DYNAMICAL PERSPECTIVES ON TEAM COGNITION

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A theoretical perspective based on dynamical systems theory is applied to the concept of team cognition. Important postulates based on this perspective include a division of labor based on the elements of information involved in performing a team task, as well as the notion of coordination among information elements occurring through elemental couplings via a coupling medium. These features of our perspective are outlined, with the important notion of mediational means receiving the most attention. The dynamics of discourse-based mediation are considered in light of empirical data involving changes in the content of discourse over time in an uninhabited air vehicle reconnaissance task.

INTRODUCTION

Traditionally team cognition (Cooke, Salas, Cannon-Bowers, & Stout, 2000) has been viewed in terms of shared static knowledge (i.e., shared mental models; Klimoski & Mohammed, 1994). However team cognition can also be viewed as an emergent property resulting from the distribution of information elements across a system of interdependent actors who coordinate information across time and space. This latter view of team cognition is akin to dynamical systems theory (Alligood, Sauer, & Yorke, 1996; Beltrami, 1998), whereas the former is akin to a modular approach (cf. van Orden and Kloos, 2003). Specifically in taking a systems approach we emphasize the constraints and/or opportunities imposed on team members by interacting with other team members. A modular approach on the other hand is static, in that the behavior exhibited by any one team member is largely independent of team interaction over time. In this paper we will trace out some of the fundamental features of a systems-level view of team cognition, including information distribution and coordination. One of the more crucial concepts, mediated coupling, is considered in detail. Finally we present communication data that illustrate dynamical qualities of verbally mediated team interaction.

Division of Labor

Tasks that are cognitively complex are often distributed across multiple actors. For example, an operating room includes a surgeon, a nurse, and an anesthesiologist. Tasks that are performed on a very large scale, for example, airport emergency response, are also distributed, but on a broader sociotechnical scale. When dealing with large systems it may be more suitable to envision division of labor in terms of division of information elements, rather than division of knowledge among actors. For example, division of labor in a large sociotechnical system might take the form of weather, security, fire, medical, administration, etc. (DeJoode, Cooke, & Shope, 2003). What is important here is to note that an information element need not be a person. Labor divisions are drawn among the elements of information involved in the task rather than between individual actors. When viewed on this scale coordination takes place over information elements rather than among individual operators. These ideas scale down to smaller systems (e.g., three person teams) to the extent that there is distribution of information. For example, navigation, piloting, and sensor data information are elements involved in the three-person uninhabited air vehicle (UAV) reconnaissance task described in Cooke and Shope (2002).

Coordination

While the elements of information involved in performing a team task can be viewed as independent perception-action systems in and of themselves, the defining process that unites them at the team cognitive level is team coordination. Further, it is this interdependency through coordination that elevates a collection of individual information systems to a team-level system capable of meaningful action in its own right.

The concept of team coordination can be approximated by a limited set of assumptions. First, coordination can only occur between *coupled* elements. Elemental couplings are simply the establishment of interdependencies for the purposes of taking meaningful action at the team level. These couplings are such that they may be direct, i.e., one element coupled directly to another, or indirect, one element coupled to another through an interlocutor element or elements, such as an interpreter or filter. Second, level of coordination between coupled elements is affected by *strength* of coupling. Strength of coupling is simply the degree to which one element depends on another relative to some time scale appropriate to team-level action. Third, the *medium* through which elements are coupled is closely related to the strength of coupling.

Mediation among coupled elements is given breadth in the following sections.

MEDIATION

In the theoretical approach we have outlined thus far, team cognition is an emergent property of a system of coupled elements, coordinating through mediational means. This last notion of "mediational means" will be important in taking a dynamical perspective on team cognition. Therefore we devote this section to 1) defining mediational means, 2) asserting a continuum along which media may be quantified, and 3) exploring dynamics of a verbal medium.

Mediational Means

Information elements require connectivity in order to introduce the possibility of coordinated elements. Connectivity between elements obtains across lines of media. The lines of media thus can be thought of abstractly as the mediational means of coordination. Both information elements and the mediated connections that exist among them are properties of the task, and not the isolated properties of any specific human operator; e.g., things like books, charts, maps, lexical devices and verbal communication are examples of mediational means of element coordination. Thus, mediational means are introduced as a system *parameter* rather than a property of particular elements. For example, a coupling between weather and firefighting elements may exist in some task. The coordination between these two elements however is depends on the medium through which they are coupled. For instance, in a forest fire these elements are tightly coupled; that is, the state of the firefighting element depends highly on the weather element in real time and requires a coupling medium that accounts for this. Given a small house fire this coupling may be much looser. In each of these situations the coupling medium should reflect the dynamics of the inter-coupled system.

A Media Continuum

The notion of mediational means we employ is kindred with a range of conceptualizations of medium, including those found in Heider (1959), Hutchins (1995), and Wertsch (1991). We include a wide range of conceptualizations by quantifying media along a continuum of malleability. A malleable medium is highly dynamic, changing its state quite rapidly over time. Full duplex verbal communication as a means for coordinating information elements is an example of highly malleable mediation. A malleable coupling medium is necessitated by tightly inter-coupled systems where apportioning of information in real-time is high. A medium that is highly fixed on the other hand is very stable and changes are appreciable only over relatively long lengths of time. This type of mediation between elements thus provides for stilted or pedagogic forms of coordination. An example of sharing via a fixed medium would be two or more elements coordinated via a common map or chart. A fixed coupling medium is sufficient with loosely coupled systems in which elements have a great deal in common, thus interdependency in real-time is low. In between these two extremes media can be classified as more or less malleable along a continuum defined by *rate of change in the state of medium over time*.

The Dynamics of a Mediational Means

We have conducted five experiments involving a three-person UAV reconnaissance task. The results in this section are all derived from 11 teams made up of male and female ROTC students from New Mexico State University. As mentioned above, there are three elements of information distributed across the task environment: piloting, navigation, and sensor data. Each of these elements is maintained by one of three human agents who are inter-coupled though a verbal medium. In order to illustrate the evolution of mediational means and ramifications for element coordination, we will explore the dynamics of the verbal coupling medium in terms of team communication content.

The two measures of content we will be tracking involve domain relevance of content and a measure of the variability in usage of UAV lexical words. The results are based on 67 40-minute mission transcripts as diagnosed by latent semantic analysis (LSA; see Kiekel, Cooke, Foltz, Gorman, and Martin, 2002 and Gorman, Foltz, Kiekel, Martin, & Cooke, 2003 for more details).

Transcript density is motivated by the assumption that for communication to be effective, information should be conveyed in a concise manner. It quantifies the rate of meaningful discourse:

$$\text{Density} = \frac{\text{Meaningfulness}}{\text{Words Spoken}}$$

Operationally, density is the ratio of LSA vector length, summed over all statements, to the number of words spoken in a given mission.

Lag coherence is a measure of task-relevant topic shifting during a mission. Lag coherence is computed by averaging LSA cosines (semantic similarity) between utterances over varying utterance lags (e.g., 2 utterances away, 3 away, etc.). Statement cosines are averaged over a 36 lag moving window. Once the cosines are averaged, log lag is used to predict log cosine in a linear regression equation. The slope of the regression is the measure of topic shifting, or lexical variability, for a given mission, where high lag coherence indicates low lexical variability (small range of UAV topics) while low lag coherence indicates high lexical variability (broad range of UAV topics).

For the 11 teams reported here, we have observed over the course of seven missions is that transcripts tend to 1) become optimally dense, and 2) develop reduced lexical variability. Strikingly, these changes occur in a nonlinear fashion. Although each of the content measures is theoretically continuous, we have observed that there may be at least two distinct qualitative phases in their development. Figure 1 depicts the two qualitative states for the transcript density measure. On average, over the course of the first three missions, verbal coordination becomes increasingly dense with domain (UAV) specific information. This monotonic increase of domain jargon is a reflection that up to this point the verbal coupling medium is highly apportioned, indicating a tightly coupled, highly interdependent system. However at mission 4 teams undergo a qualitative shift, associated with optimal density in terms of team performance, in their rate of usage of domain specific language (Gorman et al., 2003). Facilitated by the emergence of a constant rate of jargon, this is a phase in which the system elements have become more loosely coupled and less interdependent. We presume this is due to the development of team-specific lexicons.

Figure 2 depicts a similar qualitative shift as indexed by the lag coherence measure. During missions 1-3 on average teams tended to use a broad range of lexical words. This is indicative that the verbal coupling medium is still relatively malleable at this point. At mission 4 a qualitative phase shift occurs, after which the variability in the usage of lexical words is quite constrained. This is evidence that the verbal coupling medium has become more fixed. We presume that coupled with stable transcript density each team has by this point selected a range of UAV lexical words that are a part of their own team-specific lexicons.

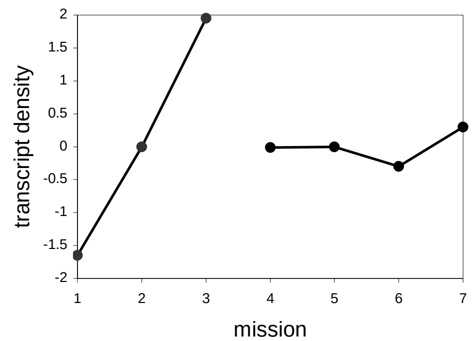

Figure 1. Mean transcript density over missions

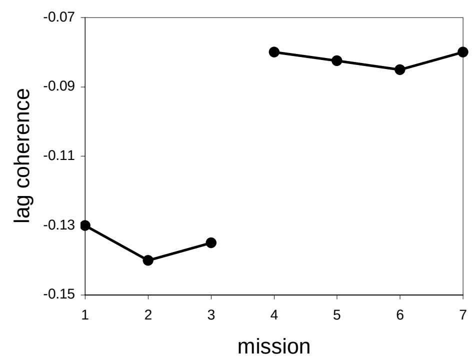

Figure 2. Mean lag coherence over missions

Both of the phase shifts discussed here map onto the average onset of asymptotic team performance depicted in Figure 3, and underlie the average team's propensity to develop a common sort of semiotic awareness through which communication and apportioned knowledge, according to division of labor, are facilitated. We believe this type of team-semiotic development additionally is the result of indoctrination of individual team members into a team-level unit capable of meaningful action in its own right. It is this ability and skill at coordinating effectively and efficiently as a team that is learned, moreso than individual taskwork knowledge or skill. In addition, this ability and skill for coordination takes time and team-member interaction to develop (i.e., the dynamics of a mediational means), whereas individual knowledge or skill only takes time (i.e., any individual team member's "role" knowledge) and individual practice, not necessarily interacting with other team members.

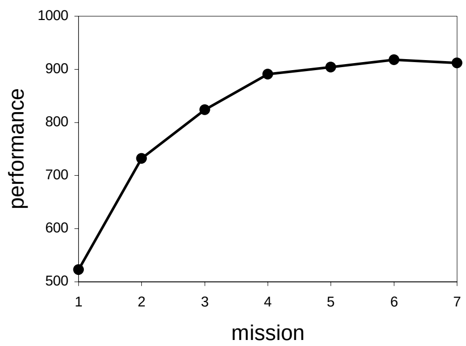

Figure 3. Mean team performance over missions

The global dynamics of the system mediator described here (i.e., content of verbal communication) are embodied in the fold catastrophe (Figure 4). Curve segments (a) and (c) in Figure 4 correspond to the two qualitatively different phases of the content metrics. Point (b) corresponds to the phase shift (bifurcation) occurring at mission 4. This type of nonlinear semiotic development may in fact correspond to a sort of underlying Vygotsky-Bakhtinian principle (cf. Cheyne & Tarulli, 1999) in which promulgation is rather sudden and revolutionary, but otherwise stable. With multiple agents interacting and thus feeding back into each other, it is not really surprising that promulgation might grow logistically. In some sense, each team member is exploring the team semiotic environment, and through interaction can explore aspects of the team semiotic environment not directly available to them. Ultimately, and rather abruptly, the entirety of the environment, or at least the relevant aspects of it are known to all team members.

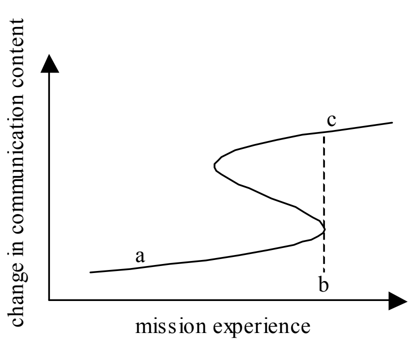

Figure 4. Change in verbal content medium modeled as a fold catastrophe

CONCLUSION

Given our research thus far, we believe dynamical models of team cognition should minimally incorporate all of the notions we have presented here. In a model the behavior of coupled information elements are tracked through a set of state equations and the conditions under which a system evolves (e.g., mediational means) are modeled as parameters, e.g.:

$$
\begin{aligned}
\dot{x}_1 &= \bar{x}_1 + K_{12}x_2 + \ldots + K_{1n}x_n \\
\dot{x}_2 &= K_{21}x_1 + \bar{x}_2 + \ldots + K_{2n}x_n \\
&\vdots \\
\dot{x}_n &= K_{n1}x_1 + K_{n2}x_2 + \ldots + \bar{x}_n
\end{aligned}
$$

Where n = number of information elements, $\bar{x}_n$ indicates a stable state of element behavior (e.g., the asymptotic stable state for x_n where x is an abstraction meaning "element position"), K_{ij} is a parameter which indicates the strength of elemental coupling from i to j (i.e., represents "mediational means" as we have discussed them here), and the equations are a set of first order differential equations. (In these particular equations, we have represented K_{ij} as a fixed parameter, however this is obviously an oversimplification as reported in the previous section.) Approximate solutions for such a set of equations can be plotted by implementing the Runge-Kutta or Euler computer algorithms. These methods are used in order to find stable system states and qualitative phase shifts in system behavior at various parameter settings. Our current work lies in refining and exploring these types of systems as abstractions of the "team mind".

Obviously the state of elements in such systems are interdependent (not modular) providing a means for identifying behaviors that evolve over time (i.e., $\dot{x}_n$ is change in element x_n at time $t + \Delta t$) due to mediated interactions as well as perturbations attributable to changes in other hypothetical system parameters. Thus we believe such models will be useful for predicting long-term coordination effectiveness based on hypothetical values of system parameters (e.g., team familiarity) or coupling structure (e.g., flat vs. hierarchical). These models do not suffer from team member modularity as in most computational frameworks. This allows for the researcher to emphasize the constraints and/or opportunities imposed on team members by interacting with other team members over time. For example, such models will be useful in predicting critical strengths of coupling at which information elements may bottleneck or beyond which coordination of information elements undergoes a qualitative phase shift.

Acknowledgments

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