EXPLORING INFORMATION SUPERIORITY

A Methodology for Measuring the Quality of Information and Its Impact on Shared Awareness

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SUMMARY

The military is formulating new visions, strategies, and concepts that capitalize on emerging information-age technologies to provide its warfighters with significantly improved capabilities to meet the national security challenges of the 21st century. New, networked C^4ISR capabilities promise information superiority and decision dominance that will enhance the quality and speed of command and enable revolutionary warfighting concepts. Assessing the contribution of C^4ISR toward achieving an NCW capability is a major challenge for the Department of Defense (DoD). Much like the development of a new branch of science, this requires defining concepts, metrics, hypotheses, and analytical methodologies that can be used to focus research efforts, identify and compare alternatives, and measure progress.

INTRODUCTION

An important first step is to improve our understanding of how improved C^4ISR capabilities and related changes in command control processes contribute to the achievement of core information-superiority concepts, such as situational awareness, shared situational awareness, and synchronization. Establishing a quantifiable link between improved C^4ISR capabilities and combat outcomes has been extremely elusive and is therefore a major challenge. In this work, therefore, we develop a *mathematical framework* that can facilitate the development of alternative measures of performance and associated metrics that assess the contribution of information quality and team collaboration on shared situational awareness. The emphasis is on the development of the framework.

The research reported here builds on the work of the ASD NII Information Superiority Metrics Working Group. This body has developed working definitions, specific characteristics and attributes of key concepts, and the relationships among them that are needed to measure the degree to which information-superiority concepts are realized and their influence on the conduct and effectiveness of military operations. The research is also consistent with the NCW Conceptual Framework, which DoD's Office of Force Transformation and ASD NII are developing jointly. The NCW Conceptual Framework is an assessment tool that includes measures, general forms for metrics, and relationships between the measures and metrics. It contains a large number of measures related to the complete array of concepts associated with NCW, ranging from networking hardware through decisionmaking capabilities and synchronization of actions. The group's metrics, and this report's scope, are largely limited to the information and awareness components of the NCW Conceptual Framework, and explore these components in more detail than does the framework.

We begin by defining a reference model for discussing such issues in terms of three domains: that of ground truth (the *physical* domain); that of sensed information (the *information* domain); and that in which individual situational awareness, shared situational awareness, collaboration, and decisionmaking occur (the *cognitive* domain). The C^4ISR process is seen as extracting data from ground truth and processing the data in the information domain to produce a common relevant operating picture (CROP). The quality of the CROP and the quality of team collaboration combine to heighten (or degrade) shared situational awareness in the cognitive domain.

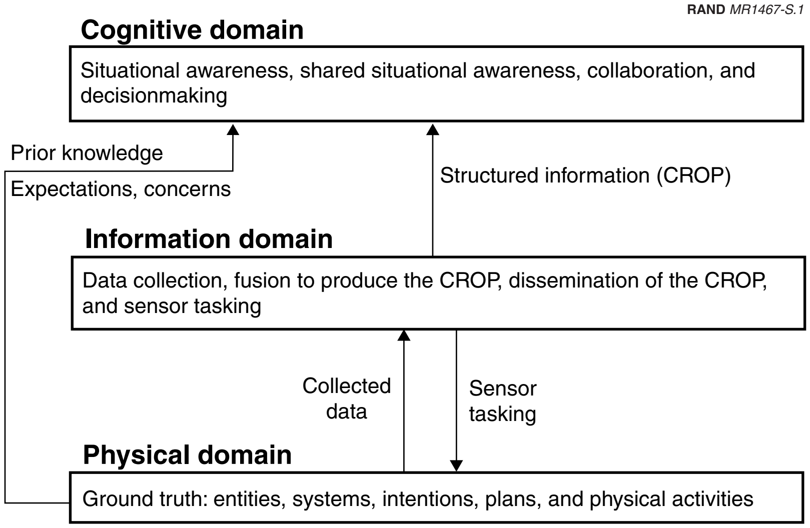
THE ANALYTIC FRAMEWORK

The objective of this research is to develop a quantitative methodology that allows us to link improvements in C^4ISR capabilities to their effects on combat outcomes. For this first effort, we have confined our work to assessing the effects of data-collection and information-fusion processes, and the dissemination of the fused CROP on individual situational awareness and, through the collaboration process, on shared situational awareness.

Figure S.1, the C^{4}ISR Information Superiority Reference Model, describes the activities associated with the above processes. This model envisions the three "domains" extending from the battlefield environment to cognitive awareness of the battlefield situation and decision.

This report uses a generic C^{4}ISR architecture to build a model representing the contributions of these processes. The architecture can be thought of as a six-stage process that comprises the following:

0. acceptance of the existence of physical ground truth, restricted here to physical battlespace entities and their attributes (the initial state)
1. sensing of ground truth by an array of network sensors
2. fusion of sensor data by a centralized set of fusion facilities
3. distribution of resulting information (the CROP) to the users over a potentially noisy and unreliable network



NOTE: The activities depicted in each of the domain "boxes" may not be complete. We focus on those activities pertinent to our research.

Figure S.1—The Information Superiority Reference Model

4. individual interpretation of the CROP, with the quality of the interpretation depending on the user's skills and abilities
5. collaboration to improve interpretation of the CROP, with the quality of the interpretation based on individual and group characteristics.

The value of the collection, fusion, dissemination, interpretation, and collaboration processes to combat operations within the above generic C^4ISR architecture is described through the several transformation functions, as shown in Figure S.2. The development of a quantitative framework is based on these transformations.

Enemy battlefield entities (units and weapon systems) are described in terms of their features or characteristics; hence, the quality of the information concerning the entities is an assessment of how well the C^4ISR system estimates the features of the collected set of enemy units in the battlespace. A conditional product form model is used to measure the effects of the NCW value chain transformations on the information-domain measures (quality of sensor information, quality of CROP, quality of shared CROP), and a more-general functional model measures the effects on the cognitive domain measures (situational awareness, shared situational awareness).

THE PHYSICAL AND INFORMATION DOMAINS

We applied the methodology to the measures in the physical and information domains. The feature matrix, $\mathbf{F} = [\mathbf{F}_1, \mathbf{F}_2, \ldots, \mathbf{F}_m]$, is a set of vectors, $\mathbf{F}_\mathrm{i}$, each of which represents the relevant physical characteristics of the enemy. In the physical domain, $\mathbf{F}_0$ is a feature matrix representing the physical ground truth features of all enemy units.

Sensor Metrics

Using $\mathbf{F}_0$ as an input, we first developed metrics formulas for the quality of sensor information, which is equivalent to the NCW Conceptual Framework's quality of organic information measure. Of the attributes the framework defined for the quality of organic information, we provide metrics for three: completeness, correctness, and currency.

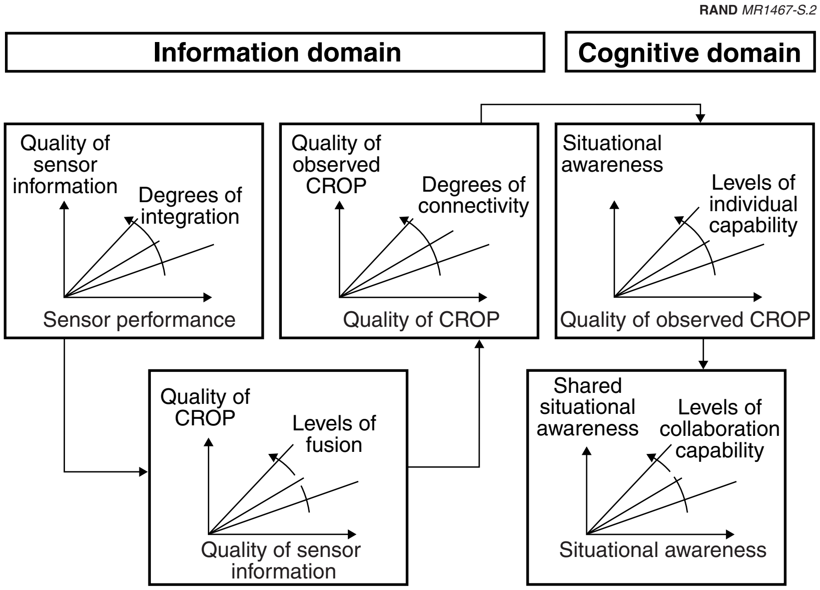


Figure S.2—The Information Superiority Value Chain

Completeness. We examined three aspects of completeness: the number of enemy units detected, the features reported for the units detected, and the sensor suite coverage area. For sensor information to be complete, all features of all units in the relevant ground truth must be known, and the entire area of operations must be under sensor observation. The suggested completeness metric has two components, both of which are between 0 and 1: c_1 is the fraction of enemy units detected (as specified in $\mathbf{F}_0$), and c_2 is the fraction of the area of operations covered. We then have the following *transfer function* that, using $\mathbf{F}_0$ as an input, combines these two components to produce a 0–1 completeness metric: $Q_{com}(\mathbf{F}_1|\mathbf{F}_0) = c_1(1-e^{-c_2})$. Here, $\mathbf{F}_1$ is the CROP as detected by the sensors.[1]

Correctness. The metrics we suggest for correctness either support controlled experiments or support actual operations (in which analysts can only approximate ground truth from sensor inputs). In

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[1] The body of the report presents rationales for all the metrics' functional forms.

either case, correctness is taken to mean the degree to which the true target features approximate their ground-truth values. Estimation theory is one way to assess the deviation from ground truth for controlled experiments. Since an unbiased estimator of a parameter is one whose expected value matches the true parameter, the difference between the estimate and the known ground truth appears to be a suitable metric to measure correctness. In general, if A is a measure of nearness, then $Q_{cor}(\mathbf{F}_1|\mathbf{F}_0) = e^{-A}$ is the transfer function we used to map A to a 0–1 metric.

Assessing correctness in support of operations implies that ground truth is not known. In this case, we cluster the detections geographically using a pattern-classification technique and then calculate the variance within the cluster. For a location estimate, the variance is expressed in terms of a covariance matrix. The determinant of that matrix is a measure of precision and therefore a measure of correctness. The determinant is $p = S^4$, where S^2 is the sample variance in both the x and y directions. $Q_{cor}(\mathbf{F}_1|\mathbf{F}_0) = e^{-p}$ is the transfer function we used to produce a 0–1 correctness metric.

Fusion Metrics

In the architecture we present here, the sensors transmit their readings to a series of fusion facilities, each of which focuses on a single intelligence discipline. Each facility submits its fused reports to a single central fusion facility, which combines the sensor inputs into a single, common, relevant picture of the battlespace: the *fused* CROP. This subsection develops metrics for the quality of the fused CROP, which is equivalent to part of the NCW Conceptual Framework's quality of individual information measure.[2] As noted, we assumed that the underlying network transmits the sensor readings to the fusion facilities perfectly.

Fusion includes the correlation and analysis of data inputs from supporting sensors and sources. Fusion occurs at several levels, from

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[2] The quality of individual information measure is a multidimensional array measure, with the entries along one dimension corresponding to the quality of information seen by each individual. Further, one of those "individuals" is a user at the central fusion facility, who directly sees the fusion facility's output. This part measures the Quality of individual information as perceived by that user. The next section measures the quality of individual information perceived by users away from the central facility.

the simple combining of tracks and identity estimates to assessments of enemy intent. Our focus here is on the lower levels of fusion, which seek to improve the accuracy and completeness of the sensor reports on enemy units' features.

Completeness in the fusion subdomain focuses on the number of sensor-detected enemy units that have been *classified*, i.e., described in terms of their relevant features. The number of enemy-unit features the fusion facilities can classify depends on the architecture of the fusion suite, the degree of automation used, and the ability of the system to retask the sensors. The proposed formula for a 0–1 completeness metric is

$$Q_{com}\left(\mathbf{F}_2 \mid \mathbf{F}_0, \mathbf{F}_1\right) = \left[1 - \prod_{i=1}^{k}\left(1 - c_i\right)\right] c_c \ ,$$

where k is the number of subsidiary fusion facilities, c_i is the fraction of the detected enemy units that fusion facility i can classify per unit of time, c_c is the fraction the central processing facility can process, and $\mathbf{F}_2$ is the CROP after it has been through the fusion process.

Correctness in the fusion subdomain measures how close the fused estimate for each enemy unit feature is to ground truth. That is, how accurate are the classifications of the reported detections? One way we might address this problem is to examine the variance in the feature estimates for each reported unit. This results in the following formula for a 0–1 correctness metric:

$$Q_{cor,1}\left(\mathbf{F}_2 \mid \mathbf{F}_0, \mathbf{F}_1\right) = \sum_{i=1}^{n} w_i \sum_{j=1}^{p} \omega_j \, e^{-s_j} \ .$$

In this formulation, w_{i} and ω_j are weights. The former accounts for the relative importance of the reported enemy unit, and the second accounts for the relevant importance of the features being reported. The values of s_j are sample standard deviations for each of the p features for a given enemy unit, derived from the number of reports arriving on the unit. The second subscript on Q is used to distinguish this correctness transformation from the tracking metric discussed next.

An additional task is measuring how well we are able to track enemy units. The correctness of the tracks of enemy units can be measured in terms of the number of previous tracks that have been confirmed on the present scan and the number of new tracks initiated. The tracking portion of the correctness component of the transformation function is taken to be $Q_{cor,2}(\mathbf{F}_2|\mathbf{F}_0,\mathbf{F}_1) = T$, where T is the fraction of the enemy units that correlate with previous tracks.

Combining the two correctness metrics using an importance weight, $0 \leq \omega \leq 1$ yields the following for the correctness component of the transformation function:

$$Q_{cor}\left(\mathbf{F}_2 \mid \mathbf{F}_0, \mathbf{F}_1\right) = \omega W + \left(1 - \omega\right) T,$$

where $W = Q_{cor,1}(\mathbf{F}_2|\mathbf{F}_0,\mathbf{F}_1)$.

Finally, an appropriate 0–1 metric for the currency attribute of quality of the fused CROP is $Q_{cur}(\mathbf{F}_2|\mathbf{F}_0,\mathbf{F}_1) = e^{-t}$, where t is the total time required to update the fused CROP. This function emphasizes the importance of updating the fused CROP quickly.

Network Metrics

Following fusion, the architecture distributes the fused CROP to the force network's users, resulting in the *observed CROP*. Here, we provide metrics for the quality of the *observed CROP*, which is the remainder of this report's instantiation of the NCW Conceptual Framework's quality of individual information measure.[3] In these calculations, we allow the network to incur errors and delays in distributing the CROP. Thus, although we do not specifically incorporate the NCW Framework's Degree of Networking and Degree of Information "Shareability" metrics in this report, these metrics would directly influence the parameters of the functions used to generate the quality of the *observed CROP* metrics.

Thus, completeness here measures how well the communications network accommodates the transmission of relevant aspects of the CROP to each user. A metric for this measure is the probability that all users will receive the CROP. This is an assessment of the network's

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[3] This section describes how to calculate the quality of individual information metrics for those users not at the central fusion facility, who must receive the CROP over the network.

reliability in terms of its robustness. The resulting completeness metric has the following formula:

$$Q_{com}\left(\mathbf{F}_3 \mid \mathbf{F}_0, \mathbf{F}_1, \mathbf{F}_2\right) = \prod_{i=1}^{k} p_i \, .$$

In this formulation, k is the number of users of the CROP, and p_i represents the probability that user i will receive the CROP.

Network correctness is an assessment of the likelihood that CROP users receive the distributed information without degradation. One way to measure this is to use the probability of correct message receipt (PCMR). The PCMR is a conditional probability that the message sent will be the message received. The probability that user i will receive the CROP (or a portion of it) as transmitted is $P_i(\mathbf{F}_3,\mathbf{F}_2) = P(\mathbf{F}_2)P_i(\mathbf{F}_3|\mathbf{F}_2)$, where $P_i(\mathbf{F}_3|\mathbf{F}_2) = p$. We therefore get the following PCMR for user i:

$$\mathrm{PCMR}_i = P_i\left(\mathbf{F}_3, \mathbf{F}_2\right) = P\left(\mathbf{F}_2\right) p_i \, ,$$

where $P(\mathbf{F}_2)$ is the probability that a user receives the CROP without error, given that the user receives the CROP. Therefore, our formula for a 0–1 metric for correctness is

$$Q_{cor}\left(\mathbf{F}_3 \mid \mathbf{F}_0, \mathbf{F}_1, \mathbf{F}_2\right) = \prod_{i=1}^{k} \mathrm{PCMR}_i \, .$$

The end-to-end time required to transmit the CROP from the central fusion facility to the users serves as a measure of network currency. One way to determine this is to calculate the average of all paths from the source to the user. The overall average network transmission delay, then, is taken to be the average of these times, $\bar{t}$, so that a 0–1 metric for currency is

$$Q_{cur}\left(\mathbf{F}_3 \mid \mathbf{F}_0, \mathbf{F}_1, \mathbf{F}_2\right) = e^{-\bar{t}} \, .$$

Shared Information

Shared information is an essential ingredient to ensure effective collaboration. Recall that the CROP users receive is the *observed* CROP. Matrix $\mathbf{F}_2$ represents the *fused* CROP. Each user's observed CROP is a subset of the fused CROP. The overlap among these subsets constitutes the information shared among the users. Information not in the overlap has the potential to be shared through the process of collaboration. The ability to collaborate therefore has the potential to increase the amount of information shared among the users, thus contributing to shared situational awareness.

Since “shared information” applies to subsets of the observed CROP, the quality measures for Quality of Shared Information are equivalent to those for the Quality of the Observed CROP. A new attribute, however, is the *extent* to which the observed CROP is shared. The body of the report discusses various set-theoretic metrics for determining the extent of information sharing.

THE COGNITIVE DOMAIN

In the information domain, the data collected on the physical domain are processed and disseminated to friendly users. In the cognitive domain, the products of the information domain are used to take decisions. The mental processes that transform CROP into a decision and a subsequent action depend on a range of factors, a few of which are psychological. The cognitive processes that transform the CROP into a decision and subsequent action must be described for participants in the decision process, both as individuals and as interacting, collaborating members of a decisionmaking team. In this report, we restrict our attention in the cognitive domain to how well users can assess the situation presented to them through the observed CROP. With respect to the NCW Conceptual Framework, we restrict our attention to the Individual and Shared Awareness measures, which are subsets of the framework’s Individual and Shared Sense-Making measures, respectively.

Modeling Individual Situational Awareness

Several factors influence what it will take for an individual decisionmaker to correctly assess the situation presented to him. Among these is the *quality of the information* presented. This metric assesses *the degree to which the decisionmaker is aware of the situation facing him*, emphasizes the use of the individual components of the CROP, and includes a reference to the *ability* of the individual decisionmaker. It is interpreted to be the fraction of the observed CROP the decisionmaker realizes.

We developed an agent representation of a decisionmaker using combinations of capability attributes (education and training, experience) and defined two discrete points for each attribute. From this, we produced four decision agents possessing these attributes at one of the two points. The agents suggest a functional relationship in which the dependent variable is "degree of awareness" and the independent variables are information quality measures (completeness in this case).

The end result of this process is an explicit relationship between the quality of the observed CROP and the ability of the decisionmaker.

Modeling Shared Situational Awareness

To describe *shared situational awareness*, we augmented the individual shared awareness model by representing the complex interactions in situations involving more than one individual. The metric we chose for this is *the fraction of fused feature vectors in the observed CROP that members of a team realize similarly, whether or not they collaborate*. This metric emphasizes the importance of individual situational awareness and allows agreement to exist even when individual decisionmakers have not collaborated.

We hypothesized, however, that *when collaboration is used, it is critical for determining shared situational awareness*. We focused on assessing the important attributes that affect teams that *do* collaborate and therefore have either positive or negative effects on the degree of shared awareness.[4]

One ingredient of the shared situational awareness process is the concept of a *common ground*. For our purposes, this term refers to the knowledge, beliefs, and suppositions that team members believe they share. During a team activity, therefore, common ground accumulates among team members.

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[4] Note that these attributes, and the effectiveness of collaboration in general, are part of the NCW Conceptual Framework's Quality of Interactions measure.

We further hypothesized that, *to be effective, collaboration requires both the development of common ground among collaborators and familiarity with the capabilities of other collaborators*. Common ground does not develop instantaneously when there is collaboration; there is a period of “initial calibration” during which participants “tune in” to each other and move from a state of common sense to states of common opinion and common knowledge.

A structural model for defining and analyzing this phenomenon is a *transactive memory system*, defined as a set of individual memory systems in combination with the communication that takes place between individuals. It is concerned with the prediction of group (and individual) behavior through an understanding of how groups process and structure information.

Information can be stored and retrieved internally by an individual according to the individual’s encoding, storage, and retrieval processes. If an individual stores information externally, the storage and retrieval process must also include the location of the information. If externally stored information resides in another person, a transactive memory system exists. Individuals can be assigned as information stores because of their personal expertise or through circumstantial knowledge responsibility. Each individual participating in the transactive memory has a set of memory components. These memory components capture the key elements of the collaboration. They represent information that some individuals store externally in other individuals and some individuals retain on behalf of other individuals in the transactive memory system. There can be direct links between an individual and the retrieval of a memory item and there can be indirect links that take “hops” through the transactive memory system until the memory item is accessed.

As participants develop stronger relationships with other participants through repeated or continued team interaction, the links between the participants become stronger. This suggests a second common ground hypothesis: *The completeness of the system for recording and retrieving information depends on how frequently the team has recently collaborated*. This concept is referred to as “team hardness.”

A time-dependent functional model for team hardness is $0 \le TM(T) \le 1$, where $TM(T)$ is a function whose values are between 0 and 1, t represents the time elapsed since the start of the operation, and τ represents the length of time the team has been training or operating together, and $T = \tau + t$.

Consensus plays a central role in developing a transactive memory system. It is the majority *opinion* of a team arrived at through active collaboration. Its definition *implies the existence* of shared situational awareness. Noting that not all collaborating individuals have to agree before a decision and subsequent action can take place, we are interested in a measure of the degree of consensus. We hypothesized that *the degree of consensus can be estimated by the number of pairwise combinations of collaborating individuals who interpret feature vectors similarly*.

Models of shared situational awareness integrate the modeling proposed earlier. First, we placed the individual in a team and measured his situational awareness in a team setting. Note that this is not the same as team awareness but is rather the effect of team dynamics on an individual member of a collaborative decisionmaking process. The contribution is essentially derivative of the transactional memory function and, therefore, team hardness. Second, we addressed the consensus that develops among collaborating individuals and its effects on the team's shared situational awareness. Finally, we accounted for the diversity of decision-agent capabilities among the collaborators that results in our composite model for the degree of shared situational awareness.

FUTURE DIRECTIONS

As suggested, this work is clearly incomplete. We have described a mathematical framework that might be used to develop detailed mathematical quantities that represent what are generally considered qualitative concepts. In some cases, data may exist in the military C^4ISR community to confirm or disconfirm both the process and any of our examples. In these cases, locating and assessing the data are required. Where data do not exist, further experimentation or historical analysis will be required.

Much remains to be done in the cognitive domain. The relationship between information quality and situational awareness is the first step in the decisionmaking process. Further work is needed to codify the relationship between situational awareness and the ability of the decisionmaker to make inferences from the CROP—that is, his understanding of the situation.

Several techniques might be used to advance our knowledge in this important area. Among these are the following:

- **Data fitting.** We can use existing data either to confirm the validity of the relationships suggested in this work or to suggest different relationships.
- **Experimentation.** Experiments might provide additional insights about the relationships between information quality and awareness. For example, we could select decisionmakers that have various combinations of awareness characteristics. The degree to which they are able to realize enemy intent from what is presented, then, is an indicator of their level of awareness.
- **Decision and action.** The link between awareness and decision needs to be established. The level of awareness affects the ability to understand, i.e., to draw inferences about the CROP, such as enemy intent. The inferences, in turn, affect the decision to be taken and therefore the subsequent actions ordered.
- **Historical analyses.** Analysis of past battles is an important source of insight into the value of information. Considerable data is available from various sources that can provide insights into the relationship between the quality of information and the level of awareness.
- **Gaming.** It is also possible to use game theory to illustrate certain effects of information imbalances between two opponents. In a two-sided game, each side strives to obtain high-quality information. At the same time, each side attempts to ensure that the opponent's information is of low quality. Several pairings of players with varying awareness characteristics might then be played against the various information-quality levels. In this way, a link is established from information quality to awareness to decisions and, finally, to outcome.