
Examining the Effects of the Value of Information on Intelligence Analyst Performance

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Abstract

Military intelligence analysts must deal with unprecedented amounts of data from a variety of sources. Data may originate from hard sensors, newsfeeds, video or interactions with other people. Additionally, time constraints, possibly severe consequences and dynamic, complex environments place even greater pressure on an already high pressure function. Intelligence analysts must investigate a broad range of data sources to have situational awareness. Given the abundance of data and time constraints, intelligence analysts would benefit from tools to help them quickly identify important information that is relevant in a particular context. The research discussed in this paper presents an approach for automatically presenting the valuable information first and an experimental design for evaluating decision-making performance.

Keywords: value of information, intelligence analysis, decision-making, human performance model, fuzzy logic, situational awareness

1. INTRODUCTION

Military intelligence analysts are overburdened by massive amounts of data, time constraints, and highly dynamic environments. Access to more data does not necessarily lead to better decision making or situational awareness. In fact, having access to too much data increases cognitive load and can result in overlooking important information. Often, the reliability of the data sources is unknown or questionable, further complicating the intelligence analysts' responsibilities. "Information characterized by high uncertainty, ambiguity, and complexity, as well as being accompanied by high consequence, presents challenges to good judgment and

decision-making" (Straus, Parker, & Bruce, 2011).

Major General Michael Flynn's report on intelligence operations in Afghanistan emphasizes the need for redefining intelligence processes. Military and civil operations are conducted in villages, placing the lower echelon intelligence analysts closest to the sources of data (Flynn, Pottinger, & Batchelor, 2010).

Commanders rely on intelligence analysts to fulfill information requirements in order to define courses of action (COA). Situational awareness is necessary in order to make decisions. The intelligence analyst makes decisions regarding what information to send to the commander,

and the commander decides on an appropriate COA. Situational awareness is necessary across all levels of the command and control structure.

Situational Awareness (SA) is formally defined as "a person's perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" (Endsley, 1999). Software tools and modernized processes are needed to support decision-making in highly complex military environments. "The Army needs a fast, robust, flexible decision-making process" (Ross, Klein, Thunholm, Schmitt, & Baxter, 2004).

The research discussed in this paper provides methods and analysis to meet those needs. Technology will be described that assists an intelligence collector and/or analysts with determining which information is the most "valuable" given a particular situation. A command and control modeling environment can then be used to simulate the intelligence analysis process and provide insight into the rationale behind decision-making in a specific operational context. It is critical to understand mental models to avoid mismatching information with "false expectations".

In the process of turning large amounts of potentially disparate information into useful knowledge to aid situational awareness, it is vital to have some way to judge the importance of the individual pieces of information. This importance value is called the Value of Information (VoI) metric. The entire military intelligence analysis process is designed to gather and provide timely and relevant information to military decision makers (US Army FM 2-22.3, 2006). Determining which information is "relevant" (that is, important) is a daunting task complicated not only by the sheer amount of information, but also by the fact that importance is driven by mission context.

Determining VoI is currently a human-centric process. Intelligence analysts use a multi-step methodology to subjectively rate the importance of information across differing operational contexts. Doctrinal guidance for determining VoI is vague at best (US Army FM 2-22.3, 2006; NATO, 1997) and does not include any scheme for accommodating mission context into the decision.

To help alleviate this problem, recent research has been initiated to provide analysts with automated assistance for judging VoI. A fuzzy-based prototype system for capturing VoI has been developed (Hammell, Hanratty, & Heilman, 2012). Formalized knowledge elicitation was performed with subject matter experts (SMEs) to formulate the fuzzy rules for the system (Hanratty, Heilman, Dumer, & Hammell, 2012). Preliminary results have been validated in principle and context by the SMEs and the system shows great promise for further development.

Information drives decisions and as mentioned above, an unprecedented amount of data is available to intelligence analysts. Modeling the information flow within the intelligence analysis process helps us understand the impacts of specific information items, analyst workload and analyst performance within an Army command and control organization. The U.S Army Research Laboratory (ARL) sponsored development of the Command, Control, and Communications: Techniques for the Reliable Assessment of Concept Execution (C3TRACE) modeling and data analysis tool. C3TRACE provides an environment for modeling function and task networks with user defined staff profiles and organizational structures. Simulations can then be run based on military or civil scenarios and the performance of the intelligence analysts and the types of information used within the process can be analyzed.

This paper presents an approach and experimental design to determine the effects of making VoI weights available to intelligence analysts in varying military contexts. This will be accomplished by analyzing information flows, decision making and human performance using the C3TRACE modeling environment. The remainder of this paper is organized as follows: Section 2 presents the difference between "quality" of information and "value" of information, and briefly outlines current research under the auspices of the Army Research Laboratory in both areas. Relevant collaborative research efforts between ARL and the International Technology Alliance Collaboration System (ITA) and the Network Science Collaborative Technology Alliance (NS-CTA) are also discussed. Section 3 describes the fuzzy VoI prototype system, while Section 4 presents the C3TRACE environment. The experimental concept and design is presented in Section 5, while conclusions are presented in Section 6.

2. VOI CONSTRUCT AND COMPLEMENTARY RESEARCH

The following section outlines an approach to determining the effects of the VoI construct on decision-making by intelligence analysts in a tactical environment. Other current research efforts are introduced to illustrate the breadth of the problems intelligence analysts face and to reinforce the uniqueness of the approach outlined in this paper.

Value of Information Construct

The VoI construct will prioritize and present the most valuable information for a specific military context, based upon source reliability, information content, and latency in combination with the operational tempo of the specific mission. It is the ability to codify subtle yet important aspects of the Commander/Soldier communication flow and intelligence analysis process within a mission context that is truly unique.

As mentioned earlier, guidance for VoI determination is vague at best (FM 2-22.3, 2006; NATO, 1997) and only addresses the most rudimentary of characteristics for arriving at such a judgment. Tables 1 and 2, respectively, show scales for judging the “reliability” and “content” of a piece of information. No process for combining these determinations into a VoI metric is provided, nor is any opinion offered about how mission context should influence such a determination. Intuitively, one would think that information with higher scores (“A” or “1”) in the domains would be more “valuable” than information with lower scores. However, it is clear that determining how the categories combine to produce a valuation is highly subjective and ambiguous. Additionally, an idea of the “timeliness” of the information (that is, how long ago it was collected) might also impact the value of the information.

Further complicating the VoI determination is the operational mission context. “Operational tempo” refers to the immediacy of the mission and is defined by the amount of time available in the plan, prepare, and execute cycle for a specific mission. Differing operational tempos could cause the same piece of information to have different VoI values depending on the mission.

Table 1: Source Reliability (NATO 1997)

A	Reliable	No doubt of authenticity, trustworthiness, or competency; has a history of complete reliability
B	Usually Reliable	Minor doubt about authenticity, trustworthiness, or competency; has a history of valid information most of the time
C	Fairly Reliable	Doubt of authenticity, trustworthiness, or competency but has provided valid information in the past
D	Not Usually Reliable	Significant doubt about authenticity, trustworthiness, or competency but has provided valid information in the past
E	Unreliable	Lacking in authenticity, trustworthiness, and competency; history of invalid information
F	Cannot Judge	No basis exists for evaluating the reliability of the source

Table 2: Information Content (NATO 1997)

1	Confirmed	Confirmed by other independent sources; logical in itself; Consistent with other information on the subject
2	Probably True	Not confirmed; logical in itself; consistent with other information on the subject
3	Possibly True	Not confirmed; reasonably logical in itself; agrees with some other information on the subject
4	Doubtfully True	Not confirmed; possible but not logical; no other information on the subject
5	Improbable	Not confirmed; not logical in itself; contradicted by other information on the subject
6	Cannot Judge	No basis exists for evaluating the validity of the information

For example, consider a “tactical” mission where the operational tempo is measured in hours. In this case, it might be that the timeliness of the information is the most critical aspect in judging value; since only a limited amount of time is available to assess the situation, perhaps only

the most recent information would be of real value. On the other hand, consider a “strategic” mission where the operational tempo is measured in months. In this case there may be time to consider information without regard to its timeliness (such as the past political climate of the region, historical allegiances of an enemy, economic trends, etc.). Thus, the combination of content and reliability might be the driving factors for determining VoI.

Differentiating Quality and Value

Data can be incomplete, incorrect and in a counterinsurgency operation, intentionally distorted. Army doctrine recognizes these possibilities and provides the following guidance to help prioritize information usage when it might be imprecise and under uncertain circumstances:

- “Incomplete or imprecise information is *better than* no information.
- Untimely or unusable information is *the same as* no information.
- Irrelevant or inaccurate information is *worse than* no information” (Army, 2003).

Data quality standards are necessary to address the volumes of disparate data streams available in the highly dynamic, heterogeneous sensor environments of coalition operations. Using data quality attributes that are important to the data consumer (Wang & Strong, 1996), the Soldier in this case, the following research efforts target delivery of sensor-generated data in resource-constrained military environments.

Quality of Information (QoI)

The ITA and NS-CTA efforts established an ontology-based framework to describe quality of sensor data. The key quality attributes relevant to this paper are:

Accuracy is a measure of the closeness between the type of data available to the type of data requested.

Precision is the level of detail provided by the available data.

Timeliness refers to the usefulness of the data as a function of time.

Freshness refers to the age of the data.

The International Technology Alliance and Network Science Collaborative Technology Alliance research efforts focus on sensor-generated data and its delivery via information

and communications networks. To further emphasize the separation of quality and value, these efforts established the view that quality of information relates to its *fitness* (as judged by the four quality attributes above) while the value of information pertains to its *utility* within a specific application “relative to its receiver” (Bisdikian Kaplan, Srivastava, Thornley, Verma, & Young, 2009). The division between the QoI and VoI concepts is shown in Figure 1.

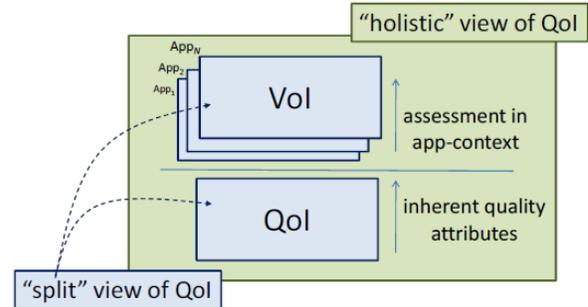


Figure 1. QoI and VoI Boundaries (Bisdikian, et al., 2009).

Value of Information

The VoI research discussed in this paper derives its value definition from (Wilkins, 2003) and the ITA and NS-CTA research efforts. In communication theory, the receipt of a message reduces uncertainty, influencing the value of the information; the meaning of a message is not considered.

Instead, Wilkins considers the practical importance of the information to the receiver, suggesting that information with value supports the receiver’s ability to make informed decisions.

A key point to remember is quality must be considered at every step and value is relative to the end user and a specific application; the intelligence analyst and the mission context.

Within the Current ARL Research

ARL is the U.S. Army’s central laboratory for materiel technology. ARL is comprised of the Army Research Office (ARO) and six directorates that specialize in providing innovative science and technology to the Soldier (ARL, 2012). The ARO serves as the broker for far-reaching basic research initiatives to ensure that cutting-edge discoveries can be best and fully used to develop and improve Soldier systems. Multidisciplinary

University Research Initiatives (MURI) are managed by the ARO and support rapid research breakthroughs while potentially training science and engineering students in areas of interest to the Army.

The ARL engages in collaborative technology efforts with other government agencies, academia and industry. The remainder of this section discusses current collaborative research efforts that are complementary to the research thrust of this paper.

ITA and Value of Information: Two research tasks within one of the ITA projects uses the phrase "value of information" to describe how the "cognitive value" of information could yield different outcomes depending upon the communication context in a military coalition environment. This ITA project will examine military coalition communication for insight into group decision making and "how network features contribute to the cognitive abilities of human-agent collectives" (Smart, Braines, Preece, Kao, Poteet, & Xue, 2011).

The separation between QoI and VoI is at the point where decisions (any command decision) are made and where the context of the decision is known.

NS-CTA and Quality of Information: The research tasks of the Quality of Information in the NS CTA context are to "Measure, predict, and adapt composite networks to deliver the most valuable information with dynamically changing network resources, rather than the most bits, or queries" (NS-CTA). Value in this context is related to the quality attributes defined in the QoI section. For example, whether the resolution of the available image is high enough to be of value to the analyst, and how compression techniques affect the precision and timeliness of the data as well as network performance are facets of value.

In this context, the separation of QoI and VoI occurs at the point where the attributes become situation-dependent.

Value-centered Information Theory for Adaptive Learning, Inference, Tracking, and Exploitation MURI: The research under this program focuses on improving the acquisition, processing, fusion and management of raw sensor data. Its primary goal is to develop a

general framework for "autonomous and distributed sensing systems" (ARO-MURI).

To clarify, the MURI research is aligned with QoI attributes and the research objectives in this paper target the VoI.

Fuzzy-Based Value of Information for Battlefield Situational Awareness:

A collaborative agreement between ARL and Towson University exists to study value of information within specific military contexts. The overall goal of this research is to provide more accurate battlefield situational awareness.

A fuzzy logic-based prototype system was developed under this agreement to generate VoI determinations for specific pieces of information. This system is described in the next section.

Innovative Results

Using the VoI determinations within the C3TRACE modeling environment will provide new insight to the decision making reasoning of intelligence analysts in complex military environments. This will support algorithmic prioritization of context-relevant information, development of a metrics framework, and generate validated task network models of how information flows through the intelligence analysis process.

Pairing the mission context and the VoI weight represents a new approach in transforming data to decisions.

A research objective of this paper seeks to establish metrics by which to grade task performance and codify reasons behind decisions made by military intelligence analysts in a tactical environment. These efforts share the common goal of getting the right information to the right person within an actionable timeframe (Bisdikian et al., 2009), (Flynn et al., 2010).

3. FUZZY VOI PROTOTYPE SYSTEM

A Fuzzy Associative Memory (FAM) model was chosen to construct the prototype VoI system. A FAM is a k -dimensional table where each dimension corresponds to one of the input universes of the rules. Each rule antecedent has an input universe or input domain. The i th dimension of the table is indexed by the fuzzy sets that comprise the decomposition of the i th input domain.

For the prototype system, three inputs are used to make the VoI decision: source reliability, information content, and timeliness. The timeliness domain is needed to include mission context as part of the VoI judgment. Timeliness in this context applies to the age of the information. For information to have value, it must be recent enough to be useful in a specific application.

The overall architecture of the prototype fuzzy system is shown in Figure 2. Two inputs feed into the Applicability FAM: source reliability and information content; the output of the FAM is the metric formed by pairing the reliability and content characteristics and is termed "information applicability". Likewise, two inputs feed into the VoI FAM: one of these (information applicability) is the output of the first FAM; the other input is the information timeliness rating. The output of the second FAM and the overall system output is the VoI metric. Note that there will be a separate, automatically selected VoI FAM for each operational tempo.

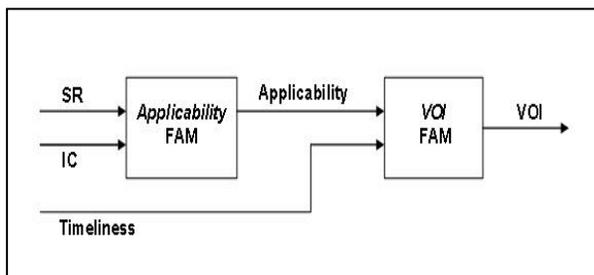


Figure 2. Prototype System Architecture.

With three input domains, a 3-dimensional FAM could have been used as opposed to two, 2-dimensional FAMs. The rationale for this decision was presented in detail in (Hammell et al., 2012) but basically it provided a simpler knowledge elicitation process for the SMEs, decreased the total number of fuzzy rules, and provided the output of the first FAM as a useful product of its own.

The first step in the design of a fuzzy inference system is to decompose the input and output domains into fuzzy sets. This decomposition defines the "language" of the rule base and determines the terms that may appear in the antecedents and consequents of the fuzzy rules.

Within the Applicability FAM, the two input domains (source reliability and information content) are divided into five fuzzy sets following the guidance provided in NATO STANAG 2022

(NATO, 1997) as mentioned earlier. As an example, Figure 3 shows the decomposition of the source reliability domain with the degree of fuzzy set membership value shown on the y-axis. Note that the "cannot judge" category was omitted from both these input domains because the data were entirely conceptual, rendering that category meaningless for this exercise. The "information applicability" output domain of the FAM was decomposed into nine fuzzy sets.

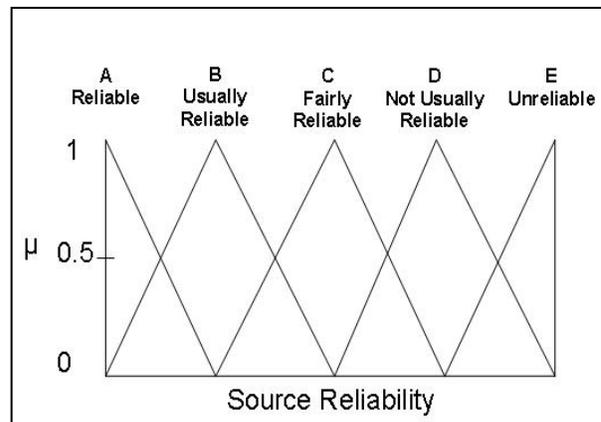


Figure 3: Decomposition of the "Source Reliability" Domain.

Similarly, for the VoI FAM, the information applicability domain has the same nine fuzzy sets. The "timeliness" input domain is decomposed into three fuzzy sets, and the VoI output domain contains eleven fuzzy sets.

The rules elicited from the SMEs are represented in the appropriate FAMs and form the fuzzy rule bases. The number of fuzzy sets for each domain, as just described, was determined during the knowledge elicitation process. Note that rules for three different VoI FAMs were obtained from the SMEs; there is one VoI FAM for each of three different mission operational tempos, thus allowing the inclusion of mission context in the VoI determination. The appropriate FAM is selected automatically based on user input as to the operational tempo. Detailed information as to the knowledge elicitation process can be found in (Hanratty et al., 2012).

Fuzzy rules encapsulate the relationships between the input and output (or in the terminology of rules, the antecedent and consequent) domains. Since both FAMs are 2-dimensional, the fuzzy rules in each will have two antecedents and one consequent; that is,

the fuzzy rules will take on the form: "if x is A and y is B then z is C," where A and B are fuzzy sets in the input domains; C is a fuzzy set in the output domain; x and y are the inputs; and z is the output. As a specific example for the Applicability FAM, a possible rule is: "If Source Reliability is Usually Reliable (UR) and Information Content is Probably True (PT), then Information Applicability is Highly Applicable (HA)".

The shape of the fuzzy sets defines the membership functions for the system. While there are various shapes that can be used for the fuzzy sets (triangular, trapezoidal, and the like), triangular membership functions as depicted in Figure 3 are used for all domains in the system to enhance the efficacy of the inference calculations. The inference process is made even more efficient by requiring the membership functions to be isosceles triangles with bases of the same width. This triangular partition with evenly spaced midpoints has been referred to as a TPE system (Sudkamp & Hammell, 1994). It is clear that the TPE restrictions ensure that any domain input will belong to at most two fuzzy sets; that is, any input will have non-zero membership in no more than two fuzzy sets.

The output from the system is determined by the standard centroid defuzzification strategy. In theory, every rule in the fuzzy rule base is "fired" for each set of inputs to determine the overall output. That is, the degree to which each rule influences the overall output is directly related to the degree to which its inputs match its antecedent fuzzy sets. However, for a TPE decomposition of a 2-dimensional FAM structure, it is clear that at most four fuzzy rules will have non-zero degrees (two rules will have "x" antecedents satisfied by input x and two rules will have "y" antecedents satisfied by input y; their intersection in the FAM defines the four fuzzy rules that should be "fired"). This aspect, plus the fact that the degrees for all rules will add to one (thus eliminating the need for the final division operation in the centroid defuzzification calculation), allows the TPE structure to provide a computationally efficient defuzzification process. More detailed descriptions of the FAMs, the fuzzy rules bases, the domain decompositions, and other implementation aspects of the prototype system can be found in (Hammell et al., 2012).

The system has been exercised across numerous scenarios (that is, various combinations of input

values) to produce VoI determinations. These preliminary system results have been demonstrated to the SMEs and the system performance has been "validated" in principle and concept. That is, the system output is consistent with expectations and has shown the viability of eliciting and using expert knowledge to produce a VoI metric.

Note that there is no current system against which the results can be compared. As such, the system has not been tested exhaustively due to the human-centric, context-based nature of the problem and usage of the system. A comprehensive experiment to more formally validate the VoI system is currently under development.

4. COMMAND, CONTROL, AND COMMUNICATIONS: TECHNIQUES FOR THE RELIABLE ASSESSMENT OF CONCEPT EXECUTION (C3TRACE)

In the 1990s, the Human Research and Engineering Directorate (HRED) of the U.S. Army Research Laboratory (ARL) developed command and control human performance models. These models represented analog communications occurring at the battalion level in a tactical operations center (TOC). The "digital battlefield" (Warwick & Archer, 2002) generated unprecedented amounts of data. The ARL developed human performance models to study "information-driven" (Warwick & Archer, 2002) decision making within the command and control structure. Models defined for specific organizational concepts produced data that made it possible to assess decision quality. This capability was needed for a variety of scenarios at multiple levels of the command structure. A user-friendly graphical user interface and user-configurable scenarios were included in the next generation human performance modeling tools.

The ARL HRED funded development of the C3TRACE programming and modeling environment. C3TRACE provides an environment specifically for modeling U.S. Army command and control systems (Middlebrooks, 2006).

C3TRACE is a dynamic, discrete event network modeling tool. It provides an environment for evaluating Soldier performance and the effects of introducing information technology to the environment. In this environment, the individual's performance as well as the "overall

system performance” can be evaluated (Kilduff, Swoboda, & Barnette, 2005). Using task network modeling, communication bottlenecks and decision-making vulnerabilities are exposed. C3TRACE can represent user-defined organizational levels, individual staff, and their functions and tasks. The models are driven by communication between tasks, exposing the amount, frequency and urgency of communication (information) between tasks.

C3TRACE models are built upon context-specific entities including personnel, functions, and tasks. Functions are decomposed into networks of tasks to model sequencing and decisions. Using output results such as operator use, interrupted and dropped tasks, and operator workload, the researcher can examine effects of information of varying value.

The C3TRACE decision-making architecture is completely user-configurable and combines the information elements defined by the Army’s accelerated military decision-making process with the information accuracy score to examine an individual’s performance. Information accuracy is calculated in the environment by selecting from multiple built-in decay functions. The environment also supports C# scripting, which will be the mechanism for inserting outputs from the VoI construct.

5. RESEARCH APPROACH

To gauge effectiveness, the impact of VoI on how intelligence analysts perform must be examined (Crandall, Klein, & Hoffman, 2006). A comparison of baseline performance to performance using the VoI-enhanced system will expose changes in performance measures.

The research thrust for this effort incorporates the VoI construct and C3TRACE modeling environment to study the effects, if any, of having access to the value of information rating. Specifically, weighted information from the VoI construct will be injected into task network models developed in the C3TRACE environment and military intelligence analyst performance will be observed and analyzed. This arrangement provides a baseline for comparison of intelligence analyst performance based on the information available and information required for decisions.

Model-Test-Model (M-T-M) Concept

M-T-M is a method of using testing and evaluation to iteratively refine simulation models in the Army for more than two decades. The MTM concept evolved from an exercise of evaluating armored tanks for compliance with design and performance specifications. The original concept consisted of three phases: pre-test modeling, field test, and post-test modeling. For this research effort, the field test of the second phase will be replaced by model validation and additional testing (East, 1991). M-T-M is recognized by the Army as a technical method of increasing validity of modeling and simulation experiments (US Army, 1999) .

Experimental Design

A two-day training session for using C3TRACE was conducted to ensure the modeling environment offers full capabilities of generating the data needed for this research effort. The programming interface was also exercised to verify compatibility with the VoI construct. After running these preliminary simulations, the experimental design was developed.

Pre-test Modeling: A military scenario with several vignettes will be developed. Intelligence tasks at the tactical level will be the focus of the scenario. C3TRACE will expose the cognitive processing steps that tax human decision-making. Using the VoI construct, prioritized information will drive the C3TRACE model. The methods intelligence analysts employ to classify and use knowledge will be codified. Performance metrics will include accuracy assessment of intelligence products in relation to the commander’s intelligence requirements and ground truth. Task completion timing and error analysis will be included in a metrics framework.

The U.S. Army Training and Doctrine Command (TRADOC) Scenario Gist Book will be used to as the basis for a robust, realistic scenario. These experiments will be conducted with military intelligence units. Training and experience profiles will be included in the final reports.

Test: Laboratory experiments will be conducted to determine the effects of the VoI on intelligence analyst performance. The metrics framework will be populated with data produced by the C3TRACE Operator Performance Report and Decision Data Report.

Model: The data provided in phase two (Test) will provide the basis for refining the C3TRACE models to reflect task critical processes. Modeling and simulating the intelligence analyst's processes at the tactical level is likely to expose tasks that are suitable for decision support.

A between-subjects design with two groups is planned for the experiment. The baseline will be established without the VoI construct and the second group will have access to the VoI ratings.

Intelligence analyst performance will be assessed as subjects step through a series of tasks related to a tactical scenario. Task completion time will be used as one of the measures of performance. An example task could be to provide an outgoing patrol the safest route to a particular location. The intelligence analyst would have 15 minutes to complete the task, creating time pressure on the analyst.

Expected Results

By comparing the baseline performance to performance using the augmented system, cognitive measures will show, among other things, whether there was an increase in effectiveness and a decreased cognitive load, and a decrease in time and effort required for the intelligence analyst to fulfill the commander's intelligence requirements. Decision quality will be calculated as a function of the information flow and VoI. This approach will provide the basis for a metrics framework that may lead to establishing standards for intelligence products and modernized training programs.

6. CONCLUSIONS

Military intelligence analysts must deal with unprecedented amounts of data from a variety of sources. Additionally, time constraints, possibly severe consequences and dynamic, complex environments place even greater pressure on an already high pressure situation. The combination of the VoI construct and the C3TRACE modeling environment will support the study of the interaction between the value of information and the intelligence analysts' decision making rationale. Codifying the analysts' reasoning strategies in context-specific situations will provide the foundation for developing software tools in the context of their

cognitive abilities and will be inherently collaborative.

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