An Ecological Perspective on Team Cognition

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An Ecological Perspective on Team Cognition

Why Team Cognition?

Technology has complicated the role of the human in most complex systems. Manual or motor tasks carried out by a single individual have been supplanted by multiple-person tasks that are highly cognitive in nature. Assembly lines have been replaced by teams of designers, troubleshooters, and process controllers. Teams plan, decide, remember, make decisions, design, trouble shoot, solve problems, and generally think as an integrated unit. These activities are examples of team cognition, a construct that has arisen with the growing need to understand, explain, and predict these cognitive activities of teams. But does *team cognition* mean that teams think or is it that the individuals within the teams think, relegating team cognition to a collection of individual thinkers? Questions like these are important prerequisites to understanding team cognition.

But why focus on team cognition? Just as applied psychologists have linked individual cognition to individual performance (Durso, Nickerson, Schvaneveldt, Dumais, Chi, & Lindsay, 1999) team cognition has been linked to team performance. The idea is that a great number of team performance deficiencies or errors in complex cognitive systems can be attributed to problems with team cognition. There are many notable examples supporting this claim. Team decision making and coordination failures are at least partially tied to the Vincennes–Iranian airbus incident of 1988 (Collyer & Malecki, 1998), the Challenger disaster in 1986 (Vaughan, 1996), and recent failures in organizational response to Hurricane Katrina (CNN, 2005). A better understanding of team cognition and its relationship to team performance should enable us to measure and assess it and intervene through training and design as needed.

Team Cognition: Definitions

In this chapter the focus is on *team,* rather than *group*, cognition. We define a team as a special type or subset of group; one in which the members have different, though interdependent roles. This definition is compatible with that of Salas, Dickinson, Converse, and Tannenbaum (1992) who define a team as "a distinguishable set of two or more people who interact dynamically, interdependently, and adaptively toward a common and valued goal/object/mission, who have each been assigned specific roles or functions to perform, and who have a limited life span of membership" (p. 4). Though much of what is being learned about team cognition should also apply to group cognition, there are some interesting issues that arise when groups with heterogeneous or specialized team members are considered.

We define team cognition as the cognitive activity that occurs at a team level. Thus, if more than one individual is involved in planning and these individuals depend on each other for different aspects of planning, there is team cognition. The presence of team cognition does not imply the absence of individual cognition. Both occur simultaneously. In fact, one-level (individual) is nested within the other (team). The focus of this chapter, however, will be on team-level cognition. Parallel to theories of individual cognition, there are a number of theoretical perspectives that can be taken on team cognition. In this chapter an ecological perspective on team cognition is described and contrasted with more traditional perspectives. The ecological perspective stems from the early work of William James, James Gibson, and Roger Barker (Heft, 2001) and is not a mainstream perspective for either individual or team cognition. Mainstream perspectives for team cognition have been largely inspired by cognitive psychology and the information processing approach to cognition. Before proceeding with a detailed analysis of how the two perspectives explain team cognition some background on ecological psychology as contrasted with the more traditional information processing perspective will be provided.

Information Processing vs. Ecological Psychology

Whereas the information processing approach focuses on the "analogy between the mind and the digital computer" (Eysenck & Keane, 2000, p. 1), ecological psychology focuses on the changing relationships, or dynamics, between people and their environment (which includes other people). Some defining characteristics of each of the two approaches are listed in Table 1. To summarize, major differences between the two approaches can be found in the general metaphor for formulating psychological questions, the philosophical tradition of each theory, and the locus of cognitive processing.

Table 1. *Basic Characteristics of Information Processing and Ecological Psychology.*

Information Processing Theory

A. Computer metaphor – Perception and thought are inherently computational
B. Mind-environment dualism
C. The locus of cognitive processing is "within" the individual

Ecological Theory

A. Dynamical systems metaphor – Perception and thought are inherently dynamic
B. Mind-environment mutuality
C. The locus of cognitive processing is "between" the individual and their environment

The information processing perspective has been inspired by the computer metaphor. (Lachman, Lachman, & Butterfield, 1979). Information flow diagrams are commonly used to convey stages of input, output, processing, and feedback loops along the way. Cognitive structure or representation is central to much theorizing. Computational systems operate on this database or "knowledge base." In this tradition, the processes that operate on this database (cognitive processing) are also a form of knowledge, "hence the program that governs the behavior of a symbol system can be stored, along with other symbol [knowledge] structures, in the system’s own memory, and executed when activated” (Simon, 1981, p. 22). The strong view of information processing holds that all perception and thought is inherently computational, with a program tapping into memory in order to construct a meaningful representation from meaningless stimulus inputs.

In contrast ecological psychology has been associated with a dynamical systems metaphor and holds that perception and thought are inherently dynamic. According to this view, perception and action are the basis for perceptual systems (Gibson, 1966) and further that the intersection of actor and environment is the basis of the conscious mind (James, 1904). The dynamical systems metaphor for addressing psychological questions characterizes psychological phenomena using equations of motion, interactions, or generally activity, and modeling how the system evolves qualitatively in time, including stable states, bifurcations (e.g., symmetry breaking), and coordinative states (e.g., self-organization).

The information processing perspective is also one of constructivism and mind-environment dualism. Stimulation is imbued with meaning by cognitive processes, secondary qualities are inferred from primary qualities (e.g., color from wavelength), and “psychological” quantities are scaled to “physical” dimensions (e.g., psychophysics). In contrast, the ecological perspective is one of direct perception of mind-environment mutuality. For example, perceivers or actors directly perceive change and non-change (i.e., not stimulation *per se*) in their relationship to the ambient environment (these invariants are stimulus information, but not stimuli; Gibson, 1979) where potential relationships are just as meaningful as realized relationships to the extent they can alter our opportunities for action.

Finally, the locus of cognition according to the information processing approach is “within” the individual, whereas for ecological psychology the locus of cognitive processing is "between" the individual and his or her environment. Thus the starting point for information processing is the individual, whereas the starting point for ecological psychology is the coupling between the individual and his or her environment.

An Information Processing Perspective on Team Cognition

The traditional view of team cognition portrays a team as an information processor, consisting of a collection of individual information processors. Thus, most often the information processing metaphor is applied to individual team members, cognition is measured at the individual level, and then results are aggregated to reflect the team level. In addition, the target of most measurement efforts is cognitive structure (e.g., mental models, situation models) as opposed to the process of aggregation itself. However, there are some exceptions in which the information processing is applied at the team level and measures reflect team process as well as structure (e.g., Hinsz, 1999).

Interestingly, the input-process-output (I-P-O) framework, the generic model for early conceptualizations of team performance, was inspired by theories from the social psychology of small groups and industrial organizational psychology. This framework was originally oriented toward team process more than structure. It was suggested that team interaction processes be studied as mediators of the effects of individual, group, and environmental factors on team output and cohesiveness (Hackman, 1987). A generic version of the I-P-O framework is presented in Figure 1.

However, in the course of applying the I-P-O framework to team cognition, the locus of team cognition has been credited differentially to each of the three components of the framework. For instance, Mathieu, Goodwin, Heffner, Salas, & Cannon-Bowers (2000) conceptualized team cognition as an outcome while others have considered collective cognition as an input in the I-P-O framework (e.g., Mohammed & Dumville, 2001). Others have viewed team cognition in terms of process behaviors such as leadership, assertiveness, adaptability, communications, planning, and decision-making (Brannick, Prince, Prince, & Salas, 1995) that are thought to transform individual inputs into effective team outcomes. Most importantly for this discussion, there has been an increasing tendency to locate team cognition at the "Input" portion of the I-P-O model. Accordingly, team cognition is often conceived as the collection of knowledge about the task and team held by individual team members (see Figure 2).

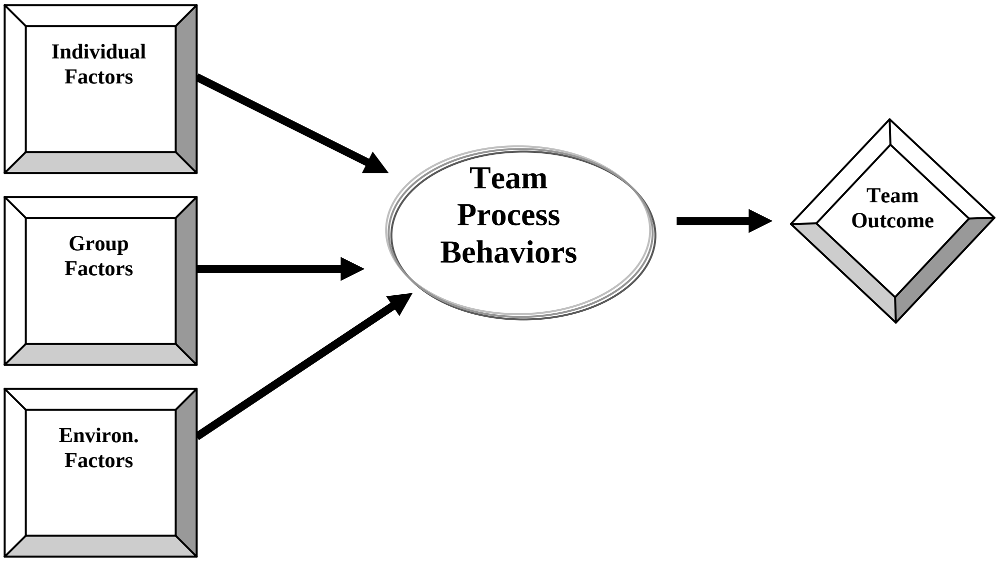

Figure 1. A Generic Input-Process-Output (I-P-O) framework.

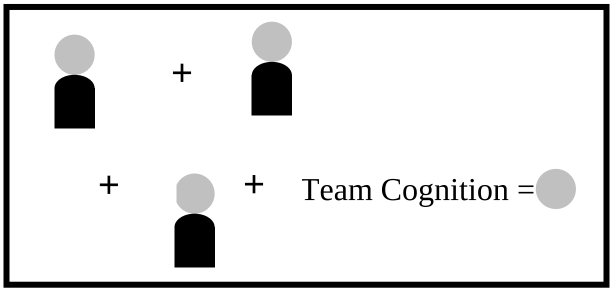

Figure 2. Team cognition as aggregate of team member knowledge.

Shared Mental Models

Theories of shared mental models are exemplary of input-oriented theories of team cognition that focus on knowledge or cognitive structure and rely heavily on individual measurement and aggregation. Researchers have demonstrated that team mental models greatly influence several aspects of the team including team process and team performance (Mathieu et al., 2000; Stout, Cannon-Bowers, Salas, & Milanovich, 1999). For instance, the shared mental model literature indicates that a high similarity of mental models within a team should lead to effective team performance (Blickensderfer, Cannon-Bowers & Salas, 1997; Converse, Cannon-Bowers, & Salas, 1991; Stout, 1995; Mathieu, et al., 2000). Furthermore, high knowledge similarity within a team should lead to anticipatory process behaviors (Entin & Serfaty, 1999).

However, results stemming from shared mental model research have been inconsistent (see Mathieu, et al., 2000; Levesque, Wilson, & Wholey, 2001; Cooke, Kiekel, Salas, Stout, Bowers, & Cannon-Bowers, 2003; Smith-Jentsch, Campbell, Milanovich, & Reynolds, 2001, Rentsch & Klimoski, 2001). Team member mental models are assumed to converge over time because of increased intra-team interaction (Clark & Brennan, 1991; Levesque, et al., 2001; Moreland, 1999; Rentsch & Hall, 1994; Liang, Moreland, & Argote, 1995), whereas some studies indicate that mental models converge with sheer experience, and that this convergence predicts team performance (Smith-Jentsch, et al. 2001;Rentsch & Klimoski, 2001). Other studies do not find a relationship between convergence and team performance (Levesque, et al., 2001). Some differences can be explained in terms of task or domain dependencies, whereas others may be linked to choice of measurement methods.

At the most basic level, the degree to which a mental model is shared by team members can be estimated through a comparison of the knowledge structures of team members. One way that shared mental models have been assessed in this manner is through comparisons of conceptual representations derived using Pathfinder (e.g., Stout, et al., 1999). The similarity between two Pathfinder networks can be quantified in terms of proportion of shared links. Accuracy of a conceptual representation like Pathfinder can similarly be estimated through comparison with an expert or other referent representation. Other methods utilized to measure mental models are think aloud protocols, interviews, diagramming, and think verbal troubleshooting (Rowe, 1994; Rowe & Cooke, 1995). When these methods have been applied to the measurement of team mental models, measurement tends to occur at the individual level and individual team member results are aggregated for team-level measurement.

Although it has been central in the team cognition literature, the term *shared mental model* is somewhat ambiguous (Cooke, Salas, Cannon-Bowers, and Stout, 2000). First, the target of the mental model is not always clear (e.g., knowledge of the task, knowledge of team roles, understanding of equipment, team member beliefs). The term *sharing* is similarly vague. To share can mean to have or use the same entity such as share the beliefs, but it can also mean to distribute as in share the dessert (see Figure 3). In the context of team cognition and shared mental models, sharing can imply either knowledge similarity or common knowledge that is held among team members (i.e., everyone knows the same thing) or knowledge distribution in which knowledge is shared by apportioning it to team members according to expertise or role (see Figure 4). In this sense knowledge is complementary, not common with respect to the team. It has been suggested that realistically, team knowledge is not likely completely common or distributed, but rather overlapping with portions that are distributed or common (Cooke et al., 2000; Klimoski & Mohammed, 1994).

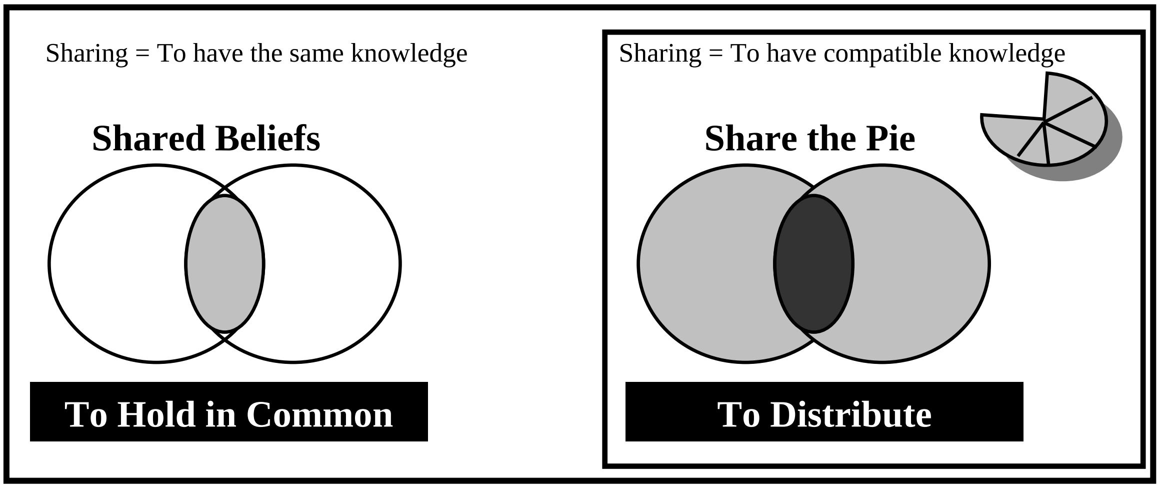

Figure 3. Two connotations of sharing.

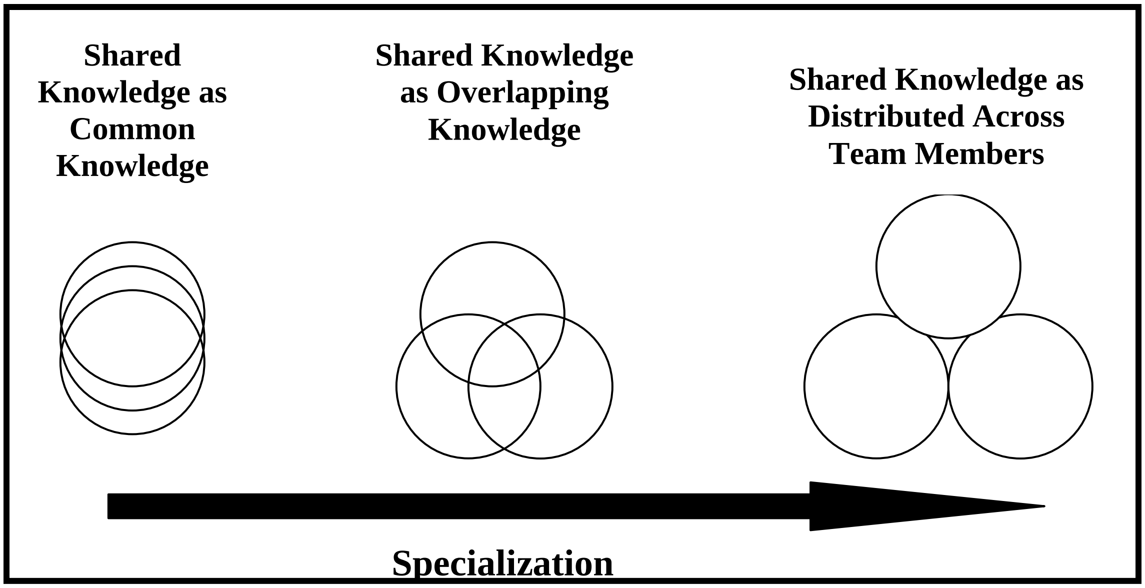

Figure 4. Varieties of shared knowledge. (Circles represent knowledge or mental models held by individual team members.)

Team Situation Awareness

Another input-oriented and traditionally individual-knowledge-focused construct is team situation awareness (TSA). Shared mental models and TSA are theoretically linked in that a shared mental model, or a long-term understanding of the task, team, or equipment on the part of the team is thought to be an important factor in TSA, and specifically in the construction of a team situation model (Cooke, et al., 2001). A situation model is a representation of a state of the world or system that reflects a snapshot of a typically dynamic target. Like shared mental models, much theorizing on TSA has been adopted from theories of individual situation awareness.

The aviation industry has made situation awareness (SA) at the individual level a topic of much interest (Durso & Gronlund, 1999; Endsley, 1995; Fracker, 1989; Orasanu, 1995; Robertson & Endsley, 1995; Wellens, 1993). Endsley (1988) defined situation awareness (SA) as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" (p. 97). SAGAT (Situation Awareness Global Assessment Technique) is a tool that has been utilized to measure team SA in a manner aligned with this definition (Endsley, 1995). SAGAT is administered using a freeze technique, where in the midst of an activity the activity is stopped and specific situation awareness probes, or queries, are answered by the participant. It is challenging to measure SA at the individual level in this manner because, among other reasons, the situation often changes more rapidly than individuals can be queried.

Applied to teams, TSA has been defined as the collection of the SA (shared or unique) of individual team members (Bolstad & Endsley, 2003). To achieved a TSA score utilizing SAGAT Bolstad and Endsley average each of the team member's scores to achieve a TSA score. Bolstad and Endsley (2003) reported results for a study involving U.S. Army officers participating in a simulation exercise. SAGAT, administered using the freeze technique, was used to measure each individual's situation awareness. Composite scores were then created by averaging the individual query score for each SAGAT query. Results indicated that accuracy on queries varied across the roles in the task and was not shared to the degree expected within the group; however, there was no information on performance provided and it is not clear whether these teams required a common understanding of the knowledge tested to do their jobs.

Cooke, DeJoode, Pedersen, Gorman, Connor, & Kiekel (2004) measured TSA in a UAV ground control task similarly using individual SAGAT-like queries. During UAV missions questions were given that asked specific mission related SA questions of each team member. In addition, a consensus measure was used in which the team as a whole was asked to respond after coming to consensus. This consensus procedure was an attempt to avoid aggregation. Unfortunately the consensus process may have been unrepresentative of team process in the actual task, making the team result of questionable relevance to the real task. Although the aggregate-team SA correlated positively with team performance there was concern that the measure was not as pertinent to the team's awareness of the situation, as much as the awareness of the experimental procedure (e.g., anticipating upcoming queries).

Not all investigations of TSA have focused on knowledge. Other research in this arena has indicated that process factors such as early collection and exchange of information, coupled with planning, are linked with high levels of SA (Orasanu, 1995), and furthermore, high levels of SA are linked with high levels of performance.

Summary

Shared mental models and team situation awareness are two key constructs relevant to team cognition from an information processing perspective. Both constructs are input-oriented with regard to the I-P-O framework. That is, the knowledge involved in shared mental models and team situation awareness knowledge requirements are taken as the starting point in decision making or planning and other cognitive activity, leading to a final outcome. Thus the measures tend to capture and represent knowledge of individuals, and not the cognitive process across individuals. Finally, both constructs focus on the individual as the unit of analysis, not the team. This focus is also reflected in the individually-oriented metrics and the aggregation process that transforms multiple individual results into a team result.

Not only are information processing theories of team cognition intimately tied to the measures that are used, but they also have implications for the types of research questions that are asked and the kinds of interventions that are suggested by the results. For instance, the shared mental models and TSA constructs and surrounding theories tend to lead to research questions that center on team member knowledge similarity and the relationship between that similarity and performance. Findings that speak to this similarity may suggest applications for increasing knowledge similarity among team members such as shared displays or cross training, but it is not clear that such applications would be beneficial for highly specialized teams.

Limitations of the Information Processing View Applied to Team Cognition

The application of information processing to team cognition has generated numerous concepts, theories, metrics, and research findings, the perspective, like any perspective it has its limitations. In this section we identify some limitations of this perspective.

Heterogeneous Teams and Division of Labor

The information processing perspective typically takes the individual as its unit of measurement and then aggregates across individuals on the same team in order to approximate the team level. Sometimes aggregation schemes can be quite complex and are based on hypotheses regarding team process behavior (Hinsz 1995; 1999). However, in most cases the aggregation procedure involves averaging or summation (e.g., Langan-Fox, Code, & Langfield-Smith, 2000). There are two assumptions that underlie these basic forms of aggregation.

First underlying the most simple aggregation schemes (i.e., sum, average) is the assumption that all team members are equivalent when it comes to their contribution (i.e., knowledge, skills, abilities) to specific team outcomes. Although this may be true for homogeneous groups that one would find on juries or perhaps in business meetings or in classroom experiments, it is not the case for heterogeneous teams. For instance, emergency response teams bring together individuals with very different skills and backgrounds to comprehensively address the emergency (e.g., weather, terrorism, aviation, HAZMAT, fire safety and others depending on the event). We can find examples of heterogeneous teams in many settings including operating rooms, nuclear power plants, military command and control, and commercial aviation. In fact, Salas et al.'s (1992) definition of "team" stresses the fact that members are interdependent with specific roles or functions to perform. Heterogeneity is also consistent with the division of labor that becomes increasingly necessary with the growing complexity of a task. It is not clear that averaging is appropriate for a team that consists of highly differentiated team members.

Whereas one aspect of this limitation has to do with heterogeneity of team member background, another has to do with the condition that even for homogeneous teams with very similar backgrounds, participation in a decision or problem solution may not be equivalent across team members. Some team members may be more confident or vocal than others. Some may have leadership qualities. Others may simply be having a bad day. Averaging or summing scores across team members assumes that team member inputs are all combined in the same manner. This limitation is thus not one of heterogeneous structure, as is the first limitation, but rather heterogeneous process. Heterogeneous process may be a natural byproduct of heterogeneous background (e.g., an expert in a particular area may contribute more to a decision in that area than another nonexpert team member). On the other hand, heterogeneous process may also be a factor on homogeneous teams simply because there are individual differences in participation style. To summarize, basic aggregation schemes are not appropriate for teams that are heterogeneous in regard to *either* structure (i.e., knowledge) or process.

In general, however, the most basic limitation is that the (linear) aggregate is treated as the whole. This is not appropriate for coupled processes, such as team member interactions, which are usually nonlinear, involving many interactions. For example, taking twelve individuals and telling them each one word of a meaningful twelve-word sentence, having them individually think about each word and then adding together their reports of these thoughts (not necessarily in the order of the original sentence), does not faithfully reproduce the meaning of the sentence (cf. James, 1890, p. 160). In order to accomplish this, the twelve must interact. A lack of incorporating interaction similarly limits the aggregation model for studying complex systems such as those in team environments.

Scalability Issues

As previously mentioned, the information processing approach tends to evaluate team cognition in terms of knowledge similarity. Teams with members who are on the same page in regard to taskwork and teamwork knowledge or who hold common mental models or a shared understanding of the situation are predicted to be more effective. However, the “common knowledge” criterion seems to break down as teams grow to sizes not typically reflected in the experimental work on team cognition. Not only does the “common knowledge” notion lose its meaning for heterogeneous teams, but it also is questionable as teams grow from three-person teams to the hundreds found in some military command-and-control environments. For these very large teams, is “common knowledge” still a reasonable objective? Pushed to its extreme we see decision making biases such as “group think” (Janis, 1972) that result when too much is shared. It may also be that too much common knowledge on a very large team might lead to a type of “cognitive loafing” that parallels “social loafing” (Karau & Williams, 2001). In this latter case, several individuals may relinquish their participation in decision making because they perceive that their input is redundant and unneeded.

Admittedly exclusive reliance on the “common knowledge” criterion creates a straw man of the information processing perspective. However, the concepts of similarity or sharedness *are* the basis of most current research on team cognition, including shared mental models and team situation awareness, even if the “common knowledge” criterion makes little sense as teams grow in size.

Decentralized/Self-Organizing Teams

The sheer volume of cognitive activity in modern work systems has tended to make centralized and hierarchical teams slow and unresponsive to rapid change. These considerations are linked to the elimination of a single dominant centralized or executive controlling mechanism in teams, which oversees all aspects of operations, and a growing need for decentralized and self-organizing teams. A limitation of the information processing view on team cognition is rooted in the emergence of decentralized and self-organizing teams in military, business, and other socio-technical environments (Franz, 2004; Appelbaum, 1997). Specifically, this type of team structure exhibits a high degree of functional, and dynamical, organization rather than assigned sets of routines. Team cognition in decentralized and self-organizing teams leads to limitations for the information processing view that can be described as two related computational problems when dealing with complex systems: first, the problem of reduced degrees of freedom and second, the problem of the delegating action in a highly complex environment.

As a computational problem delegating actions in a many-element system by a central controlling device (e.g., a shared mental model) can quickly become infeasible. In terms of computational complexity, tracking such a state space grows as nk^2, where n are subsystems and k are system elements--in this case, team members and their tasks. Clearly this state space grows exponentially with the number of elements in the system, proportional to the number of subsystems controlling them. The second computational problem is how to achieve a reduction in the number of variables to be tracked and controlled. The degrees of freedom problem introduced by Bernstein (1967) involves a reduction in the number of variables (degrees of freedom) that need to be controlled in order to perform coordinated action. A functional or ecological description accomplishes this by defining systems (and subsystems) by the functions they serve. For our purposes, a team consisting of n team members each responsible for k elements, can be reduced to a low dimensional parameter if we typify the supposed computational problem as one of mutual *adjustment,* rather than executive *control*. In other words, integration is central rather than differentiation. A parameter relevant to team cognition, for example, might be a variable that captures coordination as opposed to tracking the nk^2 elements individually.

Statics Versus Dynamics in Team Cognition

Essentially a static (or static equilibrium) is a balance of forces, such that all forces are in a constant relation to one another and there is no dynamic component. Psychology does not deal with physical forces however, but rather with information. In terms of team cognition then, by narrowing in on knowledge structure as opposed to process, IP has become preoccupied with the acquisition of a static (knowledge) distribution of information across team members. In other words, what should be the constant and unchanging relations among team member knowledge for enhancing process and performance (Figure 5)?

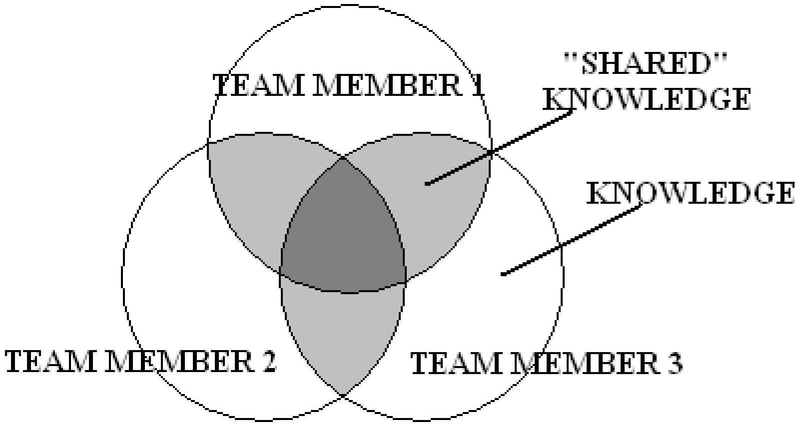

Figure 5. A static distribution of knowledge, in this case situation awareness requirements (adapted from Endsley & Jones, 1997).

However, in practice, teams must often go beyond a static model of the task in order to complete the task. For example, a UAV team can photograph targets even when one of several lines of crucial communication is cut (Gorman, Cooke, Pedersen, Connor, & DeJoode, 2005). Thus the function can be identical even when the circumstances of the task are far from ordinary; that is, it can be *adaptive*. In light of this, team cognition may involve *more* than just a static distribution of knowledge, namely novel (or self-organized) interaction dynamics that are specific to novel task conditions. Though a focus on team process over structure is a step in the right direction, IP theory does not provide us with the analytical tools to proactively address this sort of adaptive behavior on the part of the team. The issue of team adaptation to novel task conditions will be revisited in our discussion of measuring TSA from an ecological perspective.

Empirical Evidence

Finally, based on the information processing perspective, predictions that can be made regarding the relationship between team cognition and team performance appear to vary greatly with the task. In particular, the accuracy and intrateam similarity of knowledge is thought to be predictive of team performance. In addition, as teams gain experience it has been proposed that degree of overlap among shared mental models increases.

However, some researchers failed to find convergence among mental models over time even though they did find general support for the relationship between knowledge and performance (Mathieu et al., 2000). While others (Levesque, et al., 2001) have found that there is divergence among team members in terms of knowledge over time. This pattern might be expected for teams with a high division of labor, while the former would not.

Numerous studies have reported correlations between team cognition and team performance (Hinsz, Tindale, & Vollrath, 1997; Mathieu, et al., 2000; Stout, et al., 1999), but others have found no relation. For instance manipulations affecting the process of knowledge sharing impacted the knowledge or mental model, but did not impact team performance (Cooke, et al., 2003; Cooke, et al., 2004).

These mixed results are not surprising given the complexities involved in team research. Null results could arise for any number of reasons (e.g., low statistical power, insensitive measures) and results in the unexpected direction often arise from task differences. However, it is also possible that the input-oriented constructs, central to the information processing view of team cognition, only account for a small portion of variance in team cognition.

An Ecological Perspective

This section will extend the ecological perspective described earlier to team cognition. It is proposed that the ecological approach to team cognition addresses many of the limitations of the information processing approach. This discussion of the ecological perspective on team cognition focuses on team coordination and team situation awareness.

Whereas the information processing perspective considers the locus of team cognition to be within the individual team member, the ecological approach views team cognition as an emergent feature that results from a history of interactions between team members. Thus, according to this view, measuring any aspect of the team independent of the team in action does not directly address team cognition. Operational definitions, therefore, need to be developed at the level of team activity, and specifically team member interaction. For example, how do we measure team members' communication and how do we measure changes in patterns of interaction over time? Additionally, how do team members act as sources of information for other team members? Thus, the ecological perspective puts the focus on team activity and interaction dynamics rather than individual knowledge, and as a result raises a different set of research questions with different implications for theory and practice.

Team Coordination

What does it mean to consider team interaction as the fundamental unit of team cognition? Consider a General Problem Solver with the relatively simple goal of reaching a destination (Simon, 1981). Consider, as Simon did, an ant traversing a beach in order to reach a destination. The complexity of the ant's path is not the result of complex cognition on the ant's part, but rather is rooted in the complexity of the task environment that the ant is coupled to (i.e., the undulations of the beach). Thus, the complexity of the ant's behavior lies at the intersection between the ant and the beach. We might say that the ant's behavior is *coordinated* with the layout of the beach. If we consider only the ant's "knowledge" independent of its coupling with the structure of the beach we are left with an incomplete description of its behavior. A similar problem arises when we do not take team member-team member couplings to be the irreducible elements of team cognition. This is precisely where an ecological approach becomes most useful.

It is a relatively simple matter to demonstrate the utility of focusing on interaction dynamics in the examination of team cognition. We have conducted a series of experiments on simulated unmanned aerial vehicle operations (Cooke, et al., 2004). Consider, for example, a sequence of observations made on the transcribed utterances of a *single* team member, without reference to the utterances of the other team members:

1) Okay, I am headed back on course now.

2) 2.5.

3) Yeah, we have now changed course to S-STE.

4) Go ahead.

5) *Roger that.*

This apparently incoherent sequence of utterances is similar to listening to one side of a telephone conversation. However, by embedding this sequence in the utterances from the other team members this sequence becomes meaningful and goal-directed; that is, the amount of "randomness" in this conversation can be reduced by viewing it in light of surrounding constraints. In this case, the utterances are *coordinated* with the structure of the conversation:

> *1) Okay, I am headed back on course now.*
>
> *What's the radius for PRK?*
>
> *2) 2.5.*
>
> *OK. Your altitude seems really low.*
>
> *3) Yeah, we have now changed course to S-STE.*

AVO I have some more information… Would you let me know when you are ready for that information?

4) *Go ahead.*

Immediately after S-STE, you will need to dive down to max. 1000 altitude. Does that make sense?

5) *Roger that.*

While the explanatory utility of embedding action in context may seem obvious, we have found it seldom used in team cognition applications. As noted above, this is not surprising given the computational complexity involved in studying the embedded behavior of teams from an IP perspective. Thus we have made efforts to develop low dimensional (relative to the number of team members) ecological measures of team cognition; that is, measures taken at the team member-team member and team member-environment level of analysis.

In our most recent round of UAV experiments, we have measured the *"pushing and pulling"* of information elements specific to the timing of navigation and photographing of ground targets by a team of three UAV team members, a pilot, navigator, and photographer. Three information elements were identified for this purpose: t_I – navigation to pilot information, t_N – back-and-forth pilot to photography negotiation, and t_F – photography to "all" feedback. Essentially these three elements are interrelated over time; that is, they may overlap reconnaissance targets. However, a more general question is whether or not these elements serve as mutual informational constraints on team cognition over time; that is, can they be integrated into a measure of coordination?

We developed a local optimal model (LOM) that relates each of the information elements to each other (Figure 6). In the model, the onset of navigation to pilot information (I) is ideally the first element in the sequence, followed by pilot to photography negotiation (N), which culminates with feedback (F) from the photographer. The slope of the line relating the onset times F – I to the times F – N gives a measure with two qualitative states separated by a transition point at F – I = F – N = 1. Deviations less than one indicate poor coordination relative to the LOM, while deviations greater than one indicate good coordination relative to the LOM. Specifically, high scores (>1) indicate a high degree of frontloading in terms of route planning, while low scores (<1) indicate the absence of any such frontloading. These scores can be further modeled using time-scaling techniques (Gorman, 2005) in order to gauge the amount of randomness vs. development of constraint in terms of deviations from the nominal strategic process embodied in the LOM. These models also provide more detailed information concerning various "styles" of coordination by teams treated differently in an experiment. For example, these models can tell us if teams in one condition should develop stricter, mean-reverting coordination "boundaries" as compared to teams in another condition.

Team Situation Awareness

In general system-theoretic terminology (von Bertalanffy, 1969), the perturbation of an element of a system will have an effect of on other elements of the system. In terms of coordination dynamics this means that perturbation of a team member, or team members, can push the trajectory of the team as a whole off its course. In contrast to the more traditional information processing knowledge elicitation methods, we have been exploring these concepts as

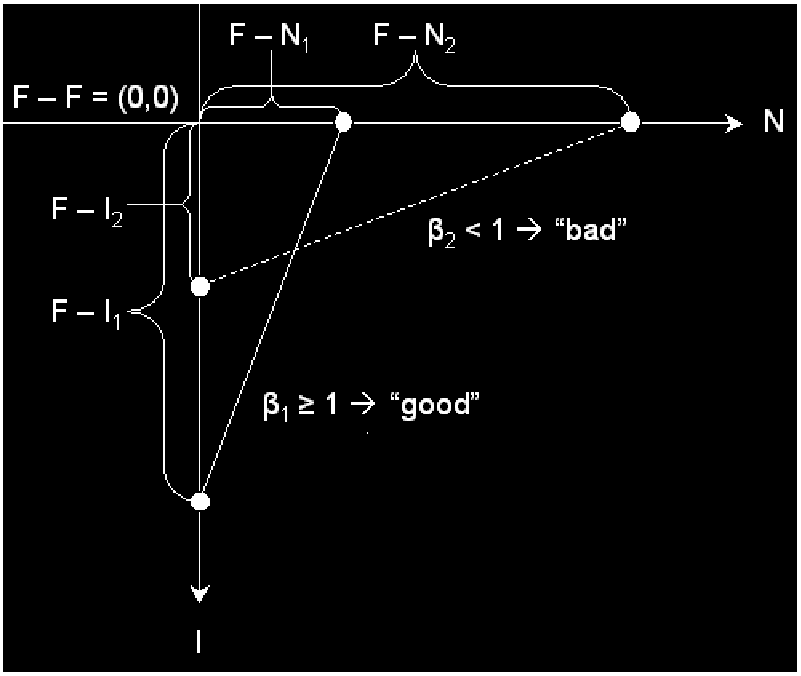

Figure 6. The slope relating the onset of elements I, N, and F as a measure of coordination.

a way to measure TSA relative to experimental perturbation (or "roadblock") that pushes coordination dynamics away from its mean state. A well-placed (or from a team's perspective, badly placed) roadblock can displace the trajectory of team coordination, such that teams will require some time before reacquiring their stable trajectory (Figure 7). In this case, the timing of three information elements involving information, negotiation, and feedback that normally approximate a line when plotted against each other is pushed away from this trajectory by a TSA roadblock; recovery time is an index of team coordination stability.

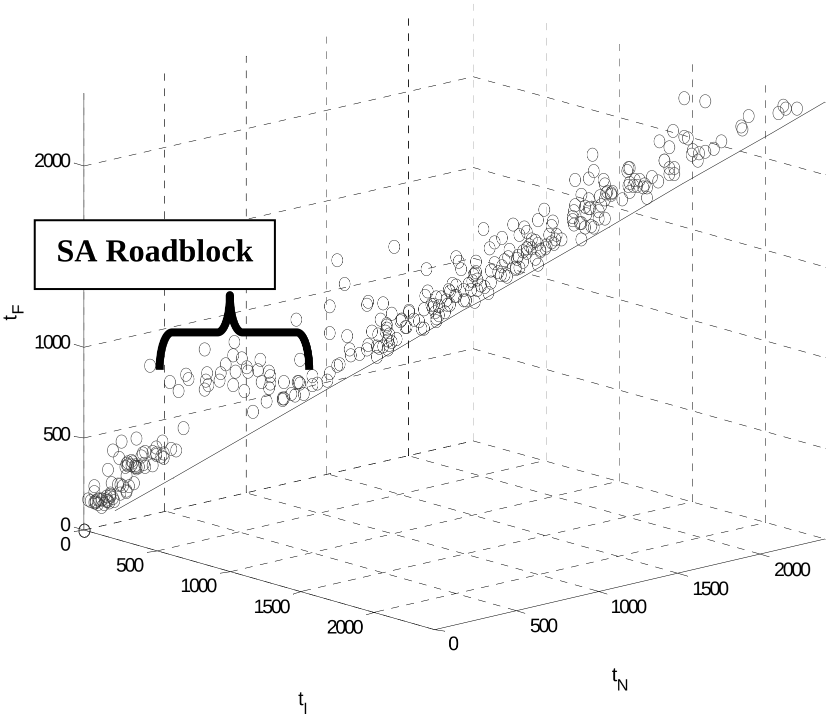

Figure 7. Team coordination dynamics inresponse to a situation awareness “roadblock.”

Rooted in ecological psychology, firsthand perception (Reed, 1996) is the notion that given a division of labor, each team member will experience the roadblock in a different way. For example, a pilot and a photographer will perceive a sudden drop in altitude in different ways, depending on their role in the team. In the first case, this can alter the pilot’s experience of control and in the second the photographer’s judgment of camera zoom settings. If these two share their unique perspectives of the roadblock with each other, then each now has an additional perception of the roadblock, albeit secondhand, and may facilitate a coordinated perception of the unwanted perturbation. Similarly, assuming that the various unique perspectives are coordinated, a team may be able to enact a solution that overcomes a roadblock by responding as a coordinated whole. It is crucial, however, to point out that this sort of team-level awareness is not purely introspective or knowledge-based, it is predicated on adaptation via team member interaction. Further, situational roadblocks, whether experimentally introduced or observed in reports of events (e.g., 9/11 report), should be embodied in situational exigencies that are extrinsic to the normal course of team operations. Thus, any sort of unusual event that impacts the functional synergy of a team may be ripe for measuring team SA.

In our most recent set of experiments we began introducing three types of roadblocks to teams: unusual changes to the task environment (e.g., *ad hoc* targets), unforeseen UAV route constraints (e.g., enemy activity), and unpredictable cutting of communication links (e.g., navigator to pilot). These were introduced in order to see if teams noticed and if so, what they did about it. These roadblocks were also designed so that if not successfully addressed, the team's performance would be impaired; that is, they would not be able to take a photo of their target. The CAST (Coordinated Assessment of Situation by Teams; Gorman, et al., 2005) measure was taken by monitoring team communication and action during exposure to the roadblock at three levels: 1.) independent/firsthand perception, 2.) secondhand/coordinated perception, and 3.) coordinated action (Figure 8).

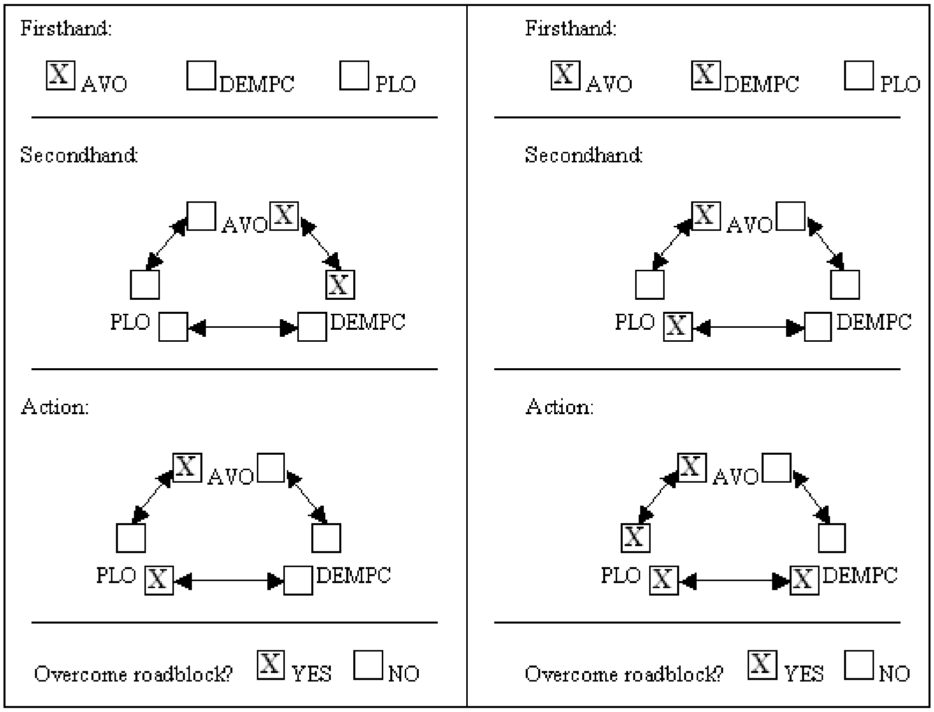

Figure 8. The CAST TSA instrument.

For analysis, each roadblock event was characterized as a signal detection trial. Specifically, some subset of check boxes (or "links"; Figure 8) was necessary (signal) and some boxes were not (noise) in order to accurately identify and deal with specific roadblocks. These formed a set of "normative vectors" that corresponded to the optimal solutions of the various roadblocks. Hits and false alarms, proportions of necessary links vs. unnecessary links, respectively, were computed for each roadblock against the normative vectors. Here we present results calculated across all three components of the CAST instrument.

Figure 9 shows the average sensitivity to roadblocks (up and left diagonal distance from the dashed line) of teams before and after an experimental manipulation. The experimental manipulation was a retention interval (3-11 weeks) crossed with the familiarity of team members upon returning from the retention interval (either they returned with the same team members or a new set of team members). Our results suggest that teams had similar sensitivity to the roadblocks prior to the experimental manipulation. Post-manipulation however, there were differences in team SA involving both accuracy of response and inefficiency, or over-sharing, during the response. We have argued that this sort of "over-sharing" can be associated with a shared mental model, and may be maladaptive when TSA is gauged as an adaptive response to novel task conditions (Gorman, et al., 2005). Specifically, high hit rate coupled with low false alarm rate is indicative of the right information getting to the right person at the right time, and no more than this, in light of an unusual situation. This was most common in the unfamiliar, long retention interval teams. This result may lend itself to further hypotheses, including the need for team-member turnover, especially over longer retention intervals, in order to facilitate good team SA processes rather than attempting to instill a shared mental model.

Conclusions

The framework within which we conceptualize team cognition has important implications for theory building, measurement, training and assessment and design relevant to team cognition. We conclude with examples of such implications.

For theory, the implications should be quite clear, yet a simple analogy is made. The questions and analysis of information processing and ecological theories of team cognition can resemble, say, the analysis of water which may take two levels, respectively. Should we analyze H_20 or the flow of this substance H_20? On one level we would analyze the combining of the parts H and O, on another how the flow (parts not withstanding) pervades over various strata. In

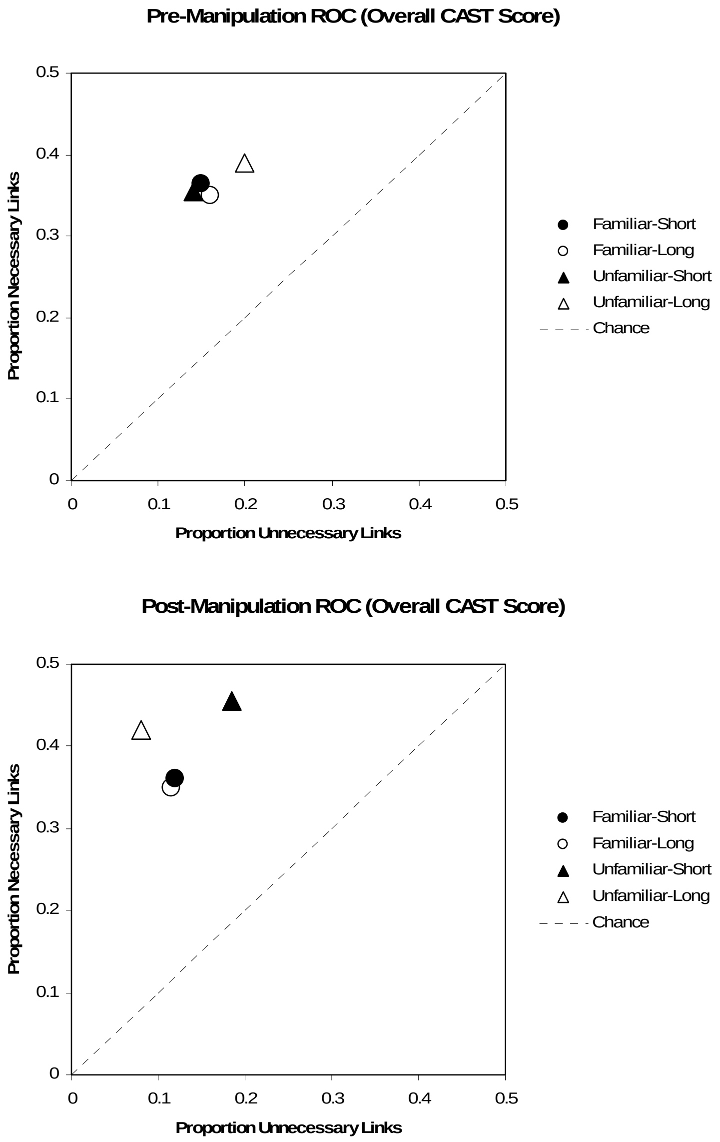

Figure 9. Mean pre-manipulation TSA (top); mean post-manipulation TSA (bottom); team sensitivity to roadblock manipulation can be interpreted as proximity to the upper left corner of the graphs.

a like manner, the study of team cognition can be reduced to an analysis of parts, or alternatively how it flows over various surfaces, or situations. In our research we have found the latter to be more beneficial to understanding the cognitive abilities of teams. Notwithstanding this result, these two perspectives formulate entirely different questions (not to mention levels of analysis) of team cognition. Two are discussed next. The first is the IP perspective. Namely, questions are addressed at the level of the individual, and then these are summed to the team level. The second is the ecological view in which questions are addressed to the interaction, and the level of the individual does not come into play. Each approach may be capable of good or harm, but nevertheless between these alternatives the scientist must choose, and theories (and thus measures) will obtain at a like scaling.   In short, the scientist must choose between analyzing the elements (IP) or the flow (EP).

We have also provided some examples of measures that have been inspired by ecological views of team cognition. In general, the ecological focus is on measuring communication and interaction as opposed to static and situational knowledge. As always the perspective prescribes the measure. For instance, under the ecological perspective we have been inspired to measure coordination, a team phenomenon that has received minimal attention under the information processing perspective. The perspective also prescribes *how* to measure. The example of team situation awareness measures is relevant here in that query-based measures such as SAGAT (Bolstad & Endsley, 2003) are much different than our interaction-based measure, CAST (Gorman, et al., 2005).

The perspective that one takes on team cognition also has interesting implications for training and design.   How should we train or design for teams to enhance team cognition and therefore, team performance? A shared mental model view advocates training or design that facilitates the convergence of knowledge. For instance, cross training in which team members are indoctrinated into the tasks and roles of other team members has been thought to induce shared mental models (Cannon-Bowers, Salas, Blickensderfer, & Bowers, 1998). Likewise shared or common displays in which team members can view information used primarily by other team members might also promote knowledge sharing (Endsley, 1988). Alternatively, an ecological perspective would focus more on the interaction. Team performance would be improved according to this perspective by focusing on communication, interaction, or coordination variation *in situ*. In addition, perturbations to coordination may positively affect training, so instead of cross training each team member, members assume the same team role but are mixed with new team members for some variety in coordination.

In summary, the ecological approach to team cognition offers an alternative way of thinking about team cognition that has unique implications for theory, measurement, training, and design. These ecological ideas open up new possibilities for research and development and are open to revision. Even in this early stage however, the ecological perspective on team cognition illustrates the practical benefits of having one or even more, good theories to guide improvements in team performance.

References

Appelbaum, S. H. (1997). Socio-technical systems theory: An intervention strategy for organizational development. *Management Decision*, 35, 452-463.

Bernstein, N. A. (1967). *The co-ordination and regulation of movements*. Oxford: Pergamon Press.

Blickensderfer, E., Cannon-Bowers, J. A., & Salas, E. (1997). Training teams to self-correct: An empirical evaluation. Paper presented at the Meeting of the Society for Industrial and Organizational Psychology, St. Louis, MO (April 10-13).

Bolstad, C. A. and Endsley, M. R. (2003). Measuring shared and team situational awareness in the Army's future objective force. In *Proceedings of the Human Factors and Ergonomics Society 47th Annual Meeting* (pp. 369-373). Santa Monica, CA: Human Factors and Ergonomics Society.

Brannick, M. T., Prince, A., Prince, C., and Salas, E. (1995). The measurement of team process. *Human Factors, 37*, 641-651.

Cannon-Bowers, J. A., Salas, E., Blickensderfer, E., & Bowers, C. A. (1998). The impact of cross-training and workload on team functioning: A replication and extension of initial findings. *Human Factors, 40*, 92-101.

Clark, H. & Brennan, S. E. (1991). Grounding in communication. In Resnick L B, Levine J. and Teasley (Eds.), *Socially Shared Cognition*. American Psychology Association.

CNN (2005). *Katrina State of Emergency*. Kansas City, KS: Andrew McMeel Publishing.

Collyer, S. C. & Malecki, G. S. (1998). Tactical decision making under stress: History and overview. In J.A. Cannon-Bowers & E. Salas (Eds.), *Decision Making Under Stress:*

Implications for Individual and Team Training (pp. 3-15), Washington, DC: American Psychological Association.

Converse, S., Cannon-Bowers, J. A., & Salas, E. (1991). Team member shared mental models. *Proceedings of the 35th Human Factors Society Annual Meeting*, (pp.1417-21). Santa Monica, CA: Human Factors and Ergonomics Society.

Cooke, N. J., DeJoode, J. A., Pedersen, H. K., Gorman, J. C., Connor, O. O., & Kiekel, P. A. (2004). The Role of Individual and Team Cognition in Uninhabited Air Vehicle Command-and-Control. Technical Report for AFOSR Grant Nos. F49620-01-1-0261and F49620-03-1-0024.

Cooke, N. J., Kiekel, P.A., Salas, E., Stout, R.J., Bowers, C., Cannon-Bowers, J. (2003). Measuring Team Knowledge: A Window to the Cognitive Underpinnings of Team Performance. *Group Dynamics: Theory, Research and Practice, 7*, 179-199.

Cooke, N. J., Stout, R., and Salas, E. (2001). A knowledge elicitation approach to the measurement of team situation awareness. In M. McNeese, E. Salas, and M. R. Endsley (Eds.), *New Trends in Cooperative Activities: Understanding System Dynamics in Complex Environments* (pp. 114-139). Santa Monica, CA: Human Factors and Ergonomics Society.

Cooke, N. J., Salas, E., Cannon-Bowers, J. A., & Stout, R. (2000). Measuring team knowledge. *Human Factors*, *42*, 151-173.

Durso, F. T., Nickerson, R., Schvaneveldt, R., Dumais, S., Chi, M., & Lindsay, S. (Eds., 1999), *The Handbook of Applied Cognition*, UK: Wiley.

Durso, F. D., & Gronlund, S. D. (1999). Situation awareness. F. T. Durso, R. Nickerson, R. Schvaneveldt, S. Dumais, M. Chi, & S. Lindsay (Eds.), *The Handbook of Applied Cognition*, Wiley, pp. 283-314.

Endsley, M. R. (1995). Measurement of situation awareness in dynamic systems. *Human Factors*, *37*, 65-84.

Endsley, M. R. (1988). Design and evaluation for situation awareness. In *Proceedings of the Human Factors Society 32nd Annual Meeting* (pp. 97-101). Santa Monica, CA: The Human Factors and Ergonomics Society.

Entin, E. E. and Serfaty, D. (1999). Adaptive team coordination. *Human Factors*, *41*, 312-325.

Eysenck, M. W. and Keane, M. T. (2000). *Cognitive psychology: A student's handbook*. Philadelphia: Taylor & Francis Inc.

Fracker, M.L. (1989). Attention allocation in situation awareness. In *Proceedings of the Human Factors Society 33rd Annual Meeting* (pp. 1396-1400). Santa Monica, CA: The Human Factors and Ergonomics Society.

Franz, G. F. (2004). *Decentralized command and control of high-tech forces: Aligning practice with doctrine at the operational level*. Newport, RI: Naval War College.

Gibson (1966). *The senses considered as perceptual systems*. Boston: Houghton-Mifflin.

Gibson (1979). *The ecological approach to visual perception*. Boston: Houghton-Mifflin.

Gorman, J. C. (2005). The concept of long memory in assessing the global effects of augmented team cognition. *Proceedings of HCI-International*.

Gorman, J. C., Cooke, N. J., Pedersen, H. K., Connor, O.O., & DeJoode, J. A. (2005). Coordinated awareness of situation by teams (CAST): Measuring team situation awareness of a communication glitch. *Proceedings of the Human Factors and Ergonomics Society 49th Annual Meeting*, Orlando, FL.

Hackman, J. R. (1987). The design of work teams. In J. W. Lorsch (Ed.), *Handbook of Organizational Behavior* (pp. 315-342). Englewook Cliffs, NJ: Prentice Hall.

Heft, H. (2001). *Ecological Psychology in Context.* Mahwah, NJ: Erlbaum.

Hinsz, V. B. (1995). Group and individual decision making for task performance goals: Processes in the establishment of goals in groups. *Journal of Applied Social Psychology, 25*, 353-370.

Hinsz, V. B. (1999). Group decision making with responses of a quantitative nature: The theory of social decision schemes for quantities. *Organizational Behavior and Human Decision Processes, 80*, 28-49.

Hinsz, V., Tindale, R. S., & Vollrath, D. A. (1997). The emerging conceptualization of groups as information processors. *Psychological Bulletin, 121*, 43-64.

James, W. (1890). *The principles of psychology vol. 1*. Dover USA (1950) reprint.

James, W. (1904). Does 'consciousness' exist? *The Journal of Philosophy, Psychology, and Scientific Methods*, 1, 477-491.

Janis, I.L. (1972). *Victims of groupthink: A psychological study of foreign-policy decisions and fiascoes*. Boston: Houghton Mifflin.

Karau, S. J., & Williams, K. D. (2001). Understanding individual motivation in groups: The collective effort model. In M. E. Turner (Ed.), *Groups at work: Theory and research* (pp. 113-141). Mahwah, NJ: Erlbaum.

Klimoski, R. and Mohammed, S. (1994). Team mental model: Construct or metaphor? *Journal of Management, 20*, 403-437.

Lachman, R., Lachman, J. L., & Butterfield, E. C. (1979). *Cognitive Psychology and Information Processing: An Introduction.* Hillsdale, NJ: Erlbaum.

Langan-Fox, J., Code, S., & Langfield-Smith, K. (2000). Team mental models: Techniques, Methods, and Analytic Approaches. *Human Factors, 42*, 242-271.

Levesque, L. L., Wilson, J. M., & Wholey, D. R. (2001). Cognitive divergence and shared mental models in software development project teams. *Journal of Organization Behavior, 22,* 135–144.

Liang, D. W., Moreland, R. L., and Argote, L. (1995). Group versus individual training and group performance: The mediating role of transactive memory. *Personality and Social Psychology Bulletin, 21*, 384-393.

Mathieu, J. E., Goodwin, G. F., Heffner, T. S., Salas, E., and Cannon-Bowers, J. A. (2000). The influence of shared mental models on team process and performance. *Journal of Applied Psychology, 85*, 273-283.

Mohammed, S. and Dumville, B. C. (2001). Team mental models in a team knowledge framework: Expanding theory and measurement across discipline boundaries. *Journal of Organizational Behavior, 22*, 89-106.

Moreland, R. L. (1999). Transactive memory: Learning who knows what in work groups and organizations. In L. Thompson, J. Levine, & D. Messick (Eds.), *Shared Cognition in Organizations: The Management of Knowledge* (pp. 3-31). Mahwah, NJ: Lawrence Erlbaum Associates.

Orasanu, J. M. (1995). Evaluating team situation awareness through communication. In D. J. Garland & M. R. Endsley (Eds.), *Proceedings of an international conference on experiment analysis and measurement of situation awareness* (pp. 283–288). Daytona Beach, FL: Embry–Riddle Aeronautical University Press.

Reed (1996). *The necessity of experience*. London: Yale University Press.

Rentsch, J. R. and Klimoski, R. J. (2001). Why do ‘great minds’ think alike?: Antecedents of team member schema agreement. *Journal of Organizational Behavior, 22*, 107-120.

Rentsch, J. R. & Hall, R. J. (1994). Members of great teams think alike: A model of team effectiveness and schema similarity among team members. In M. M. Beyerlein & D. A. Johnson (Eds.), *Advances in interdisciplinary studies of work teams: Theories of self-managing work teams* (Vol. 1, pp. 223-262). Greenwich, CT: JAI Press.

Rowe, A. L. and Cooke, N.J. (1995). Measuring mental models: Choosing the right tools for the right job. *Human Resource Quarterly;* Fall 1995; 6, 3; ABI/INFORM Global.

Rowe, A. L. (1994). *Mental models of physical systems. Examining the relationship between knowing and doing.* Unpublished doctoral dissertation, Rice University, Houston, TX.

Salas, E. Dickinson, T. L., Converse, S. A., & Tannenbaum, S. I. (1992). Toward an understanding of team performance and training. In R. W. Swezey & E. Salas (Eds.), *Teams: Their training and performance* (pp. 3-29). Norwood, NJ: Ablex.

Simon, H. A. (1981). *The sciences of the artificial*. Cambridge, MA: MIT Press.

Smith-Jentsch, K. A., Campbell, G. E., Milanovich, D. M., & Reynolds, A. M. (2001). Measuring teamwork mental models to support training needs assessment, development, and evaluation: two empirical studies. *Journal of Organizational Behavior, 22*, 179-194.

Stout, R.J., Cannon-Bowers, J.A., Salas, E., and Milanovich, D.M. (1999). Planning, shared mental models, and coordinated performance: An empirical link is established. *Human Factors, 41*, 61-71.

Vaughan, D. (1996). *The Challenger Launch Decision: Risky Technology, Culture, and Deviance at NASA.* Chicago, IL: The University of Chicago Press.

Von Bertalanffy, L. (1969). *General system theory*. New York: George Braziller.