interaction can take place via time-space signals (skill-based processing).
- Provide a consistent one-to-one mapping between the processes and the cues provided by the interface (rule-based processing).
- Display functional structure to externalize the user's mental model (knowledge-based processing) (Burns & Hajdukiewicz, 2004).

EID is most commonly leveraged for complex, time sensitive, or information critical systems. The goal of EID is to have less reliance on human memory and mental calculation, easing the burden of the user. Ideally, a user interacting with an EID achieves transparency in that there is no conscious awareness of the interface itself, it just becomes part of performing the task (Burns & Hajdukiewicz, 2004). To build an ecological design, researchers often rely of the Gestalt principles of grouping: proximity; similarity; closure; good continuation; and symmetry (Bennett & Flach, 2011; Burns & Hajdukiewicz, 2004). Alternatively, design could be accomplished through Garner's (1974) dimensions of perceptual input: separable; integral; and configural. The separable dimension occurs when each interface element is processed separately and maintains its own identity. This is a contrast to the integral dimension where understanding of one variable is interdependent with another (Bennett & Flach, 2011).

In between these two extremes is configural display design, where although each element maintains their own unique identity they can also be joined to produce higher level meaning or emergent property (Bennett & Flach, 2011; Bennett & Flach, 2012). Emergent properties are defined by Pomerantz & Pristach (1989) as line segments that are easier to see by the human through their relationship with each other, rather than each line on an individual level. Additional support for the integration of multiple variables comes from the proximity compatibility principle (Wickens & Carswell, 1995) which states that performance will improve when objects that need to be considered together can reduce mental workload by having them closer together.

EXAMPLE APPLICATION OF WDA: THE AUGMENTED REALITY SANDTABLE (ARES)

This section uses the process defined in Naikar (2013) to use WDA to assist in mapping out domain requirements to support interaction with ARES.

Step 1: Establishing the Purpose

The purpose, as mentioned in the introduction, was to demonstrate the applicability of WDA in simulation interface development, using ARES as an example application. As Naikar notes, identifying an objective at the outset of an analysis will reveal what constitutes the system and what does not, and the depth or granularity of the analysis.

Step 2: Identifying the Project Constraints

This research employs technical documentation, previous research, and a few key subject matter experts. The research needed to take place within one year.

Step 3: Setting the boundaries of the WDA

An effective WDA addresses a system with a distinct boundary; in this case, a single user working within an operational domain. This excludes the system's location as well as simultaneous operation by multiple users, both of which would complicate the analysis.

Step 4: Determining whether it is necessary to develop multiple models for the analysis

The purpose of this analysis is to demonstrate commonalities across domains, so it naturally requires multiple models. The model chosen represents two different domains that impose separate (but overlapping) constraints on users.

1. Land Navigation: Analysis related to this domain provides information on domain requirements as well as avenues to help fulfill the needs of the domain by means of appropriate subject matter experts.
2. Teaching of military tactics: This area was chosen because it is the subject of a larger research effort to integrate intelligent tutoring with tangible interfaces.

Step 5: Assessment of where on the causal intentional continuum the system falls

Causal systems are those systems which are governed by physical laws, such as manufacturing or processing systems. Intentional systems are those systems where the user's goals primarily govern actions. Intentional systems are often systems such as user interfaces. A system may exist on a continuum between these two types. Systems can be broken down into three sub types according to their placement on this continuum:

1. Tightly Coupled Causal Systems in which the conceptual actions that occur reflect the physical interaction of system components based on physical laws alone. Such systems include power generation and manufacturing.
2. Loosely coupled intentional systems, which are not governed strictly by the laws of natural science but are instead governed by communal or societal laws according to an organization. The systems operate according to constraints based organizational policies. Hence, the system itself does not control the user interaction but rather is mediated through the use of tools.
3. User-driven intentional systems, which do not depend on actually changing physical processes but our interaction with the system is directly based on overall purpose and goal. With this type of system what comes into play is also the functional and conceptual limitations of the user to influence functioning.

Step 6: Determining the sources of information for the analysis

Documents are involved in defining the domain for the analysis, which typically include things such as field observations and subject matter expert consultations. Crucially, these documents do not actively address what an individual should do, as in a traditional task analysis, but why the task should be performed and how many different ways there are to reach the desired objective.

Step 7: Construct the contents of the abstraction decomposition space

Due to its size and length, the construction of the abstraction decomposition space is the topic of the next section.

Step 8: An assessment of the validity of the abstraction decomposition

It is the hope that this research will begin further discussion and allow for the verification of the abstraction decomposition space.

CONSTRUCTING THE ABSTRACTION DECOMPOSITION SPACE

Land Navigation

Information gathered for the land navigation domain came from consultation with a land navigation subject matter expert and the map reading and land navigation field manual (Headquarters, 2013).

Functional Purpose Level
The land navigation domain consists of activities aimed at three primary objectives:

1. Maintain an understanding of the current location of the soldier and how that position relates to the environment.
2. Understand the elevation and relief characteristics of the environment.
3. Understand how the information which is presented on the map translates into the current environment.

Abstract Function Level
This domain has the abstract functions of managing information flow to the user and support instruction of the user based on this information flow. These functions will help to structure the presentation of information in an intuitive nature.

Generalized Function Level
The generalized functions of this domain are distance determination, bearing determination, contour interpretation, line of sight, and route selection. These functions were chosen specifically because of their role in the learning objectives, as well as, by determining the functional areas the system requires, in the management of information flow and understanding.

Physical Function Level
The physical function level refers to the components of the system that generalized functions require. The components for land navigation are: the compass tool; the line drawing tool; the protractor tool; and the Mission, Enemy, Terrain, Troops, and Time available (METT-T) tool. The compass supports distance and bearing determination, as well as land navigation during the process of dead reckoning. When an individual is trying to determine a bearing (which also requires a compass), it is possible to triangulate a position by drawing lines. The protractor tool allows the individual to get angular readings to support navigation, as when dead reckoning to determine direction and distance, which requires a protractor. The METT-T tool provides information on the terrain feature (i.e. majors / minors) as well as time-based information which could support at each level.

Physical Form Level
The physical form level takes each one of these components and describes specific design criteria to which each must conform. This is where EID is incorporated.

Below is a diagram of the abstraction decomposition space for land navigation as an example. In this case the functional purposes reside at the whole system level, as that is something that someone looking at the full system from a high level would be interested in. At the subsystem level lies the abstract functions and the generalized functions, while the physical functions reside at the component level.

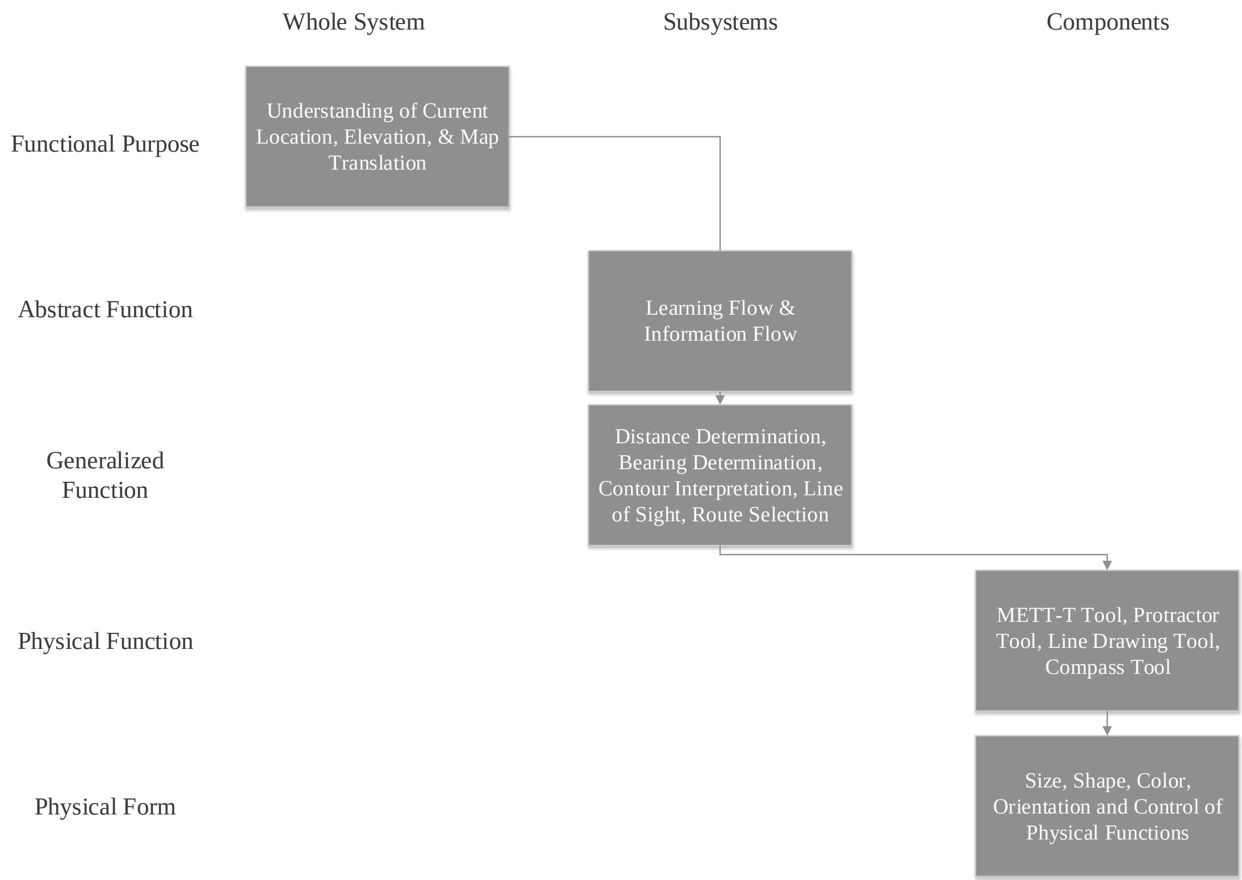

Figure 3: Abstraction Decomposition Space for Land Navigation

Military Tactics Training

While military tactics training, like land navigation, is related to military functioning, the needs associated with each domain are in fact quite different. The first important aspect is that students may not have a complete or correct mental model of the course material. The instruction must therefore provide support to users who may not have strong conceptual knowledge. The information for this domain may be gathered from military tactics of Subject Matter Experts (SMEs), the Army field manual on offense and defense (Headquarters, 2013), as well as from existing literature on military command and control such as the work of Hall, Shattuck, and Bennett (2012).

Functional Purpose Level

For our sample domain the military tactics domain consists of activities aimed at three primary objectives:

1. Maintain a positive force-ratio in comparison to enemies.
2. Understand mission progression in terms of expected objectives achieved versus actual objectives achieved.
3. Apply the appropriate maneuver given mission objectives and environmental characteristics.

Abstract Function Level

The abstract functions which govern this domain are the flow of information to students, the amount of risk a commander is willing to take in a given situation, and the balance of momentum within a battlespace. The information flow remains from the previous domain since the analysis is still focused around the interface of ARES.

Generalized Function Level

Enemy composition intelligence refers to information related to the capabilities, strengths, and position of the enemy. Targeting guidance and priorities encompass the commander's intent, as well as high value targets or instruction from higher command as to the importance of objectives. Maneuver availability refers to the maneuvers or strategies that a commander may have. Time restrictions describe the relationship between the higher level objectives and the available time to execute the tactical plan. Communication management takes information and distributes it to the necessary parts of the interface so as to not overwhelm the interface with information. Historical analysis provides trend data and recommendations for upcoming actions based on known data.

Physical Function Level
The physical functions for decision making present aggregated components of information. The force capacity and structure module provides readouts that describe friendly unit capability, trends regarding various groups of units, and comparison between choices of action and chance of success, based on risk. The communications module provides both intelligence coming from upper echelons of leadership and information coming in from the unit themselves. It also contains information on when the information displayed was received. The Mission, Enemy, Terrain, Troops, & Time (METT-T) module also provides information relevant to student learning, on topics such as enemy resources, terrain structure, and mission goals.

Physical Form Level
The physical form level takes each one of these components and describes specific design criteria to which each must conform.

Below is a diagram of the abstraction decomposition space for military tactics training.

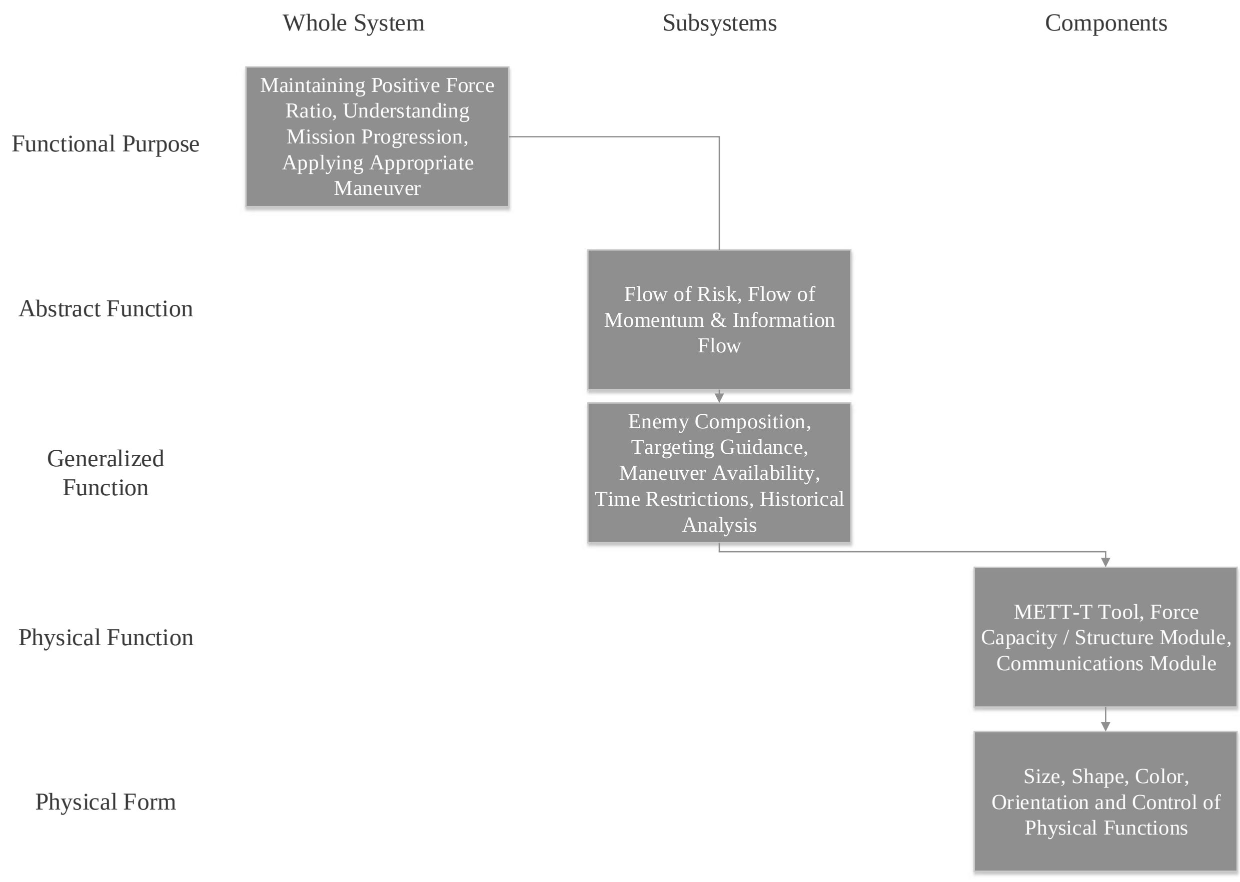

Figure 4: Abstraction Decomposition Space for Military Tactics Training

TRANSITIONING TO INTERFACE DESIGN

One of the common shortfalls of research involving WDA is that once the model is created the analysis stops and the product is never brought to fruition. This makes advocating for the use of WDA more challenging, especially with individuals not familiar with cognitive work analysis (CWA). Therefore, to take this effort a step further one of the domains, military tactics training was further developed in the form of a mockup interface.

To ground the mockup development in established theory, the interface guidelines proposed in Rasmussen & Vicente (1989) were considered. They are:

1. Making the limits of acceptable performance visible where actions are observable and reversible.
2. Provide users with feedback so they can bridge the gap between actions and system response. This includes making the latent constructs visible so the users can understand situational constraints.
3. Consistent and unique mapping with the signs that define cues for action, and the symbols that describe how the process functions
4. Provide users the tools to test hypotheses in unforeseen situations
5. Make overview displays so that ongoing processes can be monitored via fringe consciousness
6. Make cues for action an integrated pattern based on defining attributes and serving
7. Support memory with the externalization of mental models
8. Develop consistent information transformation concepts for data integration
9. Present information in a structure that can serve as an externalized mental model
10. Support of items that are not part of an integrated design can be useful

The following interface layout and mockup were created:

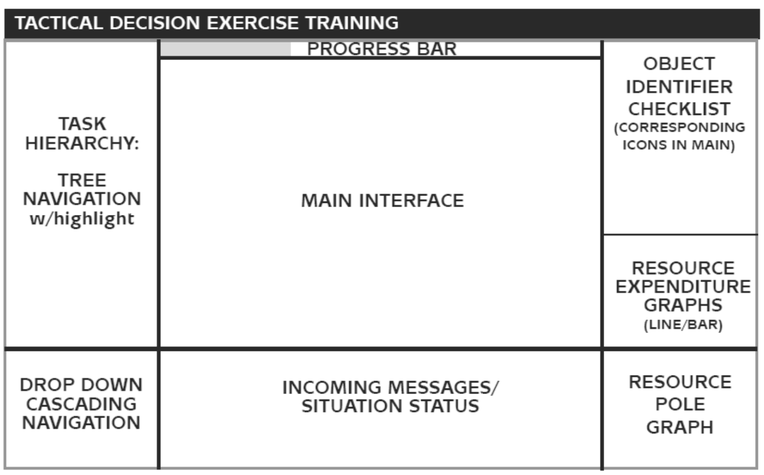

Figure 5: Layout for Mockup Interface

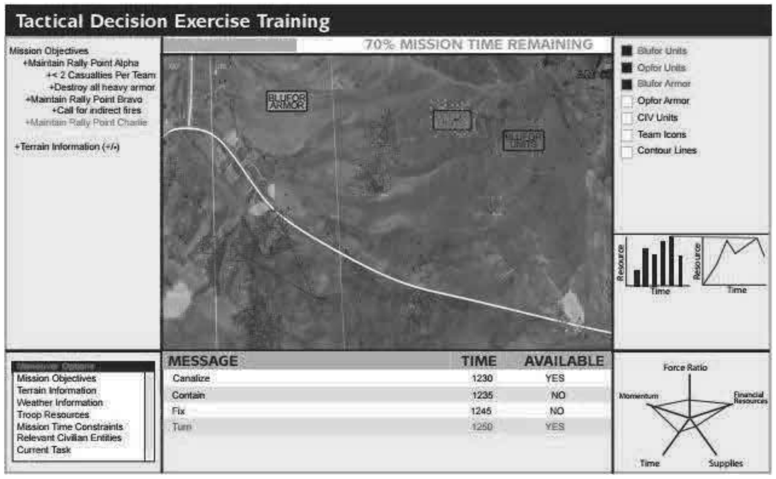

Figure 6: Mockup Interface for Military Tactics

This interface leverages several of the guidelines proposed in Rasmussen & Vicente's work. It demonstrates the limits of acceptable performance through the use of time and resource measurement. It provides an aggregate display of variables and how those variables relate to other variables of interest through the polar graph. It provides access to tools, presents an overview display in the form of the tree navigation, and provides capability for filtering and defining desired attributes. Finally, it provides avenues to try different actions through its menu selection feature and checklists. This design is not intended to be a final design, but rather an initial concept sketch of how information gained through WDA can be applied to EID.

DISCUSSION

This paper aimed to show the utility of WDA supporting interface design constraints of simulations. Through the use of a case study, interface constraints for different but related domains were analyzed. From this analysis, key components to support mission requirements were identified. WDA can be used as a starting point to identify information, which needs to appear on display, as well as determining the optimal form of various display elements. Using principles of EID, it was shown how this theoretical framework can be transitioned into rationale for user interface design decisions.

Looking across both scenarios, three domain independent characteristics emerge:

1. The need for at-a-glance resource identification and environmental impact factors, whether it is an obstruction in the terrain or an opposing enemy force. This information needs to take into consideration the flow of information to maximize comprehension by the user and minimum strain on cognitive load.
2. A consistent display of the current state of progress towards the desired objectives, actions that might have impeded progress, and trajectories to achieve objective completion.
3. Display design can assist in grouping functionalities and minimizing screen real estate to avoid obstruction of the overall environment.

The analysis provided the beginning of a larger analysis of ARES. As the number of applications for the system continued to grow, and with that the understanding of how various pieces of information can be displayed, WDA will continue to be a useful tool. With increased involvement of subject matter experts and verification and validation using unexpected events, WDA can continually be updated and modernized, while the principles of the system's construction remain the same. The incorporation of tailored WDAs into interface design is an area of future work, especially as work tasks become more complex and consequences for not understanding interface information become even greater.

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