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"C2 Network Analysis: Insights into Coordination & Understanding"

Topic 6: C2 Assessment Tools & Metrics; Topic 2: Networks

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Abstract

The distributed cognitive framework (Hutchins, 1995) provides a structured and theoretical approach for analyzing cognitive characteristics beyond that of a single individual to that of a system comprising of multiple individuals, tools, and the task environment. Among some of the attributes of a distributed cognitive system are: 1) coordination across agents 2) mental models, 3) situation assessment, 4) memory demands, 5) adaptability, and 6) workload management. This paper will address recent efforts, tools, and approaches on measuring and analyzing two of these distributed cognitive attributes through network analysis, coordination across agents and mental models. Network analysis was applied with different methods and emphasis to both attribute areas. The analysis of the coordination across agents applied network analysis to analyze the patterns of interactions across human and technological agents over-time. Collecting data related to coordination over time required specific capabilities that was not readily found among observational data collection tools and therefore required a custom program that we designed. Description of the requirements and implementation of this new observational network analysis tool as well as methods to visualize longitudinal network change is addressed. The analysis of mental models also utilizes a basic network analysis approach, namely structural knowledge. The examination of structural knowledge to assess individual mental models will be discussed to provide insight into understanding. Specifically applied to C2, this analysis can provide insight into the commander and/or staff's understanding.

Keywords: Social network analysis, pathfinder, structural knowledge, visualization, coordination, collaboration, distributed cognition, mental model, command and control, longitudinal analysis

Introduction

Command and Control (C2) is a complex, dynamic, and often vaguely defined area in military operations and actions. It is known by many different names such as battle command and command, control, communications, and intelligence (C4I) in an attempt to further define it or better describe the primary components of C2 (Foster, 1988). Crumley and Sherman (1990) reviewed a large body of C2 work and described, "most [C2] theorizing as simplistic rather than autistic, and to note that the major problem in the field is not that it is 'convoluted and idiosyncratic' but that too much of it lacks a clear focus" (p. viii). While not suggesting a unifying theory for C2, this paper suggests that C2 and all of its working parts and components display attributes other studied distributed systems share (e.g., Hutchins, 1995). By systematically applying such a theoretical framework for analysis and assessment of C2 systems, we hope to illuminate before unseen patterns and facilitate enduring insight and understanding.

Distributed cognition (Hutchins, 1995) is a theoretical framework that emphasizes the distributed nature of cognitive phenomena that goes beyond the cognitions of a single individual. This approach focuses on the functional system as a whole to examine the relation between individuals, the task environment, and artifacts (tools & technologies) used for task completion. This approach has been applied to several domains in the past such as naval navigation and the aviation domain and can provide a more comprehensive understanding of the functional system including the interactions of system components.

Within such a system perspective, there are several cognitive attributes (Woods, Johannesen, Cook, & Sarter, 1994) that can be affected by the other elements within the system. Many of these attributes have direct ties to major Command and Control (C2) functions and requirements (Hansberger, in press).

Distributed Cognitive System Attributes:

1) Coordination across agents
2) Mental models
3) Situation assessment
4) Memory demands
5) Adaptability
6) Workload management

Each of these component's importance and relevance can vary according to the situation and task environment. This paper will focus on two of these attributes, the coordination across agents and mental models in order to provide some detail in their measurement and analysis related to C2.

Coordination across agents refers to the interaction and communication between human agents along with human-to-computer/automated agents. The consideration of human-to-computer agents is important, as it is the element that broadens social network analysis beyond the person-to-person interactions. Our efforts in collecting and visualizing this type of data over time will be addressed in the first section of "Coordination across Agents". The mental model attribute, on the other hand, focuses on the structural knowledge and understanding an individual has on a topic or domain. The structural knowledge consists of both relevant domain concepts as well as the relationship among those domain concepts with one another. The approach and methods used to measure and collect data related to mental models and structural knowledge is addressed in the second section of "Mental Models".

Coordination across Agents

The analysis approach of measuring and analyzing coordination among the relevant agents relies heavily on social and dynamic network analysis (Figure 1) (e.g., Scott, 2000; Carley, 2003). The examination of interaction patterns as networks within a C2 environment can provide information on a wide range of organizational and individual factors (Wasserman & Faust, 1994). The nature and speed of information flow within a

C2 structure can be examined through various network measures along with important structural characteristics of the C2 organization.

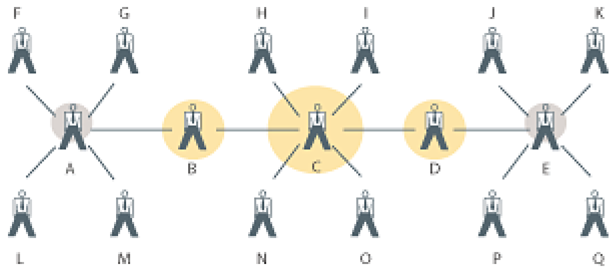

Figure 1. Social network example illustrating coordination across agents.

The majority of past network analysis has focused on discrete snapshots in time, which overlooks the dynamic and developing longitudinal nature of network change over time. This section will describe methods and tools designed to collect, analyze, and present longitudinal network data across individuals, technology, and the C2 task environment. Included in this discussion will be the introduction of a custom observational data collection tool for social and dynamic network interactions and visualizations that aid in the analysis and presentation of network changes over time.

Data Collection: Coordination across agents

The old computer science adage of "garbage in, garbage out" also holds true for data collection and analysis. It is important to collect the appropriate data for the research questions and analyses to be supported. It is also important to understand many of the constraints involved with data collection in an operational environment. For many exercises and events, participants are either already overloaded with questionnaires or there is little to no time for them, not to mention some of the methodological issues with self-report data. When computer logs of interactions and communications are available through collaborative tools, they can provide a detailed source of data. However, face-to-face interactions are lost through sole reliance of such means. Face-to-face communications can account for most if not all person-to-person interactions in many situations. Observational data collection can capture these patterns of interactions and can be the primary source for analysis or can compliment other collected data.

In order to push the field of social and dynamic network analysis beyond the analysis of discrete snapshots of interactions and speculating on what occurs between those snapshots, longitudinal data needs to be included in the data collection plan. Particularly if we are interested in exploring how C2 patterns of interactions occur, evolve, and adapt over time. The longitudinal analysis of interactions among people and tools requires timing data that is not typically available through the traditional means of data collection for social network analysis (e.g., questionnaires and surveys).

We developed a custom program called SNA (Social Network Analysis) Observer to address these challenges. SNA Observer was designed by the authors and coded by John Richardson of the Computer Information Systems Directorate, Army Research

Laboratory. The tool is used to collect relational data as to who is talking to whom, the direction of the communication flow, and the duration of the communication events. To facilitate flexibility across multiple hardware and operating systems, the SNA Observer was coded in Java and has been tested on both Microsoft Windows and Macintosh computers. The tool offers advantages in flexibility, mobility, efficiency, and interoperability for data collection focused on coordination across agents.

Flexibility. One of the first requirements for the collection of longitudinal observational data of coordination across agents was flexibility within the data collection program. Face-to-face interactions and small group formation is a highly variable and changing phenomenon with people potentially flowing in and out of group conversations that include cocktail party effects and constant creation and dissolution of sub-groups These characteristics are particularly present in highly dynamic environments like many C2 environments. In addition, individuals are also interacting with tools during these face-to-face interactions, which is critical in understanding the complete distributed cognitive system.

The SNA Observer allows the observer to create multiple groups where the agents of the group can be people and/or tools being interacted with. To account for sub-group formation, flexible membership of individuals in more than one group is supported. Therefore, if Pam, Jim, Kelly, and Dwight are interacting, their personal icons can be grouped together to represent that interaction pattern, while a sub-group interaction pattern between Dwight and the planning tool can recorded at the same time or other interactions by different agents (Figure 2). Furthermore, if additional detail is needed, specific communication patterns that indicate the sender and recipient can be illustrated and recorded (Figure 2, session 4).

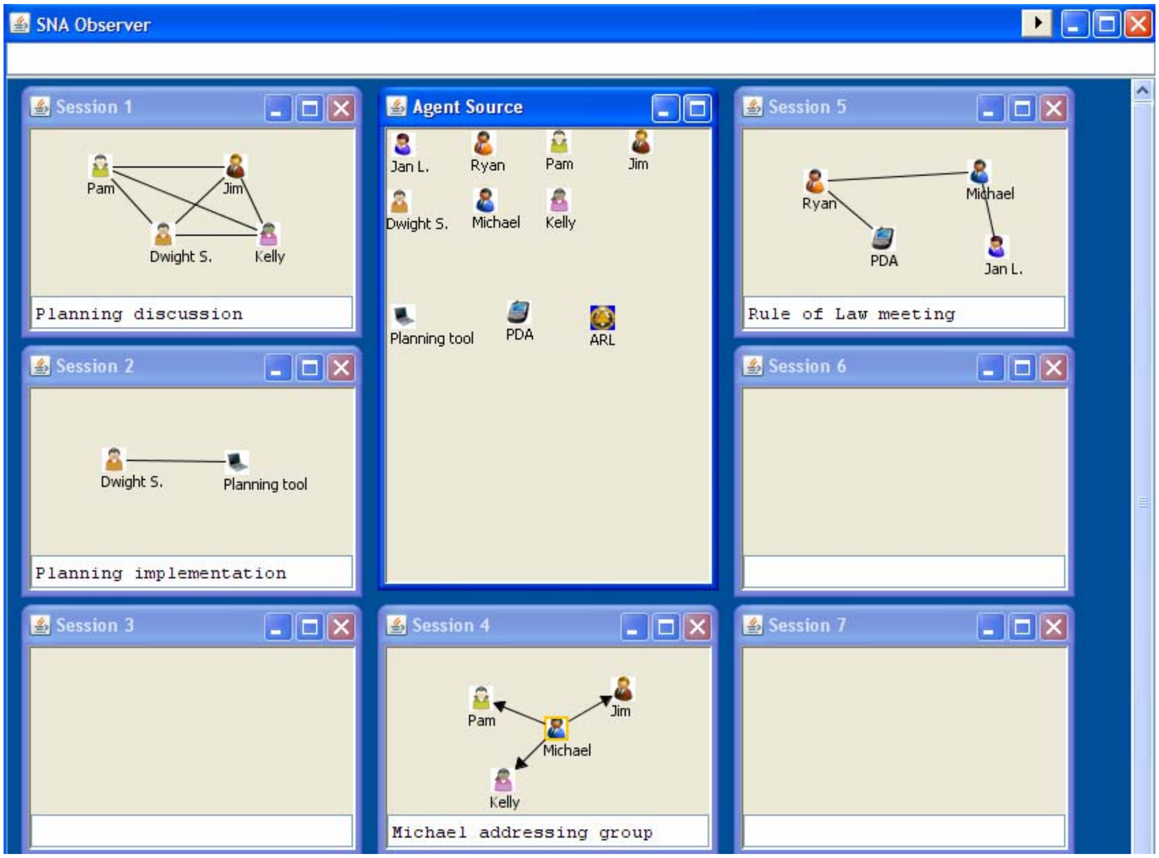

Figure 2. Display of the SNA Observer interface. Multiple session windows allow the interactions of multiple group and sub-group interactions across human and computer agents. Directional communication indicated by Session 4 window as Michael speaks to the indicated agents.

To facilitate the quick creation and modification of agent interactions, SNA Observer was designed for touch screen manipulation. Therefore, direct manipulation of the agents in and out of groups along with the detailed interactions among agents can be done directly, quickly, and efficiently.

Mobility. Another requirement that was important to consider for the SNA Observer was mobility. In order to support the observational data collection over time in field settings and exercises, the observer must be able to go where the action and people are as they flow in and out of various patterns and locations. In order to enable the mobility to track these interactions and to collect data at the same time, traditional laptop computers are difficult to use. A traditional laptop computer is designed to rest on a tabletop or lap and does not facilitate a standing or walking position while being able to operate the computer at the same time. A tablet computer (Figure 3), on the other hand, can easily be held in one hand and operated by the other hand in a sitting, standing, or walking position. A tablet computer also uses a touch screen, which the SNA Observer was designed for and therefore is a very appropriate hardware solution that provides the mobility needed for observational data collection over time for coordination across agents.

Figure 3. Tablet PC held by operator with one hand with the freedom to provide input with the other hand.

Efficiency. Another category of requirements involves efficiency ranging from the interface of the SNA Observer to automatic data manipulation to facilitate data analysis. In order to support the touch screen interaction with the program, a graphical user interface (GUI) was designed to facilitate keeping up with multiple groups and easy identification of agents through custom icons. There are default icons that allow for differentiation between individuals and tools by allowing the observer to customize the icon by gender, color, general appearance, and name. It is also possible to load custom icons such as photographs of the observed individuals for very easy and clear identification during data collection (Figure 4).

Figure 4. Use of custom icons ranging from human and computer agents to actual photographs of observed agents.

One of the more powerful capabilities of the SNA Observer is its automatic time stamping of all interactions indicated in the touch screen interface and the automatic data manipulation for data analysis preparation. The automatic time stamping allows for the analysis of longitudinal data as it records start and stop times along with the duration calculations for each interaction. Therefore the observer knows who was talking/interacting with whom, when it occurred, and how long it occurred for. The time note-taking capability also allows the observer to record notes related to particular events and actions as they occur within each group.

Interoperability. The other feature that is just as powerful and time saving is the automatic data manipulation the software does to prepare it for analysis with other SNA software such as UCINET (Borgatti, Everett, & Freeman, 2002), ORA (Carley, 2003), and SoNIA (Moody, McFarland, & Bender-DeMoll, 2005). Translation of the raw data described above into the typical metamatrix format used in the analysis of social networks can be extremely time consuming if not automated. The automation of this step improves the efficiency of processing the data in order to more directly feed into the network analysis tools of choice.

Data Visualization: Coordination across agents

The visualization of the longitudinal data just described can greatly improve insight into the evolution and changes in coordination across agents over time. Generally, the area of social network analysis uses relatively static measures of network change. Data is collected in discrete snapshots with moderate to long periods between snapshots, which allows the researcher to identify changes, but forces them to infer both why and how those changes took place. The collection, visualization, and analysis of longitudinal data eliminate the need to infer how interactions and coordination changed over time. This section will describe a method and means of visualizing network data over time along with the advantages and disadvantages of this approach.

The SoNIA (social network image animator) software (Moody, *et. al*., 2005) was designed to explore dynamical relational data through the animation of network interactions but not act as analysis software (Bender-DeMoll & McFarland, 2006). Several other network analysis packages are available that cover a wide range of quantitative analyses of networks (e.g., UCINET, ORA, PAJEK). The longitudinal data collected can be aggregated at different levels, depending on the targeted tasks, variables, or research questions ranging from a macro to micro level (Figure 5). The flexibility to examine the network at these various levels is one of the strengths as the changes in the network can be explored. At the same time, this flexibility also poses a challenge to the researcher to select the appropriate level/s of aggregation to address the issues at hand.

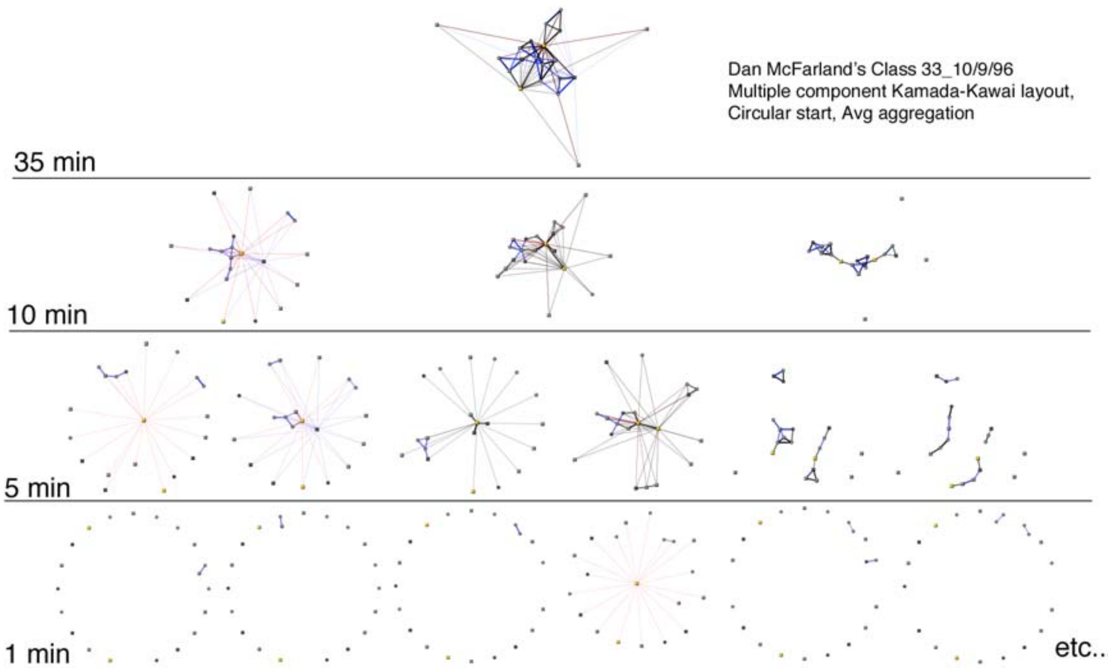

Figure 5. Interactions represented at various levels of aggregation ranging from 1 minute to 35 minutes from McFarland's classroom observations (2001). Figure originally produced in Bender-deMoll & McFarland (2005).

Bender-DeMoll & McFarland (p. 16, 2005) have suggested identifying several criteria when creating and exploring network animations through SoNIA.

> 1. What is the underlying set of relations we are really interested in looking at, and how can they be best expressed?
> 2. What is the functional relationship between collected data and relations of interest?
> 3. What time-scale are the patterns of interest likely to be visible at?
> 4. What set of transformations do we need to apply to get from the data to a consistent social space?
> 5. How might node and arc attributes relate to the pattern of network structure, and how can they best be translated into display variables in order to highlight and explore these relations?

The visualization of the network over time allow for qualitative analysis of how and potentially why any detected changes in the network occurred. Paired with more traditional quantitative network measures, the use of longitudinal network visualizations allows the development of new hypotheses, examination of network evolution and adaptation without inference between discrete snapshots of the network, exploration of transition points of micro and macro level network processes, and analysis of strategic intervention effects.

Mental Models

Mental models have a long history as the cognitive representation of accumulated knowledge and experience in Psychology and Cognitive Science (e.g., Johnson-Laird, 1983). This knowledge in the head (Norman, 1988) represents relationships and linkages between domain topics and concepts and guides decision-making, perception, and interpretation of new information. Mental models obviously have an important role and function in C2, especially regarding the establishment and communication of commander's intent between the commander and staff (Builder, Bankes, & Nordin, 1999).

There is often a distinction between types of knowledge that includes declarative and procedural knowledge. Declarative knowledge describes awareness or understanding regarding an object, event, or concept (Rumelhart & Ortony, 1977). Procedural knowledge, on the other hand, is an understanding of "how to" or the application of declarative knowledge in performing a task (Shank & Abelson, 1977). There is a dependence between the two as declarative knowledge provides the conceptual understanding of the elements to be used, manipulated, or involved in procedural knowledge. There is an intermediate knowledge type between the two, however, that mediates the translation of declarative to procedural and that is structural knowledge. Knowledge of how the domain concepts are interrelated and therefore how the declarative knowledge should be used in procedural knowledge is comprised in structural knowledge (Diekhoff, 1983). Whether structural knowledge is seen as the transitory type of knowledge (Diekhoff, 1983) between declarative and procedural knowledge or as one of two dimensions of declarative knowledge (Mitchell & Chi, 1984), this type of knowledge defines how declarative knowledge is interconnected and is critical element in understanding and evaluating mental models.

Structural Knowledge Measurement

There are a number of techniques and methodologies available to measure structural knowledge. These efforts fall into two required categories or stages of knowledge elicitation, 1) knowledge elicitation from individual or population and 2) knowledge representation and analysis of collected knowledge (Jonassen, Beissner, & Yacci, 1993). There are several methods within each stage but for this paper, only one method for each stage will be addressed (for a review of others, see Jonassen, *et. al.*, 1993). The use and application of similarity ratings will be the elicitation technique discussed while the network representation using Pathfinder nets will be the knowledge structure representation technique described.

As mentioned above, structural knowledge is the pattern of relationships between concepts in declarative memory. These concepts have varying degrees of interrelatedness with each other where some are more closely related to the targeted concept than others. In order to assess these relationships and the varying strengths of them, individuals can rate the similarity between concepts (Jonassen *et. al*., 1993). Similarity ratings are typically done on a pair-wise basis with a numeric scale where one anchor represents dissimilarity and the opposite numerical anchor represents similarity. These ratings are typically the simplest and most direct means of obtaining the distances. This implies a spatial metaphor for depicting the knowledge structure where the semantic distance is congruent with geometric distance between any two concepts. In other words, concepts like feather and bird with a close relationship would have a short distance between them compared to scale and bird with a more distant relationship. Past research has reported good reliability in judgments over time and high similarity across experts (Diekhoff & Wigginton, 1982).

The representation of the knowledge structures elicited by the above similarity ratings can be accomplished through a network approach using Pathfinder software and Pathfinder networks (PFnets) (Schvaneveldt, 1990). Pathfinder uses the pairwise proximity estimates for a set of concepts and generates a network structure (Figure 6) where the concepts are nodes and the relations between concepts are links in the network structure. Closely related concepts are represented by their proximity to one another in the Pathfinder knowledge structure.

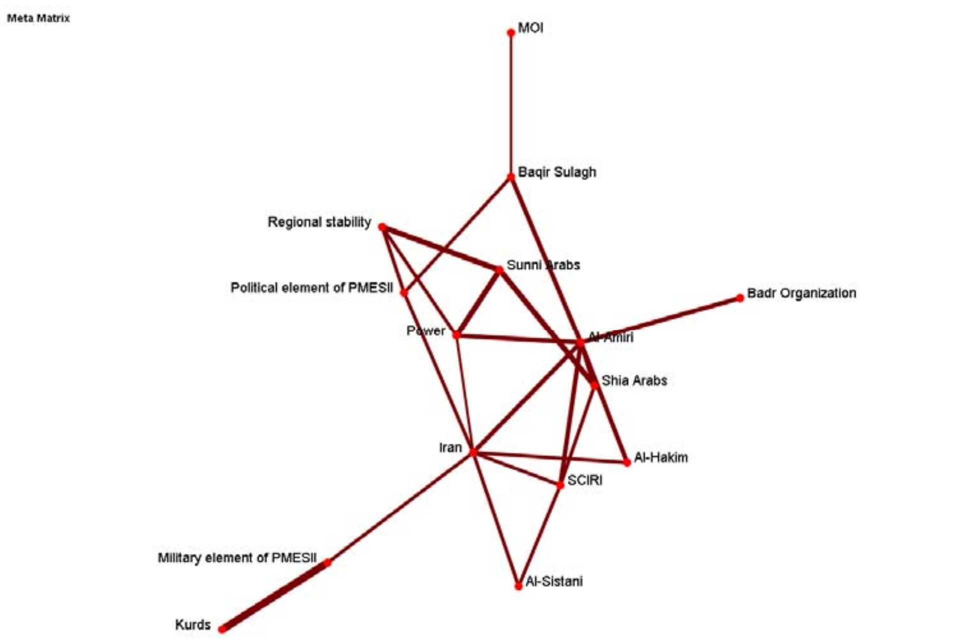

Figure 6. Pathfinder knowledge structure example where concepts are represented as nodes, relationships as links, and line weights represent degree of relatedness.

The PFnets are constructed using an algorithm that transforms the similarity ratings into a network structure. The algorithm searches for the shortest possible path between concepts and maintains those links between two concepts. Therefore, it provides all the links in the minimal spanning tree, which is a subgraph path linking all nodes by the shortest possible distance (Figure 7) (Schvaneveldt, 1990). The Pathfinder algorithm has advantages over multi-dimension scaling (MDS) as it preserves the pairwise comparisons better and it does not force a hierarchical solution like tree representations do (Jonassen *et. al*., 1993).

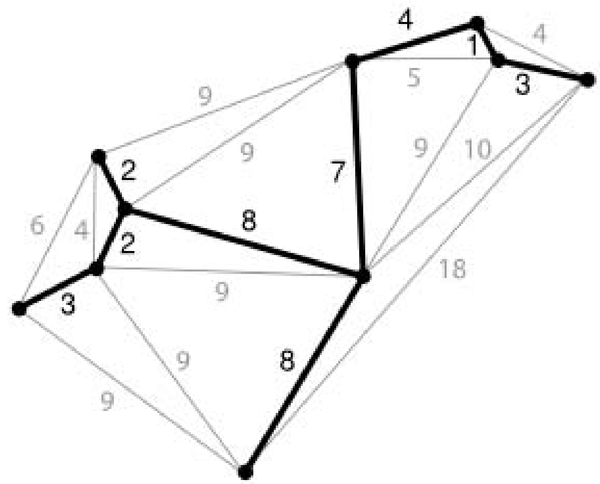

Figure 7. Example of a minimum spanning tree.

Pathfinder

Pathfinder has been in use for more than 20 years to represent knowledge structures of categories (Rubin, 1990), scripts (Durso & Coggins, 1990), room schemata (Schvaneveldt, 1990), and problem-solving schemata (Dayton, Durso, & Shepard, 1990). The Pathfinder technique has been used to identify novices from experts in the domains of air combat flight maneuvers (Schvaneveldt, Durso, Goldsmith, Breen, Cooke, Tucker, & DeMaio, 1985), computer programming (Cooke & Schvaneveldt, 1988), statistical reasoning and classroom learning (Goldsmith & Johnson, 1990). These studies have indicated that Pathfinder networks represent knowledge structures in a meaningful way as it identified expert and novice pilots with over 90% accuracy (Schvaneveldt, Durso, Goldsmith, et al., 1985) and accounted for 55% of the variance in students' final course points (Goldsmith & Johnson, 1990).

The Pathfinder rating task requires the participant to rate the relatedness of each possible pairing of the included concepts. The relatedness scores are done on a 1-9 scale where 1 is "unrelated" and 9 is "related". Inclusion of 15 concepts presents 105 comparisons to be rated and takes and average time of 7 minutes to complete. The number of ratings quickly escalates as more concepts are added (e.g., 20 concepts = 190 comparisons).

Pathfinder measures an individual's knowledge structure or situational model and is able to quantify several aspects of individual and group understanding. The following list represents the different types of analyses possible with Pathfinder:

- Comparison of the PFnets across time, individuals, and/or groups. The similarity score used to make these comparisons is the proportion of shared links in two PFnets using the same concepts (theoretical range = -1.0 to +1.0) (Interlink, Inc., 1996).
    - Comparison of the situational model to a referent to evaluate similarity. Possible referents:
        - Subject matter expert knowledge structure

    - Other groups’ knowledge structure
    - Model representation
    - Commander’s knowledge structure
  - Comparison of PFnet similarity across time and individuals/groups.
    - Similarity over time: change of the knowledge structure over time.
    - Similiarity between individuals/groups: degree of congruency among team/group members’ knowledge structure along with possible changes over time.
- Measure of domain expertise (related to the concepts included)
  - Derived from Pathfinder coherence measure where coherence is a measure of how consistent were the participant’s ratings. The coherence score is a Pearson Product-Moment correlation for the internal consistency of an individual’s ratings (theoretical range = -1.0 to +1.0) (Interlink, Inc., 1996).
  - Past research indicates a strong relationship with Pathfinder cohesion and domain expertise (Gaultieri, Fowlkes, & Ricci, 1996; Stout, Salas, Kraiger, 1997).

Conclusion

The distributed cognitive theoretical framework brings together various cognitive attributes typically analyzed only at the individual level and expands them to multiple individuals, tools, and the task environments these agents are embedded in. Two of the distributed cognitive attributes, coordination across agents and mental models were addressed in this paper to describe our efforts of analyzing these in C2 environments using existing tools and techniques and developing new ones where needed. The analysis of each of these attributes alone can be valuable, but can bring additional insight and aspects of validity when brought together and interpreted through a single theoretical framework.

Each of the distributed cognitive attributes cover a wide range of behavior and in turn, possess an equally wide range of possible methods and techniques to measure them. The longitudinal network methods addressing coordination across agents and the structural knowledge methods targeting mental models are only two tools for the C2 researcher to place in their toolbox. They are powerful methods and tools that can be used in a wide range of situations and research questions but they are not the only way to tackle distributed cognitive issues for these attributes. Additional efforts in this area to further explore and refine these and other methods is needed if continued rigor and insight is to be gained of C2 as it is examined through the distributed cognitive lens.

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