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The Role of Meta-Information in C2 Decision-Support Systems

Cognitive Domain Issues, C2 Analysis C2 Concepts and Organizations

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Abstract:

Command and control (C2) in complex, dynamic, high-risk warfighting environments is clearly challenging, particularly because of the increasing complexity of available technology for processing and presenting information. Commanders need to understand and act on large volumes of information from a variety of sources and are particularly challenged by the need to reason about the qualifiers of that information, which we will refer to as *meta-information* (e.g., uncertainty, recency, pedigree). We have explored the role of meta-information in C2 using Cognitive Task Analysis (CTA) techniques to identify when and how, in current practice, human interaction with meta-information impacts decision-making, especially when that decision-making is supported by automation. Too often critical meta-information is not processed, ineffectively displayed, or not displayed at all in existing C2 decision support systems. The result of our analyses is a number of design recommendations for C2 decision-support systems and guidelines for identifying and recognizing the need for meta-information processing and display. In this paper, we present the results of our analyses and discuss their implications with respect to the design of human-system interfaces and the development of computational information processing methods.

1. Introduction

Advances in military command and control (C2) technologies have led to increasingly complex systems, and a concomitant burden placed upon the commander to process the information provided by those technologies. A commander is asked to process an ever-larger amount of information from a growing number of heterogeneous sources, then compare that information with past experiences and his or her knowledge of the current situation to form a comprehensive understanding of the current situation (termed "situational awareness" (Endsley & Garland, 2000; Endsley, 1995). Given this understanding, a commander is then asked to make an effective decision. The ability to make a decision that will lead to mission success is largely predicated on the commander's skill and experience in processing and understanding information. This ability fundamentally relies not only understanding the domain-related information but also the *qualities* of that information (e.g., recency, reliability), or the associated *meta-information*. Such qualities can critically influence how a commander will process information, understand information, and make decisions based on that information.

Our research across different C2 domains has yielded significant evidence that commanders reason using meta-information. This evidence is the result of multiple analyses of C2 decision-making and computational systems designed to support that decision-making. In some cases, meta-information is not incorporated into decision-support systems in those domains or is inadequately represented (both in terms of the underlying computation and in terms of the displays and interfaces presented to the human user). The goal of this paper is to describe our analytic efforts and describe the implications of our analysis on the development of future C2 systems. In this goal, we hope to guide future C2 research, design, and development efforts to encourage the explicit incorporation of the meta-information critical to supporting and enhancing a commander's reasoning.

We begin by describing relevant background material, covering work in related areas and its impact on our understanding of meta-information's influence on C2 decision-making (Section 2). We then present our overall cognitive engineering approach to analysis (Section 3) including a description of our specific methods and the application domains we explored (Section 4). We cover the results of our analysis, focusing on defining meta-information and the sources and types we encountered (Section 5). Finally, we discuss the implications of these results for the design of C2 decision-support systems (Section 6).

2. Background

Although there are some prior references to the term *meta-information* in the literature (Higgins, 1999), most discussions of meta-information relate to the influence of *uncertainty*, particularly with respect to human decision-making (Klein, 1996; Lipshitz & Strauss, 1996), computation (Halpern, 2003;

Parsons, 2001), and visualization design (McQueary et al., 2004; Basapur, Bisantz, & Kesavadas, 2003). As we will discuss in Section 5.1, our analyses have led us to consider uncertainty to be *one type* of meta-information and to argue that a broader categorization is necessary to fully understand the different types and influences of meta-information on decision-making. To provide background for this assertion, we present relevant background material on the role of uncertainty in decision-making, computational reasoning, and visualization below.

2.1 Uncertainty and Human Decision-Making

Human decision-making under uncertainty is recognized to deviate from classical, logical decision-making and to be based largely on experience-based heuristic methods (Kahneman, Slovic, & Tversky, 1982). To better understand how uncertainty affects decision-making, several attempts have been made to categorize different types of uncertainty and to identify how they affect the decision-making process. One method for classifying uncertainty is to look at its source; for example, dividing uncertainty into forms that come from computational models as opposed to a human interpretation (Booker, Anderson, & Meyer, 2003), or using the broad classes of *physics uncertainty, computational uncertainty, visualization uncertainty*, and *cognitive uncertainty* (Schunn, Kirschenbaum, & Trafton, 2003). Another method for classifying uncertainty is to look at how it is used in the decision-making process. This method has resulted in the development of categories such as *executional uncertainty, goal uncertainty*, and *environmental uncertainty* (Yovits & Abilock, 1974). Another set of classifications developed by Lipshitz and Strauss (1996), divides forms of uncertainty into *inadequate understanding*, *lack of information*, and *conflicted alternatives*. Similar taxonomies were developed by Schunn et al and Klein (1998). These classifications of uncertainty have proven useful in guiding descriptions of how human decision makers cope with uncertainty. For example, Lipshitz and Strauss (1996) identify five general strategies for coping with uncertainty: (1) reducing uncertainty by collecting more information, (2) reasoning by using assumptions to fill in gaps of knowledge, (3) weighing pros and cons, (4) forestalling, and (5) suppressing uncertain information. Decision-support systems can be, and have been, designed around supporting appropriate strategies for dealing with uncertainty. While these classifications of uncertainty and an understanding their impacts on decision-making have been useful in the development of C2 decision support system, they may not generalize to other types of meta-information that are not fundamentally based on uncertainty (e.g., Do decision-makers reason about the recency of information in the same way they do about the certainty of information?).

2.2 Uncertainty and Computational Systems

Computational systems have been developed for an enormous range of applications within the C2 domain. Inherent to the development of such systems has been the need to reason computationally about uncertainties present in the real world in tasks ranging from mission planning and course of action development to mission execution and monitoring to after action review. To support this development, a variety of computational approaches have been developed to explicitly support reasoning about one or more types of uncertainty (Halpern, 2003; Parsons, 2001). These approaches include: probability measures, Dempster-Shafer belief functions (Russell & Norvig, 2003), extensions to first-order logic (e.g., defeasible reasoning (McCarthy & Hayes, 1969), argumentation (Lin, 1993)), ranking functions, "plausibility" measures (Halpern, 2003), fuzzy set theory (Zadeh, 1965), and causal network methods (e.g., Bayesian belief networks (Pearl, 2001; Pearl & Russell, 2000), similarity networks (Geiger & Heckerman, 1996), influence diagrams (Howard & Matheson, 1984)). This list, by no means exhaustive, represents the focus of computational research on the need to support automated reasoning about uncertainty.

Some efforts have been made within this community to define uncertainty and to describe taxonomies of uncertainties that computational systems may reason about. Of these, Smets (1997), Smithson (1989), and Bosc and Prade (1997) are notable, but it is worth mentioning that the discrepancies among these taxonomies would seem to support Elkan's (1994) assertion that developing such taxonomies is largely a philosophical exercise. Elkan's assertion points to the problems faced by the developers of such computational methods who are not tightly tied to the needs of human users in a particular application domain, where the development of such definitions of types of uncertainty (and, more generally, types of meta-information) can be achieved through formal knowledge elicitation approaches.

Relatively recently, there has been increased interest in the management of *meta-data*, a term used to describe more broadly the various ways that data may be qualified (Havenstein, 2006; Marco & Jennings, 2004). This term has been applied to file systems, computer programs, images, relational databases, and data warehouses (i.e., its application is largely contained within the information technology community). Examples of meta-data include how, when, and by whom a particular set of data was collected, and how the data is formatted. This work has been focused on the tagging and handling of data according to its meta-data, largely to support system interoperability and search, rather than on computational reasoning or computational intelligence that can be applied to these data qualifiers. Also, these efforts have been focused on the qualities inherent in the data rather than the qualities of the information that are used by a human decision-maker. That is, they are data-centered rather than human-centered in their focus.

2.3 Uncertainty and Visualization

While some recent work by Lefevre et al. (2005) and Pfautz and his colleagues (2005a; 2005b; 2005c) has focused on the visual representation of meta-information, the majority of relevant literature is focused on the representation of one type of meta-information – uncertainty (Trickett et al., 2005; McQueary et al., 2004; Bisantz, 2002; Barnes, Wickens, & Smith, 2000; Andre & Cutler, 1998; Pang, Wittenbrink, & Lodha, 1997a; Fisher, 1993). Research based in scientific visualization and geographic information systems (GIS) has explored graphical parameters which could be used to encode the uncertainty in large data sets, including attributes of scene geometry (e.g., color, shading, and bumpiness (Pang, Wittenbrink, & Lodha, 1997b)) or traditional graphic variables used in cartography (e.g., texture, color, orientation, and shape (MacEachren, 1992)). Pang et al. (1997b) suggested the use of glyphs (graphical forms such as arrows or vertical lines), in part because it frees other graphical dimensions for other purposes. Glyphs have previously been used to represent magnitude and direction of winds and ocean currents along with the uncertainties in these dimensions. In one example, the general shape of the glyph was an arrow with the width of the arrowhead represented uncertainty in heading, while multiple arrowheads represented uncertainty in magnitude (Lodha et al., 1996). Lodha et al. (1996) claim that the use of such visualizations results in an integrated graphic "so that users cannot help but interpret the resulting image holistically." Therefore, these graphics can be seen as examples of object displays, which have been proposed for the integrated display of system information (Carswell & Wickens, 1996; Bennett, Toms, & Woods, 1993). Other suggested techniques have included pairs of graphics showing a value and corresponding uncertainty (simultaneously or alternately (MacEachren, 1992)), animation (via the degree of motion), and sound (Pang et al., 1997b). However, such representations have not been systematically evaluated. In all of these cases, no work has been done to extend our understanding of how such representations might be applied to different types of meta-information (or, for that matter, even different types of uncertainty).

3. Method – Cognitive Systems Engineering

Our goal across the multiple projects discussed in this paper has been to identify and study types of meta-information and their influences on decision-making with the express purpose of aiding in the design of new C2 decision-support systems. To accomplish this goal, we chose a particular set of analytic methods encompassed as part of Cognitive Systems Engineering (CSE). CSE was developed as a result of experiences with new technology where increased computerization did not guarantee improved overall human-and-computer system performance and, in some cases, led to catastrophic errors (e.g., confusions leading to pilot error and fatal aircraft accidents) (Woods & Dekker, 2000; Roth, Malin, &

Schreckenghost, 1997; Woods, Sarter, & Billings, 1997). Cognitive Systems Engineering (CSE) attempts to prevent these types of failures in the design and development of complex systems by addressing design issues through careful analysis of the problem domain, the tasks to be performed by a human-computer system, and the limitations of both the human and the machine.

The field of CSE encompasses a variety of analysis and design methods (e.g., (Burns & Hajdukiewicz, 2004; Eggleston, Roth, & Scott, 2003; Elm et al., 2003; Endsley, Bolte, & Jones, 2003; Vicente, 1999; Rasmussen, Pejtersen, & Goodstein, 1994)). These methods share a commitment to analyzing the cognitive and collaborative demands imposed by the domain of practice and identifying implications for information, visualization, and decision-support requirements. CSE methods generally entail a multi-phase, iterative design approach that includes a cognitive analysis phase, a concept development and prototyping phase, and a user evaluation phase. The cognitive analysis phase typically employs knowledge elicitation methods such as interviews of domain practitioners and observations of work in context. These methods uncover the cognitive and collaborative processes involved in making decisions and performing tasks in the domain and the challenges that arise (Potter, Roth, Woods and Elm, 2000; Roth and Patterson, 2005). A variety of representational formalisms are used to synthesize and communicate the results of the analysis and the design implications. These formalisms range from graphic representations such as goal-means graphs, to structured tables, to prose summary descriptions (Elm, Potter, Gualtieri, Roth & Easter, 2003; Eggleston, Roth, Whitaker and Scott, 2005; Endsley et al, 2003; Vicente, 1999; Wampler, Whitaker, Roth, Scott, Stilson & Thomas-Meyers, 2005). The cognitive analysis phase is followed by a concept development phase that involves identifying aiding concepts to address the challenges identified by the cognitive analysis, and developing storyboards and prototypes to realize those concepts. The prototype is then tested in the user evaluation phase. Experienced domain practitioners are the test participants. They assess the viability of the aiding concepts and drive further design. CSE is an iterative process that typically involves multiple iterative loops through the cognitive analysis, concept development, and user evaluation phases. This cyclic process is illustrated in Figure 3-1.

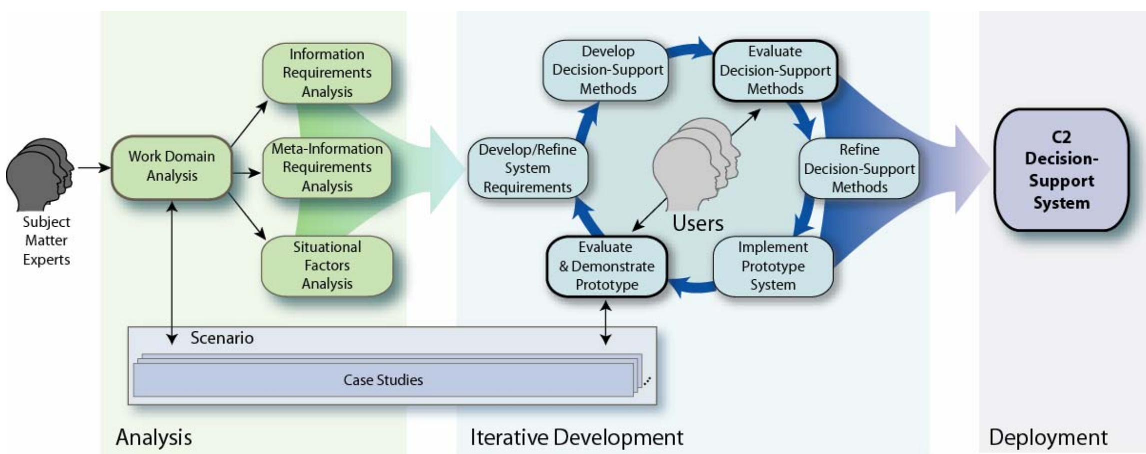

Figure 3-1: Cognitive Engineering approach to C2 decision-support system design, development, and evaluation

The nature of military decision-making analysis tasks in the face of increased information flow suggests that the design and development of tools to support decision-making will be greatly aided by the adoption of a CSE approach. This approach incorporates an understanding of the problem domain and its complexities, an analysis of the functional demands on the human user and any support tools, and an analysis of human perceptual and cognitive limitations in the context of a realistic set of case studies, and so provides a significant amount of highly relevant information to the system designer as regards the interdependencies between information and decision-making. Because of these qualities, we have chosen it as our fundamental methodological framework for the study of meta-information effects on decision-making. In addition, the CSE approach allows for a spiral design process, whereby initial designs can be evaluated with expert analysts to see how effectively each design supports the decision-making process. We and our colleagues have used this approach for a wide variety of projects (Roth & Patterson, 2005; Pfautz et al., 2004; Roth et al., 2002; Grecu, Sullivan, & Zacharias, 2001; Das et al., 2000) and its use is espoused throughout the system engineering community (Eggleston, 2003; Woods & Roth, 1988).

4. Analysis

In the process of designing and developing a variety of systems to support different aspects of C2 across different application domains, we applied the CSE methodology and discovered a number of consistencies regarding the types and sources of information and meta-information about which a commander may reason. Below, we discuss the problem domains studied, our specific analytic goals, and the nature of the work performed.

As a team, we have applied CSE methods to system design and development in a wide variety of domains, from Air Force mission management and planning tools to Army Intelligence collection tools (Wampler et al., 2005; Pfautz et al., 2005c). In this paper, we are consider only the work performed to understand C2 decision-making and the impacts of various types of C2 decision-support systems, including analyses performed across the domains shown in Table 4-1

Table 4-1: Domains studied in analysis efforts

Intelligence operations	We analyzed the planning and collection of Army intelligence to help develop tools to support collection planning and information fusion. For example, we studied how commanders and intelligence analysts reason about how the *credibility* of a source of intelligence interacts and the confidence stated by that source (Pfautz et al., 2004).
Small-unit tactical maneuvers	We investigated how platoon-level Army commanders plan and execute tactical maneuvers in urban and open-field terrain to support the development of systems to aid in training spatio-temporal reasoning skills. For example, a commander may reason about the *recency* of information about downed power lines along a key corridor to determine if it is trafficable for large vehicles.
Sensor management	We studied the planning and collection of intelligence using relatively novel sensor field technologies. In this domain, a commander needs to reason about the "*health*" of the source and the *frequency* of data collection (Pfautz et al., 2005c)
Weather impact assessment	We studied C2 decision-making in Army and Air Force missions to help develop systems that help commanders and their staff reason about the influence of weather events on tactical operations. For example, a commander may reason about the *timing and severity* of an incoming storm to determine whether or not to send a UAV on a reconnaissance mission (Lefevre et al., 2005; Wampler et al., 2005)
Natural disaster management	We explored how firefighters were managed and directed during wildfire events in the Western U.S. to support the development of decision-aids for reasoning about asset allocation. For example, a decision-maker might reason about the *validity* of a firespread model in determining whether or not to evacuate a nearby town (Pfautz et al., 2005a).

All of these domains involve a commander or decision-maker who must reason about incoming information and its associated meta-information. While this is not a complete set of possible C2 application domains, we believe that it represents a sufficiently broad set to identify particular commonalities across the types of information and meta-information required to make effective decisions.

In each of the above domains, we performed an analysis to identify characteristics of the domain and decision-making in the domain that had important implications for system design. We adapted CSE methods such as Cognitive Task Analysis (CTA), and while we were focused on the features of a particular domain, we also established some common analytic goals across domains. These goals included identifying:

- Key decisions and decision types
- Sources and types of data informing those decisions
- Sources and types of meta-information influencing those decisions
- Contextual (e.g., situational, environmental) factors influencing information and meta-information needs

The analyses were based on structured interviews with a number of experienced experts in each of the domains listed in Table 4-1. Two converging techniques were used to elicit information on the role of meta-information in complex decision-making situations. One technique relied on critical incident analysis. In this case, the domain experts were asked to describe actual military situations they experienced in which they faced cognitively demanding decisions. A second technique involved the development and analysis of hypothetical scenarios that characterized decision-making demands in complex situations involving sparse, noisy, conflicting, and ambiguous data. The scenarios were typically designed in collaboration with the domain experts that participated in the analysis and provided a vehicle that enabled the domain experts to concretely articulate the kinds of complexities that arise in the domain that pose challenges to cognitive and decision-making processes. The exercise of developing the scenarios and analyzing the potential sources of complexities that would be imposed on decision-makers enabled the domain experts to expose knowledge of the domain and sources of complexity that would otherwise be difficult for them to articulate. In some cases, the hypothetical scenario was presented to one or more additional domain experts to elicit additional perspectives on what made these situations challenging and how experts and less experienced operational personnel would respond in these complex decision-making situations. Given these scenarios, the domain experts were interviewed about their decisions at various points in the scenario. Specific implications of decisions were studied, with particular regard to the types of conditions and factors impacting on the decision-making process. In each domain, a set of cognitive tasks was identified, along with particular cognitive challenges arising in the performance of those tasks. In this paper, we are presenting the results from our analysis of the challenges related to the processing and integration of meta-information.

5. Results

Our experience performing analyses of decision-making across different C2-related domains led us to recognize some common concepts and issues related to meta-information. As part of our analysis, we developed some general concepts about what should be designated as "meta-information" and how we might define types of meta-information in a particular domain. In addition, we developed a categorized list of types of domain-specific meta-information we discovered, which may aid in the development of meta-information needs for other domains. Finally, we identified some key characteristics of how commanders reason about meta-information, therefore supporting the development of future C2 decision-support systems.

5.1 General Meta-Information Concepts

Before we can develop an understanding of what qualifies information (i.e., What is meta-information?), we need to distinguish between *data* and information. The distinction between data (minimally processed, time-sequenced output from sources such as sensors, humans, or algorithms) and information (in which data, often from multiple sources or times, is integrated based on the needs of human decision makers) is common within the field of Cognitive Engineering. Elm et al. (2003) describe a "data-to-information" transition as part of their cognitive engineering methodology. Specifically, this transition transforms parameters (i.e., based on sensed data and computation) into information that is relevant to operator goals (e.g., whether a parameter has exceeded a limit). Elm et al. provide several rules-of-thumb for distinguishing information requirements from data, including "if you are listing sensors, you are wrong," "does it have an intent-functional 'feel' to it," and "expect phrases and sentences, not database tags." Endsley et al. (2003) claim that information requirements (e.g., "enemy strengths") should be identified without reference to the technology with which the information is obtained, thus implicitly separating information from the data sources which provide information.

Following these distinctions, we differentiate between data (the outputs from human and non-human sensors or algorithms) and functional information (information that is relevant within a goal-directed, decision-making process). Functional information requirements are those requirements identified through methods such as cognitive task or work analysis and are clearly tied to the goals and tasks of operators. Meta-data and meta-information are *characteristics or qualifiers* of data and information in some particular context, respectively. For instance, if data corresponds to the signals transmitted from a sensor, then meta-data may "tag" the signals with temporal and location information, along with measurements of the sensor's power or known accuracy. Environmental characteristics, such as ambient temperature or humidity may also be included as meta-data. As discussed earlier, meta-data may be used in a variety of computational systems for filtering, managing, and processing data before it becomes an input to a decision-making process. It can be inherent in the data or calculated separately. Meta-information can be thought of as the qualifications or characteristics of that functional information that allows operators to correctly interpret that functional information as needed (e.g., this information is too old to be pertinent to my current situation). Meta-information *includes* uncertainty but should not be thought of as a way of describing different types of uncertainty. For example, a commander may have as a task to read a list of reports. This rank-ordered list of reports can be read without any uncertainty about this task. However, if the commander's intelligence officer tells him a different ordering, for example, that a previously low-ranked report is important and will impact his ability to accurately interpret other reports, then the commander could re-order the reports and process them differently because of this meta-information. In this example, we might argue that there is no uncertainty about the order of the reports, only a difference in the meta-information the commander has to decide the order in which to read them.

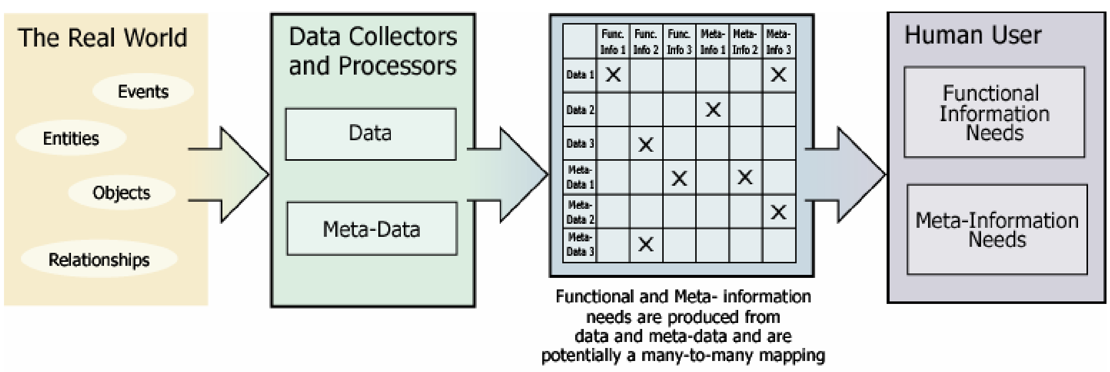

Figure 5-1: Distinguishing between data, meta-data, information, and meta-information

As shown in Figure 5-1, functional information and meta-information are derived by the human user from the transformation and integration of data and meta-data. For the purposes of designing decision-support systems, the distinction between information and data is advantageous, because it allows the identification of new requirements for data or meta-data by allowing the specification of decision-, goal-, or task-relevant information which may be currently unavailable leaving only sensor or processing capabilities to guide system design. This distinction allows us to differentiate between what needs to be known by the commander, and the data and computational methods that are available to provide that information. For instance, within this framework it is conceivable to identify information or meta-information needs that cannot be met with currently available data or meta-data and associated processing methods, or those which may be provided with higher quality as more data and more sophisticated methods for combining the data become available (Llinas et al., 2004). The identification of such needs is cited as a typical outcome of a cognitive engineering analysis (Elm et al., 2003; Vicente, 1999). Also, it is likely that the types of meta-data that could be associated with any data source (particularly when environmental information is included) are numerous to the point of being impractical (to define, identify, store, and process). Taking a top-down approach based on human-centered information and meta-information needs can serve as a constraint on the types of meta-data that need to be considered within a computational decision-support system (i.e., identified, calculated, tagged, etc.).

The types of, and distinctions between, information and meta-information are based on the task or goal being pursued, as illustrated by the example in Table 5-1. This example is taken from two tasks in a typical military C2 domain: sensor management and tactical decision-making that is dependent on sensor data.

Table 5-1: Examples illustrating the task-dependency of information and meta-information specification

	Sensor Management	**Tactical Decision-Making**
Data	Sensor X reports 42.2 dB Sensor Y reports 32.1° F	Sensor X reports 42.2 dB Sensor Y reports 32.1° F
Meta-Data	Sensor X error is ± .4 dB Sensor Y reports at 5 Hz	Sensor X error is ± .4 dB Sensor Y reports at 5 Hz
Functional Information	Location of sensors Sensor types "Health" of sensors	Location of targets Type of targets Number of targets
Meta-Information	Accuracy of sensor status Recency of sensor status	"Health" of sensors Coverage of sensors Accuracy of target information Recency of target information
Decision-Making Impact of Meta-Information	Effectiveness of sensor-relocation or employment decisions	Satisfaction of targeting policy factors (Rules of Engagement)

Note first that for both tasks, data and meta-data types are the same and are obtained directly from the sensors. Data is defined by the inherent reporting capabilities of a sensor or sensor fusion system. The meta-data in this example could be provided by the specifications of the sensor or by some calculation of average error or reporting frequency. It is when considering information and meta-information that the difference between tasks becomes apparent. The sensor management task includes decisions about whether to remove the sensors, replace the sensor, or reconfigure the sensors. In this task, the status of the sensors is the functional information, and the meta-information concerns the accuracy and recency of that status information. In the tactical decision-making task, where a commander will interpret and use information about the operational environment to direct his or her assets, the functional information is the location and type of objects of interest, while the meta-information includes the status of the sensors providing this information.

As a result of our analysis, we argue that simply considering the role of uncertainty in decision-making may be insufficient to fully understand the reasoning process and that additional types of information qualifiers should be considered. We contend that there are many different types of information qualifiers that may be termed "meta-information" and that when building decision-aids it is useful to understand the various kinds of meta-information that decision-makers use in their reasoning. To support these assertions, we have developed working definitions for data, meta-data, information and meta-information (adapted from Pfautz et al., 2005c):

- **Data** is output (processed or unprocessed) from a human, machine, or human-machine system (e.g., John said it is raining, acoustic sensor X reported 34 dB, Bill reported his GPS location is 44°23'13.02")

- **Information** (or **functional information**) is an input to a goal-directed decision-making process (e.g., because information has been received that there are high-intensity crosswinds at the launch site, the commander decides the aircraft will not be flown)
- **Meta-data** is a characteristic or qualifier of data (e.g., John has bad eyesight, acoustic sensor Y has an error of ± 0.2 decibels, Bill reported his location at 1400)
- **Meta-information** is a characteristic or qualifier of information that affect a commander's:
  - Information processing (e.g., reports flagged as "important" by an aide get read first)
  - Situational awareness (e.g., because information about adversary surface-to-air missile locations is recent and certain, the commander knows certain friendly aerial assets are under threat)
  - Decision-making (e.g., because information about the adversary's location is 30 hours old, the commander decides to send a scout to confirm the location before maneuvering)

As described above, what is defined as information and meta-information in a particular situation is inherently subject to the type of task being performed. It is necessary to understand a commander's tasks, goals, or decisions before these definitions can be applied and used to guide system design. We believe these definitions present a generalizable view of meta-information and therefore capture important meta-information that cannot be classified as a type of uncertainty.

5.2 Sources and Types of Meta-Information

A main objective of our analyses was to define and characterize types of meta-information that influence military decision-makers across a wide range of C2 situations. Our goal was to provide a broad and principled characterization of the range of meta-information that may need to be included in C2 decision-support systems to provide effective support. Through our analysis efforts, we identified the main types of decisions (and/or tasks and goals) and the types of meta-information that impact those decisions in the specific domains we studied. As described above, the specific aspects of meta-information that are (or should be) considered by the decision-maker depend on the particular domain of application. By examining the *specific factors* that contribute to and constitute meta-information in the multiple domains we examined, we were able to define a list of specific types of meta-information we encountered. We list and describe these meta-information types in Table 5-2 with the intent to describe *examples* of meta-information discovered *in particular domains*. These types are not intended to be universal across types of tasks/decisions/goals, nor across different application domains. Rather, it is intended to aid in the identification of similar types of meta-information when analyzing different types of decision-making in other domains.

Table 5-2: Sources and types of meta-information in the explored domains

Meta-Information Type	Sub-types or related types
Characteristics of the source of information	Type of data the source can produce Type of processing used Range of data generated Baseline error rates Frequency of reporting Ability to report on its status and characteristics of that report Inherent biases Past performance, history Directly observing or deriving information
Characteristics of the source as a function of other factors	Time Location in environment (e.g., terrain, weather) Types of intermediate processing Content of report

	Information context
Uncertainty	Spatial uncertainties Temporal uncertainties Uncertainties about uncertainty reporting Likelihood Probability Confidence Accuracy Precision
Ambiguity	Specificity or resolution of information Level of abstraction of information
Information context (i.e., relationship to other information)	Degree of confirming or disconfirming information Paucity of information Frequency of reporting of information Missing or degraded information qualifiers Information-to-noise ratio History
Reliability of source	W.r.t. source characteristics W.r.t. information context
Credibility of content from source	W.r.t. reliability W.r.t. type of content W.r.t. type of source W.r.t. information context
Relevance or pertinence	W.r.t. specific mission goals W.r.t. actual/perceived information needs W.r.t. broader operational context W.r.t. current hypotheses about the situation
Temporal qualifiers	Staleness Recency Certainty about time of reporting Latency Lag Absence of expected information

This list of types of meta-information represents the types discovered in the domains we studied. There are clearly interactions between types and sub-types of meta-information that deserve further study across additional domains and decision-making tasks. There are also myriad semantic issues with respect to how these types of meta-information should be defined (e.g., how should we differentiate between types of relevance meta-information?). As such, our initial goal is to simply establish the need for analysis of meta-information needs in the particular context of a decision-making task and to provide a starting point for understanding what types of needs might be identified.

5.3 Meta-Information and Decision-Making

The number of qualifiers that can impact data interpretation and utilization, and the need to integrate multiple qualifiers, makes clear the cognitive complexity faced by military decision-makers as they try to interpret the relevance and importance of any given piece of data to their decision-making process and to integrate across multiple pieces of information to draw inferences and conclusions. The difficulties faced by a decision-maker could be characterized as more generalized versions of the five cognitive strategies identified by Lipshitz et al. (1996) for coping with uncertainty (see Section 2.1). In our research, we have identified three main cognitive complexities relating to meta-information. First, the decision-maker may fail to *recognize relevant meta-information.* For example, the commander may fail to appreciate that a message received from headquarters is old (i.e., stale) and therefore may no longer be true. Second, the commander may not *process meta-information appropriately.* That is, the analyst may fail to correctly integrate reliability and credibility of a message to come up with an overall confidence in that message. Third, the commander may not *properly utilize the meta-information* to integrate multiple diverse information reports that have different meta-information qualifiers (e.g., different sources, different levels of reliability, different levels of credibility, different time stamps, different perceived relevance to the current mission). There is also evidence that humans have difficulty appropriately weighing and integrating multiple information sources that vary on meta-information dimensions (Wickens, Pringle, & Merlo, 1999), further increasing the commander's burden.

6. Implications and Discussion

We found that a commander's decision-making performance, situational awareness, workload, and trust can be influenced by the inclusion of meta-information in a system's display, interface, and underlying computational formalisms. The results of our analyses point to implications for the development of C2 decision-support tools. These implications affect specific components of decision support systems, for example, display design (e.g., present needed meta-information, but only in specific situations to avoid overload), user interaction design (e.g., allow the human user to control when and what meta-information is presented), and automation design (e.g., use computational methods that can provide meta-information about both the actions of the automated processes and their results).

6.1 Implications for Computational System Design

The need for meta-information impacts the design of computational decision-support systems at many levels. Ideally, the need for meta-information should impact the development of sensors and processing systems that can address those specific needs. More realistically (and because system engineering is often driven more by technical and fiscal constraints than by human user needs), systems need to be developed that can map existing data and meta-data to specific meta-information needs. There are a number of technologies from the data fusion community that could be retroactively adapted to provide meta-information to address the failures of the human-computer system to recognize, process, and utilize meta-information. Similarly, there are techniques in the computational intelligence community that could be easily adapted to calculating different types of meta-information. For example, Bayesian networks could be used to calculate a "confidence" value based on combining different meta-information types such as information context (e.g., degree of confirming/disconfirming evidence), source characteristics (e.g., sensor error rates), and the interaction of the source characteristics with the environment (e.g., error rates as a function of temperature). From a purely theoretical basis, there is little reason why meta-information could not be calculated for many problem domains. However, the calculation of meta-information can represent an additional computational burden and could decrease the efficiency of some systems. Ideally, meta-information calculation methods that can be incorporated with existing methods for generating needed information or that can be used selectively and/or on-demand should be developed.

6.2 Implications for Display and Interface Design

In the Cognitive Systems Engineering approach that we have employed in this work, the clear identification of information and meta-information needs leads not only to the design of computational methods to address these needs but also to the development of displays and interfaces that can effectively communicate the needed information and meta-information to the commander in ways that specifically address possible failures to recognize, process, and utilize meta-information. The knowledge that humans have difficulty appropriately weighing and integrating multiple information sources that vary on meta-information dimensions (Wickens et al., 1999) highlights the need to (1) more effectively communicate the meaning and basis (i.e., rationale) for how and why information was produced and provide (2) intelligent support for integrating and reasoning about meta-information with respect to both a given piece of information and to multiple pieces of information that differ along meta-information dimensions (e.g., differ in reliability and credibility). At the same time, our analysis and the results of developing preliminary display designs suggests that presentation of meta-information needs to be context sensitive (Lefevre et al., 2005; Pfautz et al., 2005a; Pfautz et al., 2005c). Presentation of meta-information under all circumstances can contribute to information overload conditions and result in failures to recognize and/or use meta-information in reasoning. Therefore, it is important to examine the circumstances under which decision-makers will be critically affected by the presence or absence of meta-information. Situations where there are “close calls” or where the risk associated with alternative actions is high are likely to require more careful consideration of meta-information in decision-making to improve the salience of important information while *avoiding* information overload.

Our results point to additional guidelines for display design. While some work has been done on the visualization of uncertainty (Section 2.3), comparatively little research has been done to explore the more general problem of establishing effective forms for communicating meta-information. Clearly, an important constraint is avoiding the presentation of too much information in conflicting forms, which could easily occur if meta-information is displayed without thought to how it might optimally compliment the information it is qualifying. Another approach is to provide methods for user-selected display of meta-information, although work by Wickens and Yeh (1997) suggests that an effectively designed display of all information is more efficient than a user-controlled display of particular information elements. When designing displays, an effort should be made to determine if there are “natural mappings” (Helander, 1987) between a type of meta-information and a display method that could be exploited to make the presentation of meta-information more intuitive and therefore minimize potential overload problems.

6.3 Future Research Needs

Our analysis, and the resulting broad conceptualization of meta-information needs in C2 decision-making, has illuminated a number of areas for future research. In particular, there remain unanswered questions about the impacts of different forms of meta-information on specific decision-making tasks. Reasoning should be examined with respect to the particular goal or task and the types of meta-information required, and additional effort is needed to differentiate reasoning under uncertainty from reasoning with meta-information. Computational methods are needed that go beyond reasoning about types of uncertainty to embrace the more general concept of meta-information and are developed with consideration to specific information and meta-information needs. Finally, significant work is needed in establishing efficient and effective ways to communicate meta-information to the commander; research is needed to understand how particular visual representations and interface methods are more or less effective for different types of meta-information. In all of these cases, we believe that the explicit discussion of meta-information requirements will drive the design of more effective, safe, and efficient decision-support systems.

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References

Andre, A. D. & Cutler, H. A. (1998). Displaying Uncertainty in Advanced Navigation Systems. In *Proceedings of Human Factors and Ergonomics Society 42nd Annual Meeting*.

Barnes, M., Wickens, C., & Smith, M. (2000). Visualizing Uncertainty in an Automated National Missile Defense Simulation Environment. In *Proceedings of ARL Federated Laboratory 4th Annual Symposium -- Advanced Displays & Interactive Displays Consortium*. College Park, Maryland.

Basapur, S., Bisantz, A. M., & Kesavadas, K. (2003). The Effect of Display Modality on Decision-Making in Uncertainty. In *Proceedings of Human Factors and Ergonomics Society*.

Bennett, K. B., Toms, M. L., & Woods, D. D. (1993). Emergent Features and Graphical Elements: Designing More Effective Configural Displays. *Human Factors,* 35(1), 71-97.

Bisantz, A. M. (2002). Methods in Visualizing Uncertainty. Panelist in Behind the Curtain: the Cognitive Tasks behind the Visualizations. In *Proceedings of Human Factors and Ergonomics Society Annual Meeting*. Baltimore, MD.

Booker, J. M., Anderson, M. C., & Meyer, M. A. (2003). The Role of Expert Knowledge in Uncertainty Quantification (Are We Adding More Uncertainty or More Understanding?). In *Proceedings of Seventh U.S. Army Conference on Applied Statistics*.

Bosc, P. & Prade, H. (1997). An Introduction to the Fuzzy Set and Possibility Theory-Based Treatment of Flexible Queries and Uncertain or Imprecise Databases. In A. Motro & P. Smets (Eds.), *Uncertainty in Information Systems: From Needs to Solutions* (pp. 285-324). Boston, MA: Kluwer.

Burns, C. M. & Hajdukiewicz, J. (2004). *Ecological Interface Design*. CRC Press.

Carswell, C. M. & Wickens, C. D. (1996). Mixing and Matching Lower-Level Codes for Object Displays: Evidence for Two Sources of Proximity Compatibility. *Human Factors,* 38(1), 1-22.

Das, S., Chan, C., Klinzing, K., & Zacharias, G. (2000). *Agent for Visualization and Intelligent Decision-Aiding (AVID).* (Rep. No. S98234). Cambridge: Charles River Analytics.

Eggleston, R. G. (2003). Work Centered Design: A Cognitive Engineering Approach to System Design. In *Proceedings of Human Factors and Ergonomics Society 47th Annual Meeting*. Denver, CO: Human Factors and Ergonomics Society.

Eggleston, R. G., Roth, E. M., & Scott, R. A. (2003). A Framework for Work-Centered Product Evaluation. In *Proceedings of Human Factors and Ergonomics Society 47th Annual Meeting*. Denver, CO: Human Factors and Ergonomics Society.

Elkan, C. (1994). The Paradoxical Controversy over Fuzzy Logic. *IEEE Expert,* 9(4), 47-49.

Elm, W. C., Potter, S. S., Gualtieri, J. W., Roth, E. M., & Easter, J. R. (2003). Applied Cognitive Work Analysis: A Pragmatic Methodology for Designing Revolutionary Cognitive Affordances. In E. Hollnagel (Ed.), *Handbook for Cognitive Task Design*. London: Lawrence Erlbaum Associates.

Endsley, M. R. (1995). Measurement of Situation Awareness in Dynamic Systems. *Human Factors,* 37(1), 65-84.

Endsley, M. R., Bolte, B., & Jones, D. G. (2003). *Designing for Situation Awareness: An Approach to Human-Centered Design*. London: Taylor & Francis.

Endsley, M. R. & Garland, D. J. (2000). *Situation Awareness, Analysis, and Measurement*. Mahwah, NJ: Lawrence Erlbaum Associates.

Fisher, P. F. (1993). Visualizing Uncertainty in Soil Maps by Animation. *Cartographica,* 30(2/3), 20-29.

Geiger, D. & Heckerman, D. (1996). Knowledge Representation and Inference in Similarity Networks and Bayesian Multinets. *Artificial Intelligence,* 82(45), 74.

Grecu, D., Sullivan, O., & Zacharias, G. L. (2001). *Agent-Based Semantic Data Management and Visualization.* (Rep. No. R00841). Cambridge, MA: Charles River Analytics Inc.

Halpern, J. (2003). *Reasoning About Uncertainty*. Cambridge, MA: MIT Press.

Havenstein, H. (2006). Metadata Management Returns to the Fore. *ComputerWorld*. (July 18th).

Helander, M. G. (1987). Design of Visual Displays. In G. Salvendy (Ed.), *Handbook of Human Factors*. New York, NY: John Wiley & Sons, Inc.

Higgins, M. (1999). Meta-Information and Time: Factors in Human Decision-Making. *Journal of the American Society of Information Science,* 50(2), 132-139.

Howard, R. & Matheson, J. (1984). Influence Diagrams. In R. Howard & J. Matheson (Eds.), *Readings on the Principles and Applications of Decision Analysis* (pp. 719-762). Menlo Park, CA: Strategic Decisions Group.

Kahneman, D., Slovic, P., & Tversky, A. (1982). *Judgment under Uncertainty: Heuristics and Biases*. Cambridge, UK: Cambridge University Press.

Klein, G. (1996). The Nature of Uncertainty in Naturalistic Decision Making. In *Proceedings of the Human Factors and Ergonomics Society 40th Annual Meeting-1996*. Philadelphia: Human Factors Society.

Klein, G. A. (1998). *Sources of Power: How People Make Decisions*. Cambridge, MA: MIT Press.

Lefevre, R., Pfautz, J., & Jones, K. (2005). Weather Forecast Uncertainty Management and Display. In *Proceedings of 21st Int'l Conf. on Interactive Information Processing Systems (IIPS) for Meteorology, Oceanography, and Hydrology*. San Diego, CA.

Lin, F. (1993). An Argument-Based Approach to Non-Monotonic Reasoning. *Computational Intelligence,* 9254-267.

Lipshitz, R. & Strauss, O. (1996). How Decision-Makers Cope With Uncertainty. In *Proceedings of the Human Factors and Ergonomics Society 40th Annual Meeting-1996,* (pp. 189-193). Philadelphia: Human Factors Society.

Llinas, J., Bowman, C., Rogova, G., Steinberg, A., Waltz, E., & White, F. (2004). Revisiting the JDL Data Fusion Model II. In *Proceedings of 7th Int. Conf. on Information Fusion*.

Lodha, S. K., Sheehan, R. E., Pang, A. T., & Wittenbrink, C. M. (1996). Visualizing Geometric Uncertainty of Surface Interpolants. In *Proceedings of Graphics Interface 1996,* (pp. 238-245). Canadian Information Processing Society, Toronto ON.

MacEachren, A. M. (1992). Visualizing Uncertain Information. *Cartographic Perspective,* 1310-19.

Marco, D. & Jennings, M. (2004). *Universal Meta-Data Models*. New York, NY: Wiley.

McCarthy, J. & Hayes, P. J. (1969). Some Philosophical Problems from the Standpoint of Artificial Intelligence. In B. Meltzer, D. Mitchie, & M. Swann (Eds.), *Machine Intelligence 4* (pp. 463-502). Edinburgh, Scotland: Edinburgh University Press.

McQueary, B., Krause, L., Santos, E., Wang, H., & Zhao, Q. (2004). Modeling, Analysis and Visualization of Uncertainty in the Battlespace. In *Proceedings of 16th IEEE International Conference on Tools with Artificial Intelligence (ICTAI'04),* (pp. 782-783).

Pang, A., Wittenbrink, C., & Lodha, S. (1997a). Approaches to Uncertainty Visualization. *The Visual Computer,* 13(8), 370-390.

Pang, A. T., Wittenbrink, C. M., & Lodha, S. K. (1997b). Approaches to Uncertainty Visualization. *Visual Computing,* 13(8), 370-390.

Parsons, S. (2001). *Qualitative Methods for Reasoning under Uncertainty*. Cambridge, MA: MIT Press.

Pearl, J. (2001). *Causality: Models, Reasoning, and Inference*. Cambridge University Press.

Pearl, J. & Russell, S. (2000). *Bayesian Networks.*

Pfautz, J., Bisantz, A., Roth, E., Fouse, A., & Shuster, K. (2005a). Meta-Information Visualization in Geographic Information Systems. In *Proceedings of Society for Information Display '05*. Boston, MA.

Pfautz, J., Fouse, A., Roth, E., & Karabaich, B. (2005b). Supporting Reasoning about Cultural and Organizational Influences in an Intelligence Analysis Decision Aid. In *Proceedings of International Conference on Intelligence Analysis*. McLean, VA.

Pfautz, J., Roth, E., Bisantz, A., Fouse, A., Madden, S., & Fichtl, T. (2005c). The Impact of Meta-Information on Decision-Making in Intelligence Operations. In *Proceedings of Human Factors and Ergonomics Society Annual Meeting*. Orlando, FL.

Pfautz, J., Roth, E., Jones, K., Hudlicka, E., Fichtl, T., Karabaich, B. et al. (2004). Design and Evaluation of a Visualization Aid for Stability and Support Operations. In D. Hancock, M. Mouloua, & P. Vincenzi (Eds.), *Human Performance, Situation Awareness, and Automation: Current Research and Trends*, *Volume II* (pp. 253-258). Mahwah, NJ: Lawrence Erlbaum Associates.

Rasmussen, J., Pejtersen, A. M., & Goodstein, L. P. (1994). *Cognitive Systems Engineering*. New York: Wiley and Sons.

Roth, E. M., Gualtieri, J. W., Elm, W. C., & Potter, S. S. (2002). Scenario Development for Decision Support System Evaluation. In *Proceedings of Human Factors and Ergonomics Society 46th Annual Meeting*, (pp. 357-361). Santa Monica, CA: Human Factors and Ergonomics Society.

Roth, E. M., Malin, J. T., & Schreckenghost, D. L. (1997). Paradigms for Intelligent Interface Design. In M. Helander, T. K. Landauer, & P. Prabhu (Eds.), *Handbook of Human-Computer Interaction* (pp. 1177-1201). Mahwah, NJ: Elsevier Science.

Roth, E. M. & Patterson, E. S. (2005). Using Observational Study as a Tool for Discovery: Uncovering Cognitive and Collaborative Demands and Adaptive Strategies. In H. Montgomery, R. Lipshitz, & B. Brehmer (Eds.), *How Professionals Make Decisions*. Mahweh, NJ: Lawrence Erlbaum Associates.

Russell, P. & Norvig, P. (2003). *Artificial Intelligence: A Modern Approach*. (Second Ed.) Upper Saddle River, NJ: Prentice-Hall.

Schunn, C. D., Kirschenbaum, S. S., & Trafton, J. G. (2003). The Ecology of Uncertainty: Sources, Indicators, and Strategies for Information Uncertainty. http://www.au.af.mil/au/awc/awcgate/navy/nrl_uncertainty_taxonomy.pdf [On-line].

Smets, P. (1997). Imperfect Information: Imprecision and Uncertainty. In A. Motro & P. Smets (Eds.), *Uncertainty in Information Systems* (pp. 225-254). Boston, MA: Kluwer.

Smithson, M. (1989). *Ignorance and Uncertainty: Emerging Paradigms*. New York, NY: Springer Verlag.

Trickett, S., Trafton, G., Saner, L., & Schunn, C. (2005). "I Don't Know What Is Going on There": The Use of Spatial Transformation to Deal With and Resolve Uncertainty in Complex Visualizations. In M. Lovett & P. Shah (Eds.), *Thinking With Data*. Mahwah, NJ: Erlbaum.

Vicente, K. J. (1999). *Cognitive Work Analysis*. Mahwah, NJ: Erlbaum.

Wampler, J., Whitaker, R., Roth, E., Scott, R., Stilson, M., & Thomas-Meyers, G. (2005). Cognitive Work Aids for C2 Planning: Actionable Information to Support Operational Decision Making. In *Proceedings of 10th International Command and Control Research and Technology Symposium*.

Wickens, C., Pringle, H., & Merlo, J. (1999). *Integration of Information Sources of Varying Weights: The Effect of Display Features and Attention Cueing.* (Rep. No. U. Illinois Institute of Aviation Tech. Report (ARL-99-2/FED-LAB-99-1)). Savoy, IL: Aviation Research Laboratory.

Wickens, C. D. & Yeh, M. (1997). Attentional Filtering and Decluttering Techniques in Battlefield Map Interpretation. In *Proceedings of Advanced Displays and Interactive Displays,* (pp. 2-35). Adelphi, Maryland.

Woods, D. & Dekker, S. (2000). Anticipating the Effects of Technological Change: A New Era of Dynamics for Human Factors. *Theoretical Issues in Ergonomic Science,* 1(3), 272-282.

Woods, D. D. & Roth, E. M. (1988). Cognitive Systems Engineering. In M. Helander (Ed.), *Handbook of Human-Computer Interaction*. New York: North-Holland.

Woods, D. D., Sarter, N. B., & Billings, C. E. (1997). Automation Surprises. In G. Salvendy (Ed.), *Handbook of Human Factors/Ergonomics* (2nd Ed.). New York: Wiley.

Yovits, M. C. & Abilock, J. (1974). A Semiotic Framework for Information Science Leading to the Development of a Quantitative Measure of Information. In *Proceedings of 37th American Society for Information Sciences Meeting*, (pp. 163-168).

Zadeh, L. A. (1965). Fuzzy Sets. *Information and Control*, 8338-353.

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The Role of Meta-Information in C2 Decision-Support Systems

Command and Control Research and Technology Symposium:
Cognitive and Social Domain Issues – Track 6

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June 20th - 22nd, 2006

Overview

- General Motivation and Goals
- Approach and Methods
- Description of Domains
- Results of Analysis
- Implications and Conclusions

General Motivation

- Interest in uncertainty w.r.t. system design & development
  - In Artificial Intelligence community
    - Probabilistic reasoning techniques
    - Representational formalisms
  - In Cognitive Engineering community
    - In decision-making (e.g., trust and uncertainty)
    - For visualization and interface design
  - In Military environments
    - Asymmetric warfare
    - Increase in HUMINT
    - Increase in information in NCW

- Anecdotes across many domains…

General Motivation

- “Uncertainty” is **not enough**

- Information may be qualified in other ways
  - Importance, Quality, Impact, Pertinence
  - Recency, Staleness, Timeliness
  - Ambiguity, Accuracy, Precision
  - Pedigree, Confidence, Reliability
  - ...

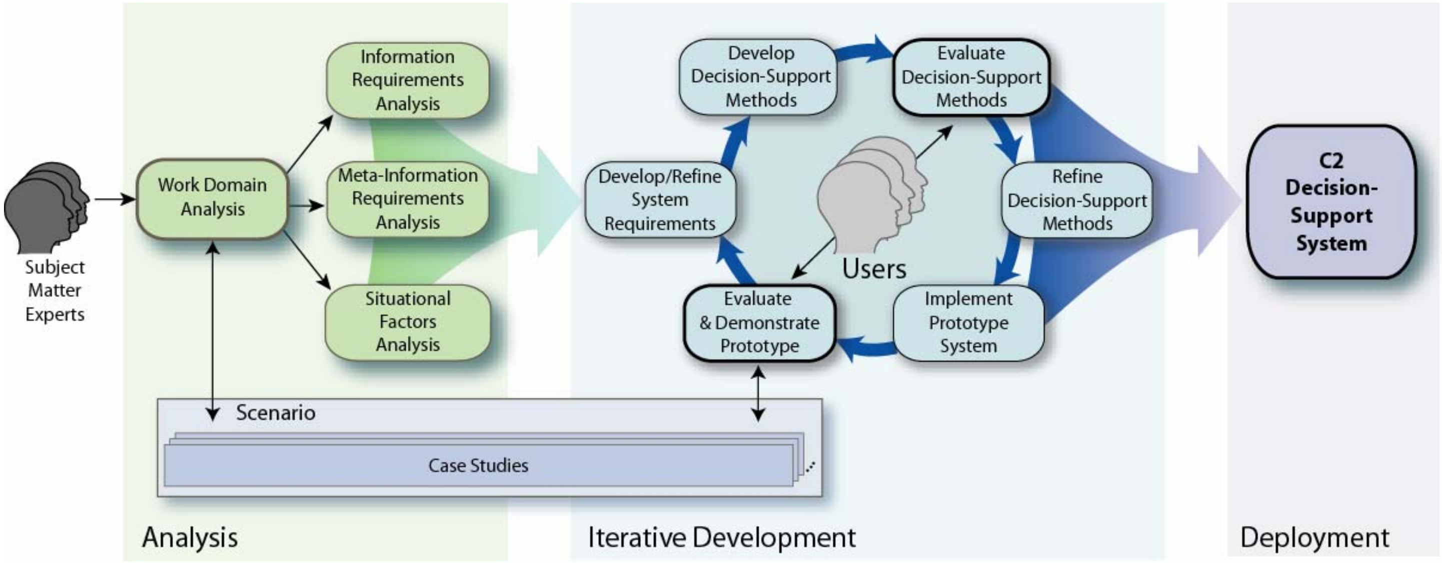
- **“Meta-Information”**
  - ... is a concept/term that captures information qualifers more generally

Goals

- Establish that meta-information must be considered in C2 system design by summarizing analyses across C2 domains
- Provide guidelines to support the design of C2 decision-support systems w.r.t. meta-information
  - Displays and user interfaces
  - Computational methods
- Encourage design processes that aid in understanding meta-information requirements
  - Because of task and context dependence of meta-information

Analysis Method

- Performed analysis as part of Cognitive Systems Engineering methodology



Analysis Approach

- Constructed hypothetical scenarios to explore context
- Conducted structured interviews with domain experts
- Performed analysis to:
  - Identify key sources of complexity and types of decisions
  - Uncover sources and types of:
    - Data
    - Meta-data
    - Information
    - Meta-information
  - Identify required information and meta-information
  - Discover situational influences on requirements

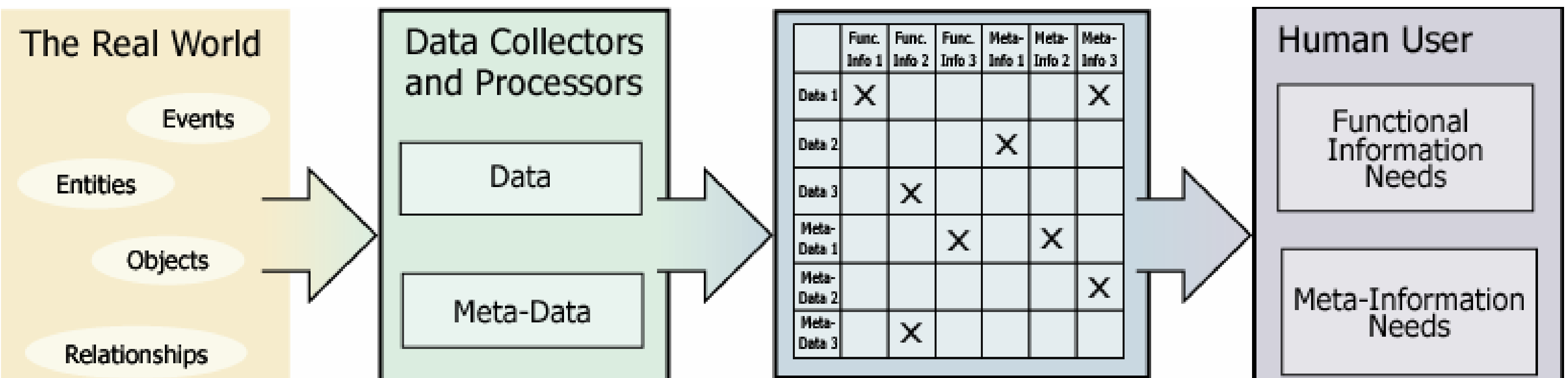
C2 and C2-Related Domains Analyzed

- Intelligence operations
- Small-unit tactical maneuvers
- Sensor management
- Weather impact assessment
- Natural disaster management

(Our thanks to the many domain experts we interviewed and observed!)

Results of Analysis

- Identified information needs
- Identified meta-information needs
- Defined meta-information concepts



Functional and Meta- information needs are produced from data and meta-data and are potentially a many-to-many mapping

Working Definitions

- ***Data***: output (processed or unprocessed) from a human or machine system – e.g.,
  - Acoustic sensor X reports 34 Db
  - Joe says it is raining
- ***Information***: an input to a directed decision-making process – e.g.,
  - A storm is coming, thus I will not launch the weather balloon until tomorrow
- ***Meta-Data***: characteristics or qualifiers of data – e.g.,
  - Temperature sensor Y has an error of +/- 0.1 deg F
- ***Meta-Information***: characteristics or qualifiers of information, affecting a human's:
  - Information processing
  - Situational awareness
  - Decision-making
  - E.g., There is a 60% chance the fire is located at {x,y} therefore I will confirm its location before sending fire trucks

Definitions, cont’d

- Is “meta-information” just “information”? No.
  - It *qualifies* information
  - It may be reasoned about differently
    - E.g., qualifiers may be ignored under high time demands
  - It tends not to be regularly captured or represented in many human-machine systems where it is needed

- How we might define data, meta-data, information, and meta-information depends on
  - The decision-making task
  - The context or situation

Meta-Information Definitions across Tasks

	Sensor Management	Tactical Decision-Making
Data	Sensor X reports 42.2 dB Sensor Y reports 32.1° F	Sensor X reports 42.2 dB Sensor Y reports 32.1° F
Meta-Data	Sensor X error is ± .4 dB Sensor Y reports at 5 Hz	Sensor X error is ± .4 dB Sensor Y reports at 5 Hz
Information	Location of sensors Sensor types “Health” of sensors	Location of targets Type of targets Number of targets
Meta-Information	Accuracy of sensor status Recency of sensor status	“Health” of sensors Coverage of sensors Accuracy of target information Recency of target information

Meta-Information Definitions across Tasks

	Sensor Management	Tactical Decision-Making
Data	Sensor X reports 42.2 dB Sensor Y reports 32.1° F	Sensor X reports 42.2 dB Sensor Y reports 32.1° F
Meta-Data	Sensor X error is ± .4 dB Sensor Y reports at 5 Hz	Sensor X error is ± .4 dB Sensor Y reports at 5 Hz
Information	Location of sensors Sensor types **"Health" of sensors**	Location of targets Type of targets Number of targets
Meta-Information	Accuracy of sensor status Recency of sensor status	**"Health" of sensors** Coverage of sensors Accuracy of target information Recency of target information

More Results

- Analyses showed wide range of types of meta-information
- The following provide examples of meta-information types we encountered...

Types of Meta-Information Discovered

- Characteristics of the source of the information
  - Type of data the source can produce
  - Type of processing used
  - Range of data generated
  - Baseline error rates
  - Frequency of reporting
  - Ability to report on its status and characteristics of that report
  - Inherent biases
  - Past performance, history
  - Directly observing or deriving information

Types of Meta-Information Discovered

- Characteristics of the source varying with other information
  - Time
  - Location in environment (e.g., terrain, weather)
  - Types of intermediate processing
  - Content of report
  - Information context
- Uncertainty
  - Spatial uncertainties
  - Temporal uncertainties
  - Uncertainties about uncertainty reporting
  - Likelihood
  - Probability
  - Confidence
  - Accuracy
  - Precision

Types of Meta-Information Discovered

- Ambiguity
  - Specificity or resolution of information
  - Level of abstraction of information
- Information context (i.e., relationship to other information)
  - Degree of confirming or disconfirming information
  - Paucity of information
  - Frequency of reporting of information
  - Missing or degraded information qualifiers
  - Information-to-noise ratio
  - History
- Reliability of source
  - W.r.t. source characteristics
  - W.r.t. information context

Types of Meta-Information Discovered

- Credibility of content from source
  - W.r.t. reliability
  - W.r.t. type of content
  - W.r.t. type of source
  - W.r.t. information context
- Relevance or pertinence
  - W.r.t. specific mission goals
  - W.r.t. actual/perceived information needs
  - W.r.t. broader operational context
  - W.r.t. current hypotheses about the situation
- Temporal qualifiers
  - Staleness
  - Recency
  - Certainty about time of reporting
  - Latency
  - Lag
  - Absence of expected information

Meta-Information and C2 Decision-Making

- Uncovered three complexities related to decision-making and meta-information
  - Failure to recognize relevant meta-information
  - Failure to process meta-information appropriately
  - Failure to properly utilize meta-information

- These complexities apply to both
  - Human decision-making
  - Machine reasoning

Implications & Future Work: Computational System Design

- Need to represent meta-information needs in data structures, computational processes
- Need to calculate meta-information from data and meta-data
- Need to aggregate meta-information
- Need to process types of meta-information simultaneously
- Need to minimize impact of additional computation

- Future work:
  - What representational formalisms are amenable to handling multiple types of qualifiers?
  - What computational processes support reasoning over qualified information?
  - To what extent can existing methods be adapted to support meta-information needs?
  - ...

Implications & Future Work: Display and Interface Design

- Need to communicate meta-information in a situation- and task- relevant manner
  - What visualization methods work for what types of meta-information?
  - How does the information type and its display method interact with the meta-information visualization?
- Need to avoid overloading the user with the presentation of meta-information
  - How and when does the presentation of meta-information cause overload?
  - What user interface mechanisms could aid in avoiding overload?
- Need to aid reasoning about and with meta-information
  - What displays/UIs facilitate a user's ability to understand and exploit meta-information?
  - How can users be trained to recognize and use meta-information?

Conclusions

- We must go beyond thinking only about uncertainty
  - Information may be qualified in many ways

- Meta-information needs should be reflected in C2 decision support systems:
  - As part of underlying computational methods
  - As part of displays and interfaces
  - With awareness of task and situation dependencies

- Additional work remains to be done…

Questions?

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