Team Coordination Dynamics and the Interactive Approach: Emerging Evidence and Future Work

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Abstract. In the study of coordination and teamwork, the primacy of team interaction is emphasized in an interactive approach. The interactive approach lies in stark contrast to the traditional, shared cognition approach to understanding team cognition. An overview of team coordination dynamics, an interactive approach rooted in nonlinear dynamics, is provided. Results from a series of experiments on team coordination dynamics are summarized. Finally, future research directions, inspired by those results, are considered.

Keywords: Nonlinear dynamics, Teams, Team coordination, Teamwork.

1 Introduction

Teamwork enables groups of individuals to accomplish complex tasks in a variety of work settings, including business, military, medical, and educational settings. Not surprisingly, interest in team cognition and coordination, and their relation to team effectiveness, is on the rise. Ideally, during the execution of a complex cognitive task, teams allow cognitive work to be efficiently distributed across a heterogeneous division of knowledge, skills, and abilities. Certainly, a good theoretical understanding of this phenomenon—*team cognition*—and its real-time coordination would have the potential to benefit work in sociotechnical environments.

1.1 Shared Cognition and the Interactive Approach

The search for mechanisms of effective teamwork and its development has traditionally centered on shared knowledge structures across team members. This approach is known as the shared cognition approach [1, 2, 3]. In the shared cognition approach, team cognition—the ability to think and react as a team—is conceptualized by two central questions concerning shared knowledge structures: What overlaps? and What is complementary? According to this approach, the development of overlapping and complementary knowledge is tantamount to shared cognition and, therefore, team cognition.

Shared knowledge structures can be quite complex. A mental model is a knowledge structure that allows an individual to describe, explain, and predict states of a system [4]. A *shared mental model* (SMM) is generally defined as the degree of overlap of team members' mental models; hence, the SMM construct addresses the question of what overlaps. SMMs extend the mental model construct to teamwork [5, 6]: here, the team is the system and a SMM allows team members to describe,

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explain, and predict team interaction. At the same time, a *transactive memory system* (TMS) [7, 8, 9] is structured knowledge about whom to ask for the correct piece of information [10, 11, 12]. By viewing shared cognition as relational knowledge across team members, TMSs address the question of what is complimentary.

The paradigm for linking shared cognition to team effectiveness is the Input-Process-Output (IPO) causal framework [13, 14, 15], wherein shared knowledge is the input, team interaction the process, and team effectiveness the output [16, 17, 18]. In the IPO framework shared cognition is indirectly linked to team effectiveness via the moderating variable, team interaction processes. Multiple studies have empirically linked shared cognition to team effectiveness using the IPO causal framework. For instance, the development of SMMs through pre-task planning has been empirically linked to the anticipation of team member interaction during task performance, thereby allowing for increased efficiency of communications [19]. In this way, SMMs may provide an adaptive coordination mechanism—so-called *implicit coordination*—during times of high workload [20, 21]. Research has similarly tied longevity of team membership to the development of TMSs, which are linked to adaptive, "backing-up" team interactions [22]. That is, long-tenured teams that have developed such a knowledge structure have members that tend to know when, and from whom, to request and accept help, ultimately leading to increased team effectiveness, particularly in high-stress environments.

Though the characterization of effective teamwork as the shared contents of team member knowledge has been (to some degree) empirically validated in some studies, it has been rejected in others. Over a variety of studies the development of shared knowledge (either overlapping or complimentary) is not concomitant with the acquisition of team effectiveness [23, 24], but the development of effective team interaction processes is consistently linked with enhanced team effectiveness [25, 26]. Therefore, the central construct of team interaction processes may provide a better foundation than shared knowledge for a theory of team cognition, especially as team cognition relates to team effectiveness [27].

Perhaps most limiting is the view that something as dynamic as effective teamwork could be based on a structure. Structures are (relatively speaking) static entities and, as it stands, the substrates upon which they may be modified during task performance are neither explicitly nor implicitly specified in the shared cognition approach. However, team interaction processes are inherently dynamic and may provide the appropriate substrate. Of course, shared cognition theorists have become aware of the inconsistency between static knowledge and dynamic task performance and have adjusted the theory accordingly (e.g., "complilational emergence" of shared cognition through team-member interaction; [28]. Indeed, it has recently been acknowledged that a feedback arrow from O to I may be required to account for new results [29]. On the other hand, if team knowledge is viewed not as antecedent to, but as incidental to, team interaction processes, then team interaction becomes the substrate upon which aspects of teamwork may be modified.

Static constructs may not satisfactorily explain something as dynamic as effective teamwork. Team interaction, on the other hand, seems to fit the bill because it is an inherently dynamic process: During teamwork, an appropriate level of awareness and agency to act as a team must be dynamically assembled through team-member interaction. Further, team-level awareness and agency to act is partially determined as the situation unfolds. Therefore, the content of team interactions may rely just as heavily upon the exigencies of an unfolding situation, as upon static knowledge. Such a viewpoint is the thesis of an interactive approach to team cognition (as opposed to the shared cognition approach). The next section describes team coordination dynamics, an interactive approach rooted in nonlinear dynamics, for studying the development of coordination as it relates to team cognition and effectiveness.

1.2 Team Coordination Dynamics

Team coordination is a process wherein team members adjust their interactions in accordance to a changing environment. As a skill, it develops when teams interact in a dynamic environment. Team interaction patterns unfold in discontinuous bursts and lulls of activity that can be described using nonlinear dynamics. Inspired by concepts from ecological psychology [30, 31], coordination dynamics [32], and Haken's [33] synergetics, team coordination dynamics employs nonlinear dynamics as a paradigm for understanding how team coordination skill develops. Just as nonlinear dynamics pervade coordination in motor and molecular systems; team coordination dynamics is the paradigm used for understanding the emergence of coordinated behavior in teams. Of course, the concept of team coordination considered from this viewpoint is quite different from shared cognition.

To say that coordination is *achieved* by team members would be to say that coordinated behavior was somehow stored within the members themselves. And that is very much how team coordination has been viewed traditionally, from a shared cognition perspective. Certainly teams have members with requisite knowledge; teams would fail otherwise. Teams must communicate this knowledge cooperatively. However, it is not enough to just communicate cooperatively. The purpose of assembling a team is to set up a system that can handle a complex, changing task environment that no one individual, working alone, could comprehend. If that is the case then it is clear that there will be changing environmental conditions that a team can experience but an individual cannot. Now, can coordination be stored in these as-yet unexperienced conditions of the task environment? It might be better to say that coordination is not stored at all. Rather, it is dynamically assembled across team interactions, such that the team remains focused on achieving its goals in the context of a dynamic environment.

2 Emerging Evidence

In this section I describe research on three-person teams conducted in an uninhabited air vehicle (UAV) simulator located in Mesa, AZ [34]. In the UAV task, the three team members—pilot, navigator, and photographer—must interact over headsets to photograph reconnaissance targets over a series of 40 min missions. In each mission, teams have to photograph 11-12 reconnaissance targets. Each team member has their own computer workstation that displays information specific to that team-member role as well as general flight information (e.g., current heading, altitude, and speed). Team members were seated in the same room with their backs to each other, such that they only communicated verbally over the headsets.

2.1 Team Mixing

Gorman, Amazeen, and Cooke [35] had three-person (UAV) teams (who had already been trained to photograph reconnaissance targets) return after a retention interval with either the same team members ("Intact") or different team members ("Mixed"). An order parameter—a collective measure of team interaction at photograph points—was developed to measure team coordination dynamics.

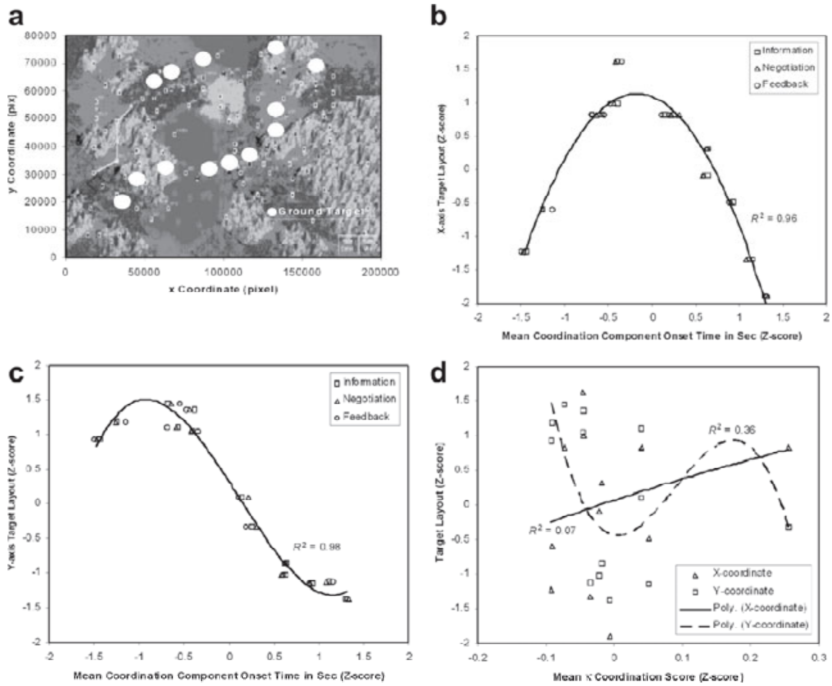

Fig. 1. The environmental layout of the UAV targets in two dimensions [x, y] (a); the relationship between target x coordinates and κ components (b); the relationship between target y coordinates and κ components (c); the relationship between [x, y] and κ. (Reprinted from [36].)

The team interactions that were the components of the order parameter were the three primary team member functions for photographing each target: (1) the navigator sends target *information* (I) to the pilot; (2) the pilot and photographer *negotiate* (N) an appropriate airspeed and altitude; and (3) the photographer provides *feedback* (F) on the status of the target photograph. Timestamps corresponding to the exact time each of these interaction functions occurred for each UAV target were collected during the experiment. These functions must be dynamically combined in a specific order to photograph each target, such that I→N→F. The order parameter, which captures these relationships, is called κ and is given in Equation 1. κ was computed for each target and is a dimensionless (unit-free) quantity because time cancels in the numerator and denominator. κ < 1 indicates a lack of coordination relative to the

I→N→F relationship, and κ = 1 is indeterminate. As long as the I→N→F relationship is satisfied, κ > 1; however, fluctuations of κ > 1 are indicative of variance in team coordination from target to target. Now, if team coordination is the dynamic assembly of team interactions in accordance to changes in the task environment, then κ should fluctuate with the changing task environment. Indeed, fluctuations ("adjustments") in κ components correspond precisely to the dynamic layout of targets in the UAV environment [36] (Figure 1).

$$\kappa_i = {\text{time}(\text{F}_\text{i}) - \text{time}(\text{I}_i)} \Big/ {\text{time}(\text{F}_\text{i}) - \text{time}(\text{N}_\text{i})} \qquad (i \;=\; 1, 2, \ldots, \#\text{targets}). \tag{1}$$

Nonlinear dynamical indices, calculated from teams' κ time series, revealed that Mixed teams had more flexible coordination, as indexed by the Hurst exponent, and greater coordination stability, as indexed by the Lyapunov exponent, than Intact teams. Counter to expectations from a shared cognition approach, Mixed teams were also more adaptive as indexed by the correlation between stability and overcoming roadblocks, which are novel events that perturb coordination dynamics. These results further suggest that Mixed teams were better able to adjust their interaction dynamics to the changing demands of the task environment. Both the coordination dynamics and subjective process ratings were correlated with team effectiveness [37], but the coordination dynamics provided insight into the Mixed team advantage: By allowing teams to experience more of the possible relations that could occur, mixing team members may have allowed teams to spontaneously self-organize coordination attractors that remained stable under novel task requirements.

2.2 Perturbation Training

In a second experiment, also conducted in the UAV task context, Gorman, Cooke, & Amazeen [38] trained teams by perturbing elements of the κ order parameter during task acquisition. This was accomplished by actively interrupting either the I, N, or F functions, forcing teams to find new ways to work around those perturbations. Different coordination links in the I→N→F sequence were perturbed multiple times during training. We found that perturbation-trained teams performed as well as teams trained using traditional methods (e.g., cross-training) under routine conditions and outperformed those teams under novel conditions, although cross-trained teams had higher levels of shared knowledge. Similar to the effect of team mixing, perturbing coordination during task acquisition may allow teams to self-organize coordination attractors that remain stable across a range of possible task conditions. This interpretation is also consistent with recent research in the motor literature that suggests unpredictable practice elements can lead to acquisition of adaptive skill [39].

3 Future Work

Much of the next round of research on team coordination dynamics will focus on three intertwined areas: real-time dynamics; perturbation training; and cross-level team coordination dynamics.

3.1 Real-Time Dynamics of Team Interaction

Given that adaptive team synergies are created, ideally we would like to detect threats to those synergies as they occur. Real-time dynamical analysis of team communication [40] is a method for detecting team coordination anomalies as they occur. The primary challenge of dynamics in real time is a methodological one. Nonlinear dynamics are usually analyzed using long time series (e.g., a minimum of 1,024 observations). However, to detect threats to team synergy, dynamical parameters have to be calculated on incoming data streams of unknown length. The approach we have employed is to calculate the dynamical pattern of interest (e.g., the Lyapunov exponent) for the incoming data stream using k different windows of size 2^k. In principle, this is a moving window analysis, except that there are multiple windows of different sizes, and the data are moving through the window.

In theory, a parameter estimate at smaller window sizes should contain a great deal of error due to the small sample size. Conversely, moving to larger window sizes should yield better estimates. The variability (*SD*) of the estimate for each window size, updated in real time, is then viewed across window size using linear regression: $\log_2(SD) = v*k$. The slope v is always negative and has a maximum of zero (i.e., if the variability scaled perfectly with window size). Steeper (more negative) values of v indicate that the dynamical parameter is relatively stable as window size increases: the team communication dynamics are not changing. However, if v begins to fluctuate toward zero, then variance persists across increasing window sizes: the dynamical parameter estimate is becoming unstable across window sizes. This is characteristic of team communication dynamics undergoing change.

When team communication dynamics do not change, the team is operating within the bounds of their own *intrinsic* dynamics. However, when there is a critical change in the environment—the *extrinsic* dynamics—the team's communication dynamics must also change to accommodate the perturbation. We have validated this approach using team communication data in which an outside confederate intelligence agent briefly interrupts team interaction. In that study [40], the intelligence agent perturbation caused a significant upward shift in v, but the team recovered their intrinsic dynamics (i.e., a negative shift in v) soon after the intelligence agent was withdrawn.

3.2 Perturbation Training

Similar to the notion of differential learning [39], perturbation training involves randomly inserting off-task elements into the coordination process during task acquisition. Ideally, training should exercise coordination variability to match the variability of the post-training environment. The general idea is that exposure to noisy interactions during training may allow teams to transfer training to even noisier post-training environments. The mechanism though which teams acquire this skill, perturbation training, may create opportunities for bottom-up organization of new coordination links in response to random changes in the training environment.

Because, in perturbation training, the organization of new coordination links is not knowledge-driven, team members are compelled to unconsciously adjust interactions in unplanned ways to maintain a balance between team dynamics and environmental dynamics. If task acquisition takes place under these conditions, then learning may continue to occur when teams transfer their coordination skill to novel post-training situations. In other words, because novel (unexpected) events in the post-training environment are similar to the conditions of initial task acquisition, perturbation training may transform novel post-training events into opportunities for continued skill development.

3.3 Cross-Level Team Coordination Dynamics

Cross-level coordination dynamics is a program of research that seeks to measure team coordination across motor (e.g., postural kinematics; [41]), cognitive (e.g., communication content; [42]), and physiological (e.g., neurophysiological synchronies; [43]) team subsystems. Efforts toward understanding how these subsystems interact to dissipate perturbations may facilitate interventions designed to enhance team resiliency under novel task conditions.

4 Conclusion

Sociotechnical work environments demand distributions of specialty knowledge across team members. To be sure, shared knowledge plays some role in a variety of sociotechnical tasks. It takes more than knowledge, however, to perform effectively in highly-dynamic, high-risk task environments. Teams must continually adapt their interactions to the changing dynamics of the task environment. Rooted in adaptive interaction, team coordination dynamics takes a nonlinear dynamics perspective on what means to learn and achieve coordinated behavior. Results from taking such a perspective have been promising thus far. However, as outlined in the last section of this paper, more work is needed to better understand dynamic nature of team synergies and how to detect threats to them. A better understanding of how coordination mechanisms, operating at many different levels of analysis, are dynamically linked may facilitate future training and learning interventions to enhance team resiliency under novel task conditions.

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