

# Toward an Understanding of Macrocognition in Teams: Predicting Processes in Complex Collaborative Contexts

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**Objective:** This article presents a model for predicting complex collaborative processes as they arise in one-of-a-kind problem-solving situations to predict performance outcomes. The goal is to outline a set of key processes and their interrelationship and to describe how these can be used to predict collaboration processes embedded within problem-solving contexts. **Background:** Teams are increasingly called upon to address complex problem-solving tasks in novel situations. This represents a domain of performance that to date has been underrepresented in the research literature. **Method:** Multidisciplinary theoretical and empirical literature relating to knowledge work in teams is synthesized. **Results:** A set of propositions developed to guide research into how teams externalize cognition and build knowledge in service of problem solving is presented. First, a brief overview of macrocognition in teams is provided to distinguish the present work from other views of team cognition. Second, a description of the foundational theoretical concepts driving the theory of macrocognition in teams presented here is provided. Third, a set of propositions described within the context of a model of macrocognition in teams is forwarded. **Conclusion:** The theoretical framework described in this article provides a set of empirically testable propositions that can ultimately guide practitioners in efforts to support macrocognition in teams. **Application:** A theory of macrocognition in teams can provide guidance for the development of training interventions and the design of collaborative tools to facilitate knowledge-based performance in teams.

## INTRODUCTION

Teams across a variety of domains, including the government, industry, and the military, frequently engage in complex performance episodes arising from unique situations requiring the coordination of diverse sets of expertise. Understanding the nature of this collaborative activity is essential to design successful socio-technical systems and to train personnel to be effective team players in these often high-stakes situations. Although much is known about the components of, and conditions for, effective teamwork (e.g., Kozlowski & Ilgen, 2006), theory and research to date have focused primarily on behavioral coordination in teams, that is, on

an understanding of how teams effectively sequence and integrate their actions over time. Although this is no doubt a critical type of team performance, it is qualitatively different from the type of collaborative performance occurring in complex one-of-a-kind situations.

The purpose of this article is to present a model of collaborative processes in complex one-of-a-kind problem-solving situations and their relationships with performance outcomes. This model is based in earlier frameworks of *macrocognition in teams* (see Fiore, Smith-Jentsch, Salas, Warner, & Letsky, in press; Fiore, Rosen, Salas, Burke, & Jentsch, 2008; Letsky, Warner, Fiore, Rosen, & Salas, 2007; Warner, Letsky, & Cowen, 2005), which describes how teams move

between internalization and externalization of cognition and build knowledge in service of problem solving. To this end, we address four specific goals derived to illustrate the foundations of our model. First, a brief overview of macrocognition in teams is provided to distinguish it from current views of team cognition. Second, a cross-disciplinary review of major conceptual drivers of team collaboration is provided, and key concepts from this review are integrated with the concept of knowledge building in teams. Third, a theoretical model of macrocognition in teams is described. Fourth, a set of initial propositions resulting from this model is presented.

### **An Overview of Macrocognition in Teams**

This section provides a brief review of the team cognition literature and the development of the concept of macrocognition as it applies to teams. In recent decades, team cognition has emerged as an overarching perspective from which to develop theories of team performance (Hinsz, Tindale, & Vollrath, 1997; Salas & Fiore, 2004). It is taken to be the interaction between intraindividual and interindividual cognitive processes (Fiore & Schooler, 2004) and parallels the distributed-cognition literature (e.g., Hutchins, 1995) in its application of the fundamental conceptual tools of cognitive science to a unit of analysis larger than the individual. Specifically, team cognition takes the view that knowledge representations and transformations on those representations (i.e., cognitive processing) occur not only within an individual mind but also between individuals and between individuals and the environment.

However, to date, the primary emphasis in team cognition research has been what Rasmussen (1983) referred to as rule-based performance, described as the enactment of relatively well-known procedures in fairly stable environments. For example, aircrews are likely one of the most well-researched units from a team cognition perspective, and much is known about how knowledge inputs (i.e., shared mental models) and team cognitive processing (i.e., communication) affect the performance of these teams (e.g., Mathieu, Heffner, Goodwin, Salas, & Cannon-Bowers, 2000). Although there are some exceptions, the

performance of aircrews is typically highly routinized in that they train for most of the situations they will ever encounter. In contrast to this, knowledge-based performance is characterized by the generation of new rules for a novel situation.

*Macrocognition in teams* has recently been used to refer to this type of knowledge-based performance or complex collaborative cognition (see Letsky, Warner, Fiore, & Smith, 2008). The general view of macrocognition (e.g., Cacciabue & Hollnagel, 1995; G. Klein et al., 2003; Schraagen, Klein, & Hoffman, 2008) originated in research on naturalistic decision making and has been used to describe a broad variety of cognitive processes in natural settings (e.g., problem solving, decision making, planning, sensemaking, causal reasoning). This was contrasted with “microcognitive” processes, which were argued to arise primarily in laboratory studies (see Helander, 2006; Hutton, Miller, & Thorsden, 2003; G. Klein et al., 2003). Additionally, macrocognition emphasizes expertise “out of context,” that is, skilled people going beyond routine methods of performance and generating new knowledge and performance processes (e.g., a physician dealing with a rare disease; see Hoffman, 2007; Rasmussen, 1983; Schraagen, Militello, Ormerod, & Lipshitz, 2008).

Although team cognition theory does include the construct “knowledge” in shared mental models and related forms of overlapping semantic structures (e.g., Cannon-Bowers, Salas, & Converse, 1993; Marks, Zaccaro, & Mathieu, 2000; Mathieu et al., 2000; Mathieu, Heffner, Goodwin, Cannon-Bowers, & Salas, 2005; Rentsch & Davenport, 2006; Smith-Jentsch, 2005), these constructs are thought of in relation to supporting the execution of previously learned task procedures in familiar environments. Therefore, macrocognition in team is distinct from more general team cognition theory in that it emphasizes “the generation or adaptation of rules to novel situations . . . [for] understanding the process by which individuals and teams generate new knowledge for addressing unique problems” (Rosen, Fiore, Salas, Letsky, & Warner, 2008, p. 15). More specifically, we define macrocognition in teams as the process of transforming internalized knowledge into

externalized team knowledge through individual and team knowledge-building processes (Fiore, Smith-Jentsch, Salas, Warner, & Letsky, 2010). Consequently, macrocognition in teams is considered a particular instance of the more general area of team cognition research. A model of this process will be specified in later sections. Next, several distinct areas of scientific inquiry contributing to an understanding of this phenomenon are reviewed.

### THEORETICAL FOUNDATION FOR MACROCOGNITION IN TEAMS

This section provides a review of the foundational theoretical drivers of macrocognition in teams. The model presented in the following section is a synthesis of theoretical approaches developed across scientific research traditions investigating collaboration and draws on four general categories of research: externalized cognition, team cognition, group communication and problem solving, and collaborative learning and adaptation.

First, the externalization of cognition and related theoretical approaches provide a means to understand the role of cognitive artifacts in the collaboration process. Second, as introduced earlier, the team cognition literature contributes the notion of information exchange for the purposes of developing mental models of problem situations. Third, the group communication and problem-solving literatures provide insight into functions of group processes in problem solving as well as the notion that group processes evolve through a sequence of stages or phases, although not necessarily in a linear progression. Fourth, research on collaborative learning and adaptation provide insights into the mechanisms by which groups develop over time and refine their knowledge and performance processes.

Table 1 provides a summary of these four areas, and each is described in more detail in the following sections. Subsequently, these contributions are discussed in terms of the bridging concept of team knowledge building.

#### Extended and Externalized Cognition

Recent and promising developments in the cognitive sciences relating the interaction of brain, body, and environment provide important

theoretical grounding for macrocognition in teams. Specifically, the concept of *extended* or *externalized cognition* has arisen as a way to describe cognition emerging and unfolding beyond just the brain and highly situated within particular contexts (see Clark, 2001; Clark & Chalmers, 1998; Hutchins, 1995; Rowlands, 1999). Traditional cognitive psychology has focused on cognition as computational rules, treating the mind as an information-processing system that acts on and manipulates formal symbols. But the computer metaphor and the view of cognition as information processing forced an emphasis on an abstract, algorithmic, and logical characterization of mind (Newell & Simon, 1972) and ignored the role of one's interaction with the environment in the understanding of cognition.

Literally, externalization means the placement of something outside its original boundary. In the context of cognition, this implies that what is normally construed as cognition within the brain can occur outside of the head (Clark, 2001; Clark & Chalmers, 2001), much like Norman's (1980) notion of knowledge in the head and knowledge in the world. A simple example involves note taking or working out a problem on paper. Conventionally, taking notes is not considered "remembering," but in the present context, it is seen as an externalized cognitive function (see Clark & Chalmers, 1998). This notion is helpful for understanding macrocognition in teams because it addresses the degree to which collaborating teams use each other, their environment, and tools to solve problems. Specifically, cognition occurs not in a vacuum but rather within and through a task and a context (see Clark, 2001; Clark & Chalmers, 1998; Hutchins, 1995; Rowlands, 1999). The emphasis is on the *practice* of cognition "by which internal representations are incomplete contributors in a context-sensitive system rather than fixed determinants of output: and they too focus on the ongoing interactive dance between brain and world" (Sutton, 2006, p. 282).

Research into external and distributed problem representations illustrates this type of interplay between person and externalization in problem solving. External representations are viewed as "knowledge and structure in the environment, as physical symbols, objects, or dimensions . . . and

TABLE 1: Overview of Theoretical Areas Informing Macrocognition in Teams

Perspective	Example Theories and Constructs	Contribution to Macrocognition in Teams Theory Development	Representative Citations
Externalized cognition	Distributed cognition External representations Cognitive artifacts	The bounds of a cognitive system can extend beyond an individual mind to encompass multiple people and the physical environment. Interaction spaces (i.e., the interaction of internal cognitive work and the physical and social context) are the source of intelligence and effective performance. Groups are information-processing systems.	Clark, 2001; Hutchins, 1995; Nemeth, O'Connor, Klock, & Cook, 2004; Zhang & Norman, 1994
Team cognition	Shared mental model theory Transactive memory systems Team and shared situation awareness Implicit and explicit coordination	The distribution and overlap of knowledge across team members plays an important role in how they are able to coordinate action, anticipate one another's needs, and adapt to task demands. Communication is the primary means by which teams build a shared understanding of their present situation. Team members' knowledge of how expertise is distributed among team members enables effective performance. Group process must focus on a set of tasks or functions to reach effective decisions.	Artman, 2000; Cooke, Salas, Kiekel, & Bell, 2004; Hinsz, Tindale, & Vollrath, 1997; Liang, Moreland, & Argote, 1995; Moreland & Myaskovsky, 2000; Salas & Fiore, 2004
Group communication theory and group problem solving	Functional theory of group decision making Problem space and problem representations in expert problem solving	Group process must focus on a set of tasks or functions to reach effective decisions. Groups with higher-quality problem representations will reach better outcomes. The nature of the analysis process (e.g., exploration of negative outcomes) is critical to effective solution evaluation.	Chi, Glaser, & Rees, 1990; Fiore & Schooler, 2004; Hirokawa, 1980; Orlitsky & Hirokawa, 2001
Collaborative learning and adaptation	Team adaptation Team learning Team development	Teams engage in recursive developmental cycles. Groups must balance stability of structures and processes with innovations and adaptations. Adaptation and learning are emergent phenomena rooted in the interactions of members.	Burke, Stagl, Salas, Pierce, & Kendall, 2006; London & Sessa, 2007; Stahl, 2006; Wilson, Goodman, & Cronin, 2007

as external rules, constraints, or relations embedded in physical configurations” (Zhang, 1997, p. 180). Important features of the problem can be distributed across an individual’s internal cognitive system and the environment (Zhang & Norman, 1994, 1995) or between multiple individuals and the environment (Zhang, 1998). Fiore and Schooler (2004) elaborated on the value of external representations to team problem solving. They suggested that “the degree the team-task requires the construction of a shared understanding, external representational tools can act as a scaffolding to facilitate the building of that shared representation” (Fiore & Schooler, 2004, p. 134). Specifically, externalizations become

a concrete manifestation of the team’s conceptualization of the problem . . . [noting that these] allow collaborators to visually articulate abstract concepts and manipulate these task artifacts as the problem solving process proceeds [and] act as a scaffolding with which the team can construct a truly shared, and concrete, depiction of the process problem. (Fiore & Schooler, 2004, p. 144)

Additionally, Nemeth and colleagues (Nemeth, Cook, O’Connor, & Klock, 2004; Nemeth, O’Connor, Klock, & Cook, 2006) have analyzed the value of externalizations in supporting medical decision making in hospitals. Highlighting the role that schedules, lists, and display boards play in distributed decision making, they note that in support of decision making and planning, these tools “mediate collective work . . . as a way to maintain an overview of the total activity . . . [and] are products of various work activities that are distributed in time and location” (Nemeth et al., 2006, p. 1013). More specifically, in the context of operating room (OR) management, they describe how the “OR Board” is a form of externalized cognition that supports assessment and planning as well as coordination for contingencies and negotiation of resources. Even in the more general area of collaborative medical decision making, researchers have developed group decision support systems in service of clinical reasoning and problem solving (e.g., Lu & Lajoie, 2008). Given the uncertainties and complexities associated with

this type of decision making, these have been developed as “cognitive-aid structures” (e.g., Rao & Turoff, 2000).

These examples illustrate a small subset of the large variety of types of external representations used in real-world problem solving. Different types of external representations can be isomorphic (i.e., represent the same information or knowledge; Zhang & Norman, 1994) but have radically different effects on performance processes and outcomes (e.g., performing mathematical operations with the Roman vs. the Arabic numeral systems; Zhang & Norman, 1995). As such, formally depicting important features of an external representation is a challenge for macrocognition as well as for the cognitive sciences more broadly.

In short, externalized cognition is a valuable theoretical contribution to macrocognition in teams, particularly when performance is supported by technology and is highly situated. However, although externalized cognition is important, the knowledge distributed across team members remains critical. Consequently, our next theoretical thread, *team cognition*, helps explain how knowledge is shared and used among team members.

## Team Cognition

Team cognition research encompasses a variety of theories with the common underlying view of groups as information-processing units. This approach applies many of the mechanisms used to describe and explain individual-level information processing, such as attention, memory, and learning, to understand group performance (Hinsz et al., 1997). Team-level cognition has been conceptualized as a multilevel phenomenon comprising interactions and dependencies between intraindividual-level processes and interindividual-level processes (Fiore & Salas, 2004, 2006). More specifically, team cognition theories are cast in terms of the *component* knowledge of team members (i.e., shared knowledge structures) as well as the dynamic processes by which team members access and act on this stored knowledge in the context of a given situation (i.e., information sharing). Individual member knowledge and expertise are viewed as an input to the team’s performance



process, but performance outcomes are heavily influenced by how the team interacts (e.g., Woolley, Gerbasi, Chabris, Kosslyn, & Hackman, 2008).

Extensive research from this tradition suggests that compatible or shared mental models underlie experienced teams' ability to coordinate behaviors, anticipate and predict each other's needs, and adapt to task demands (e.g., Cannon-Bowers et al., 1993; Marks et al., 2000; Salas & Fiore, 2004; Smith-Jentsch, Campbell, Milanovich, & Reynolds, 2001). Furthermore, for such teams, both tacit and explicit coordination and communication strategies facilitate effective performance. Explicit coordination occurs through externalized verbal and nonverbal communications, whereas tacit coordination is thought to occur through the activities of team members who have shared mental models of what should be done, when, and by whom (e.g., Entin & Serfaty, 1999). Specifically, according to shared mental model theory, highly effective teams must hold compatible knowledge structures, including a shared understanding of their teammates' roles and responsibilities as well as an understanding of the team task at a level sufficient to coordinate their actions (Cannon-Bowers et al., 1993; Fiore, Salas, & Cannon-Bowers, 2001; Rouse, Cannon-Bowers, & Salas, 1992).

The original use of the word *shared* in shared mental model theory indicated similarity (i.e., team members held the same knowledge structures); however, in teams with heterogeneous roles, use of the word *shared* has come to indicate distribution across the team (i.e., team members hold unique but compatible knowledge structures; Banks & Millward, 2000). The importance of distributed knowledge structures in teams has been investigated extensively in the transactive memory systems literature (e.g., Austin, 2003; Moreland & Myaskovsky, 2000). Here, effective performance is facilitated by an understanding of who knows what on the team (e.g., the individual expertise of members is known throughout the team) and how and when to appropriately access such knowledge.

A team's shared or distributed mental model thus allows team members to coordinate their behavior and better communicate according to situational demands (e.g., Cannon-Bowers, Tannenbaum, Salas, & Volpe, 1995; Mathieu

et al., 2000). Additionally, the concepts of information sharing in service of developing a shared problem model (Orasanu, 1994) are important contributions from team cognition research. A shared problem model consists of an agreement on a number of critical problem elements, including an understanding of the specific situation or context in which the problem is emerging, some knowledge of the nature and causes of the problem, an understanding of the available cues, an understanding of the problem goals and the relation between problem components (e.g., resources, constraints), and how they relate to reaching goals and objectives (Fiore et al., 2008).

In sum, team cognition theory contributes to an understanding of macrocognition in teams via discussion of how teams exchange information to develop a shared understanding of their task or problem. Importantly, recent meta-analytic work in the area of team cognition has shown that shared mental models predict team process when the measurement techniques capture individual mental models and that they tend to predict team performance across various measurement techniques (see DeChurch & Mesmer-Magnus, 2010a). Further, they point to important distinctions between compositional and compilational conceptualizations of knowledge within teams and how these relate to process and performance outcomes (see DeChurch & Mesmer-Magnus, 2010b). Nonetheless, although this approach discusses the role of communication in sharing information, we next discuss group communication theory, which has developed a rich conceptualization of the processes teams use to create shared knowledge about a problem and develop and evaluate problem solutions.

### **Group Communication and Problem Solving**

In this section, approaches from group communication theory and group problem solving are described as they relate to macrocognition in teams. Specifically, the functional perspective on group processes and notions of problem space construction are discussed.

First, the functional approach from group communication theory is defined by a set of four core assumptions: (a) Groups are goal oriented, (b) performance and behavior within a group varies and can be evaluated, (c) the interaction

processes of the group vary and can be evaluated, and (d) various internal and external factors influence the group's performance outcomes through interaction processes (Hollingshead et al., 2005). This general perspective has been adapted to investigate why certain groups make better decisions than others. Specifically, the functional theory of group decision-making effectiveness proposes that the performance level of the group is dependent on the degree to which group interactions contribute to the fulfillment of critical task requirements (Hirokawa, 1980; Orlitzky & Hirokawa, 2001); that is, all decision-making groups must accomplish some set of subtasks, or general functions, to successfully arrive at an acceptable decision. The amount and quality of group interactions focused on these functions determine the quality of decision-making outcomes.

These functions include, first, *problem analysis*, whereby the group uses information to create an accurate understanding of (a) the nature of the problem; (b) the seriousness, criticality, urgency, or extent of the problem; (c) feasible and likely causes of the problem; and (d) foreseeable consequences of not solving the problem. They then work to *establishment of evaluation criteria*. With this function, the group must define what an acceptable solution to the problem should look like (e.g., setting standards by which alternatives are judged and selected) and generate solutions. Finally, the group evaluates the positive and negative consequences of its generated solutions.

In short, the functional theory of group decision-making effectiveness proposes that the amount and quality of group interaction processes dedicated to each of the previously described functions play a causal role in determining the effectiveness of group outcomes. This theory has received support from meta-analytic synthesis, especially for the evaluation of negative consequences of solutions, problem analysis, and the establishment of solution criteria, all of which were strong predictors of decision-making effectiveness (Orlitzky & Hirokawa, 2001). More specifically, the data demonstrates that teams reach better performance outcomes when their members devote more discussion to possible negative consequences of a proposed solution.

Second, the group problem-solving literature indicates that problem conceptualization and the time spent on defining a problem space are directly related to problem-solving outcomes. Research comparing expert with novice problem solving finds that experts in a particular field spend a considerable amount of time representing a problem before attempting to solve it (e.g., Chi, Glaser, & Rees, 1990). The issue of problem representation is foundational to theories of problem solving (e.g., Newell & Simon, 1972), and it becomes even more critical when talking about problem-solving teams working on ill-defined tasks.

Research has long demonstrated that teams show little inclination to engage in this aspect of the problem-solving task (e.g., Hackman & Morris, 1975). For example, early research on group problem solving suggests that groups are not always "problem minded" (see Maier, 1967) in that they are disinclined to scrutinize all problem elements before coming up with a solution. Maier (1963) found that groups tend to immediately begin generating and evaluating solutions rather than studying the problem. As such, ad hoc groups can quickly set themselves into a certain routine of solving a problem. As Campbell (1968) found, "Groups seemed to settle very early on a particular line of attack, and alternative work procedures were seldom explored in the group discussion" (p. 209). Thus, groups tend to be action oriented; that is, rather than carefully reflecting on all the problem elements and then generating a number of alternative solutions, poorer-performing groups are more likely to immediately begin suggesting solutions.

There are significant points of agreement between the functional perspective of group decision making and the macrocognition-in-teams framework as proposed by Letsky and colleagues (see Letsky et al., 2008). For example, the macrocognitive model proposes a set of tasks associated with each phase (i.e., functions that the team carries out during each phase). More importantly, a significant contribution of the functional theory of group decision-making effectiveness to macrocognition in teams is the idea that the amount and quality of interaction processes focused on specific group functions are key to understanding and predicting group outcomes. Specifically, the functional approach

can help to focus the analysis of interaction to a manageable subset of critical tasks the group must complete.

### **Collaborative Learning and Adaptation**

As macrocognition is concerned primarily with novel situations (e.g., G. Klein et al., 2003), learning via adaptation of previous knowledge is a large part of performance. There has been extensive interest on collaborative and cooperative learning from pedagogical researchers (e.g., Slavin, 1980); however, much of this research focuses on the relative effectiveness of different instructional design approaches on individual learning outcomes. Research investigating how groups learn and adapt as a unit in the course of performance is more relevant to macrocognition than research focusing on groups whose sole purpose is to facilitate the learning of individual members (e.g., Kasl, Marsick, & DeChant, 1997). Consistent with the team cognition perspective, Wilson, Goodman, and Cronin (2007) conceptualize team learning in terms of three core mechanisms, all of which are intertwined and necessary for team learning to occur: sharing, storage, and retrieval. Sharing is the process of distributing new knowledge, routines, or behaviors among group members. Storage is the process of retaining knowledge that has been learned in memory repositories. Last, retrieval is the process by which group members can find and access knowledge for subsequent use.

A recent integration of the team learning literature extends this notion and proposes three distinct types of learning: adaptive, generative, and transformational (London & Sessa, 2007). Adaptive learning in teams involves changes in interaction processes triggered by environmental cues. These changes are relatively automatic in that the team selects different behavioral processes or strategies from a preexisting repertoire. Generative learning in teams involves the discovery or invention of new knowledge or skills as well as the application of this knowledge to their performance processes. Whereas adaptive learning is a switch from one preexisting process to another, fitting with our theorizing, generative learning is the creation of a process the team previously did not have. Transformative learning in teams is a process of reinvention or re-creation of the team. Members critically

evaluate the purpose, goals, values, assumptions, beliefs, and structure of the team. Additionally, current process models of team adaptation and learning outline a multilevel skill compilation process wherein top-down contextual influences, team-level factors (e.g., team leader actions), and bottom-up emergence rooted in the interaction of team members interact and unfold over time to yield changes in the performance capacities of teams (Burke, Stagl, Salas, Pierce, & Kendall, 2006; Kozlowski, Gully, Nason, & Smith, 1999).

In sum, theorizing on group learning and adaptation contributes some fundamental notions to macrocognition in teams via description of processes engaged by groups to generate new knowledge. These approaches help us understand processes involving the sharing of information in service of learning and adapting to new contexts. Finally, they articulate the manner in which teams create new processes to deal with changes to their performance environments.

### **Summary**

Our macrocognition-in-teams framework draws from the research traditions described in the previous sections, each contributing unique theoretical components to our understanding of complex collaborative processes. Taken together, these approaches provide the basis for understanding team interaction processes and distribution of cognition between team members and the environment during problem solving in novel situations. Additionally, these concepts address the development or creation of knowledge in particular contexts. In the following section, the concept of knowledge building is introduced as a core contribution of the macrocognition-in-teams perspective.

### **KNOWLEDGE BUILDING: A BRIDGING CONSTRUCT**

The process of knowledge building cuts across all of the aforementioned theoretical elements and is central to macrocognition in teams (see Fiore et al., 2008; Fiore, Elias, Salas, Warner, & Letsky, in press; Letsky, et al., 2007; Warner, Letsky, & Cowen, 2005). In this section, we further elaborate on this via discussion of the data-information-knowledge (D-I-K) transformation process (Rowley, 2007).



First, context and integration are inextricably linked with our conceptualization of knowledge building and the D-I-K transformation described in this section. The definition of context and its etymological origins are informative in this regard. Context has as its Latin root *contextus*, “a joining together,” which in turn was derived from *contexere*, “to weave together,” with *com* meaning “together” and *texture* meaning “to weave.” This etymology implies that a particular context helps us to weave together our understanding of events to form a mental model of the world with which we are interacting at any given moment in time. Furthermore, we submit that the knowledge-building process is driven by an integration of the bits of information that have been organized and made meaningful in a particular context. From this standpoint, the literature on expertise and how expert knowledge differs from novice knowledge, not just in content but in its organization, becomes relevant (e.g., Chi, Feltovich, & Glaser, 1981). Specifically, Glaser (1989) suggested that “beginners’ knowledge is spotty, consisting of isolated definitions and superficial understandings of central terms and concepts. With experience, these items of information become structured, are integrated. . . . Thus, structuredness, coherence, and accessibility to interrelated chunks of knowledge” (p. 272) are the hallmarks of expert knowledge.

Arising primarily out of knowledge management and information sciences, this D-I-K hierarchy has been discussed in a number of articles (see Ackoff, 1989; Cleveland, 1982; Zeleny, 1987).<sup>1</sup> Table 2 provides a set of definitions for data, information, and knowledge rooted in the concepts of context and integration as well as examples from recent research in macrocognition in teams, specifically, a noncombatant evacuation operation (NEO) scenario (Letsky et al., 2008). For the purposes of illustrating the core elements of the D-I-K transformation, this NEO scenario is briefly described here. The NEO scenario requires a team to develop plans for evacuating humanitarian workers stranded on an island nation overrun by rebel insurgents. The task requires problem solving among a team of specialists with diverse organizational and agency backgrounds along with varied levels of expertise. In this task, an ad hoc team must gather and synthesize information to

develop a solution, an evacuation plan for the hostages (Rosen et al., 2008); that is, the team members must build knowledge from an integration of the task content, the problem context, and their own experience.

Within the context of a NEO scenario, data are what is available in the task environment (e.g., “The CH-53 helicopter has a range of 500 miles”). By structuring and contextually grounding data, it is transformed to information. That is, when they are organized to provide meaning within a particular context, data become information (e.g., “We have two air and three land vehicles as resources for use in Nandor”). The process of transforming information to knowledge occurs when it is integrated with one’s experience or with task-related information and made useful for action via synthesis with the problem-solving context. For example, as a problem solver works to examine information, he or she may recognize the value of something by noting how one piece of information is relevant to another or to a particular facet of the problem (e.g., “The timing of high tide is important because we can transfer supplies with our rafts only at that time”).

In short, we define each stage of the D-I-K transformation process as follows: (a) *Data* are disparate and devoid of context, (b) *information* is structured or organized data within a problem-solving context but is not integrated, and (c) *knowledge* involves not only organization and context but also integration—it is the piecing together of information to produce something actionable that did not explicitly exist at the start of the collaboration (see Fiore, Elias, et al., 2010, for a fuller discussion).

A foundational idea within of our conceptualization of the D-I-K transformation process is that knowledge has to be *created* by the integration of information generated from the available data and/or from the team members’ own experiences. This distinction has both practical and theoretical value for understanding problem solving in relatively novel situations. Although problems such as the evacuation scenario are not necessarily unique (i.e., there is an unfortunate number of instances in which these occur), the context in which they occur does tend to be unique. Although there will certainly be similarities in some features of the problem from

TABLE 2: Definitions and Examples of Data, Information, and Knowledge

Concept	Explanation
Data	
Definition	Data are disparate statements or facts presented or represented separately and without context.
Example	"The CH-53 Marine Corps helicopter can hoist 250 feet with a 600-pound lift capacity."
Explanation	Here, the content is devoid of context and not organized in any way; as such, it is considered only data.
Information	
Definition	Information is organized or structured data (i.e., organized or structured statements or facts) that have been related to the problem-solving context.
Example	"The CH-53 Marine Corps helicopter can carry supplies to the Red Cross workers who have been taken hostage," or "Our three air vehicles are the CH-53, the F-16, and the E2-C."
Explanation	The first example represents a transformation in that it involved connecting the piece of data to the problem. The second example represents a transformation in that it involved organizing the data via categorization such that it can serve the problem solving; resources were organized into categories of resources that serve the problem solving.
Knowledge	
Definition	Knowledge is the integration of content from two or more categories of information into something that did not explicitly exist before and that has been made actionable by being related to the problem-solving context.
Example	"The CH-53 Marine Corps helicopter cannot be used to carry supplies because it is foggy over the southwest corridor of Nandor."
Explanation	This represents a transformation because vehicle information (a category) was integrated with weather information (another category) in such a way that it serves the problem solving; that is, it was made actionable by explaining when it could get (or not get) supplies to the hostages.

Note. We use examples from the Office of Naval Research Collaboration and Knowledge Interoperability Program noncombatant evacuation operation scenario (see Letsky, Warner, Fiore, & Smith, 2008) for illustrative purposes only and do not suggest that macrocognition arises only in this scenario context. We further discuss related task contexts in the Conclusion section.

which analogies may be drawn (e.g., this is a hostage situation; the goal is safe extraction with minimal loss of life), many contextual variables will differ.

For example, the Iranian hostage crisis of 1979 provides an illustration of the role of context in developing and applying knowledge in the course of solving problems with varying features. In working to develop a plan to rescue the hostages, the team had to consider many problem variables, such as the capabilities of the hostage takers and the location of the hostages at both the microlevel (in the U.S. Embassy) and the macrolevel (in a foreign country where

a revolution had just occurred). A key component of the developed plan involved the use of helicopters to evacuate the hostages. This decision was made on the basis of analogies team members drew between the current situation and similar ones experienced in Vietnam. However, among other issues, the team did not appropriately account for novel features of the current context, such as uncertain weather patterns, the terrain, and the possibility of resource malfunction caused by desert sand (Benson, 2007). This course of action led to the death of a number of personnel in the failed hostage rescue attempt. Considering this situation in relation to the view

of macrocognition in teams, a central question then arises: How do teams identify appropriate and inappropriate features of context with which to draw comparisons?

Although examples thus far have emphasized military planning teams, such teams are similar to a number of problem-solving teams confronted with high-stakes and time-stressed environments found in civilian organizations. For example, teams responding to emergencies, such as natural disasters or industrial accidents, are often composed of a heterogeneous mix of experts to address search and rescue. They must also deal with ambiguous data regarding casualties, work with a finite set of resources, and creatively generate solutions to satisfy constraints for impassable terrain (e.g., because of damage caused by flooding or explosions). Related areas include command centers for emergencies such as terrorist attacks, where first responders need to rapidly diagnose particular problems with limited amounts of information and deal with uncertainty while trying to coordinate resources from various team members. Similarly, in medical settings, collaborative problem solving is commonplace (e.g., in discussion of cases, during morning rounds). Fitting with team cognition research, in these contexts, the distribution of information among decision makers prior to discussion, as well as understanding and assessment of the competence of the decision maker, is thought to influence decision outcomes (Christensen & Larson, 1993). Finally, considering the primacy of knowledge building, *team science* is an additional area of research relevant to macrocognition in teams. Team science involves collaborative research projects created to address some complex phenomenon and is a unique form of highly intellectual teamwork (Fiore, 2008; Stokols, Hall, Taylor, & Moser, 2008; Stokols, Misra, Moser, Hall, & Taylor, 2008). Complementary knowledge and methods are brought to bear through interdisciplinary collaborations in which information is shared to build knowledge that addresses a pressing scientific gap in understanding.

In sum, knowledge building is defined in terms of the transformation from data to information to knowledge. Additionally, context represents a critical component of this process, as knowledge building involves integrating information and

drawing connections to the problem-solving context. In this way, knowledge building is a *process* that leads to the *product* of knowledge; it is a process whereby isolated bits of data are organized and then integrated into a tightly coupled network of actionable knowledge for use within a particular problem-solving context. Problem-solving effectiveness is enabled by expanding the amount of problem-relevant knowledge available to a team through this knowledge-building process.

### Summarizing Theoretical Foundation

The preceding review indicates several key contributions to the understanding of effective collaborative problem solving. Specifically, team cognition research emphasizes the importance of information sharing and the importance of similar knowledge structures. Team performance is a function of the level of understanding the team shares about its task and capabilities and the degree to which a team's comprehension of the critical problem components contains an acceptable amount of overlap (e.g., Fiore & Schooler, 2004; Mathieu et al., 2000). According to group communication theory, a set of stages or phases and functions characterizing the processes teams use to express and refine their problem-solving knowledge is brought forth (for a discussion, see Poole & Hollingshead, 2005). Learning and adaptation research helps to conceptualize the processes used to modify behavior contingent on the novelty of the context as well as how to create new knowledge in that context.

Furthermore, a growing body of literature in the use of technologies supporting external representations to support communication and collaboration has illustrated the important role of cognitive artifacts in problem solving. These tools help the team to discover relations, and they transform more abstract aspects of a task into a more concrete form (e.g., Dwyer & Suthers, 2005; Grabowski, Litynski, & Wallace, 1997; Stahl, 2006; Suthers et al., 2001). Across all of these ideas, we see important areas of inquiry to aid in the examination of how information sharing and analysis, communication processes, and the use of representational aids interact as collaborative mechanisms to enable effective problem solving. In the following section, an

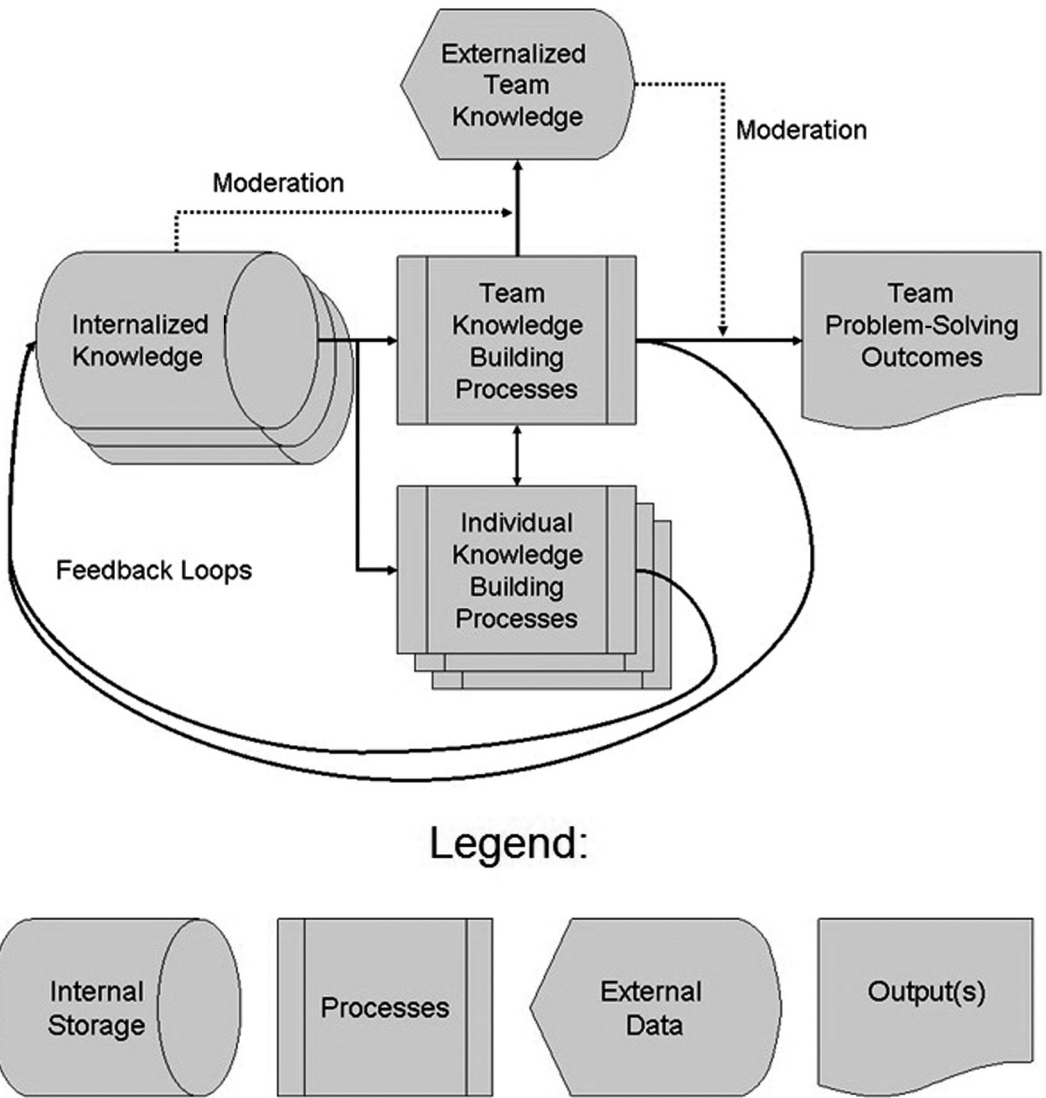


Figure 1. Framework for research on macrocognition in teams (note that multiple overlapping symbols indicate representations for multiple team members).

integrative theoretical framework built from these complementary approaches is presented.

**MACROCOGNITION IN TEAMS:  
THEORETICAL FRAMEWORK**

In this section, we introduce a process model of macrocognition in teams focusing on the building of knowledge within a collaborative problem-solving context, that is, developing new knowledge as a product of collaboration situated within a particular problem-solving context.

The components of this framework represent an attempt to capture the multidimensional nature of macrocognition in teams and to integrate the theoretical constructs described in the prior sections. We first describe a set of macrocognitive phases engaged by teams in service of problem solving. We then describe the components of our process model, illustrated in Figure 1. In addition, research propositions are offered for each of the main macrocognitive functions across the phases of collaboration.

## Stages of Collaborative Problem Solving

In studies of problem solving, evidence exists that supports the notion that problem solvers will often follow a series of stages in pursuit of solutions. Although the specific nature and/or sequence of problem-solving stages varies across studies and domains, the more general idea is that sequential and sometimes iterative stages unfold during complex problem solving. In this section, we briefly describe some of this research and then describe how we posit these phases occur within collaborative problem solving.

In the domain of scientific discovery, research suggests that problem solving involves at least two distinct steps: a search through a hypothesis generation space and a hypothesis testing space (Klahr & Dunbar, 1988; Simon & Lea, 1974). Additionally, research on expertise suggests that problem representation constitutes an important and distinct initial stage of problem solving (Randel, Pugh, & Reed, 1996). Results from preliminary studies on macrocognition in teams provide support for analogous transitions in collaborative problem solving described here (Warner et al., 2005).

Within our framework, macrocognition in teams involves a set of phases of collaborative problem solving: *knowledge construction*, *problem model development*, *team consensus*, and *outcome evaluation and revision* (Letsky et al., 2007). We choose to use the term *phase* rather than *stage* as it more accurately captures how we are conceptualizing the evolution of collaborative problem solving. Whereas the term *stage* implies a discrete and fairly fixed or stepwise process, the term *phase* is meant to describe the more transitional nature of this activity (see Kozlowski et al., 1999). As such, it is meant to capture the idea that there are varied modal frequencies for these macrocognitive processes across phases, that is, more of a “continuous series of phases, with partial overlap at transitions. Discontinuities occur at the transitions, but the shifts are not necessarily abrupt” (Kozlowski et al., 1999, p. 248). Thus, although there will be overlap of these processes across phases, the occurrence of particular macrocognitive processes will vary dependent on the phase of problem solving.

The knowledge construction phase begins by identifying the relevant domain information

required, setting up the communication environment necessary to address the problem, individual team members beginning to develop their own mental model of the problem, and developing individual and team task knowledge. The collaborative team problem model phase is when the aforementioned knowledge coalesces into a model of the problem; this model is essentially the team’s shared understanding of the problem and its parameters (problem givens, goals, and viable solutions). Team consensus is the phase at which teams work to achieve agreement among several viable solution alternatives to the problem. Outcome evaluation and revision involves analyzing, testing, and validating the agreed team solution against the goal requirement(s) and exit criteria, and included in this phase is an iteration loop for deriving other solutions for the problem if necessary.

The propositions presented in the following section are organized within and across these phases of collaborative problem solving. Although our phases have been presented as primarily sequential, we acknowledge the need to account for the dynamic nature of collaboration, in which processes sometimes move backward and forward as the problem solving proceeds. Specifically, macrocognition in teams can manifest in dynamic, iterative, recursive, and nonlinear ways, and describing this form of problem solving is essentially a “moving target” in that processes are parallel, interdependent, and continuous (Hoffman, 2007). But for the sake of explication, these processes are presented as sequential and discrete. While simplifying the overall nature of macrocognition, presenting the processes in this way allows some of the interactive elements of macrocognition in teams to be “frozen.” Table 3 provides a crosswalk of the phases of problem solving with the functions of macrocognition in teams and is used to guide discussion of the major macrocognitive processes illustrated in Figure 1 along with the associated research propositions.

## Major Macrocognitive Processes and Research Propositions

In this section, the processes arising during collaborative problem solving are briefly reviewed, specifically, individual and team knowledge



**TABLE 3:** Cross-Classification of Process and Phases of Macrocognition in Teams Along With Representative Propositions

Major Macrocognitive Process	Collaboration Phase			
	Knowledge Construction	Team Problem Model	Team Consensus	Evaluation and Revision
Individual knowledge-building processes	Proposition 1.1	Proposition 1.2	Proposition 1.3	Proposition 1.4
Team knowledge-building processes	Proposition 2.1	Proposition 2.2	Proposition 2.3	Proposition 2.4
Internalized team knowledge	Proposition 3.1	Proposition 3.2	Proposition 3.3	Proposition 3.4
Externalized team knowledge	Proposition 4.1	Proposition 4.2	Proposition 4.3	Proposition 4.4
Team problem-solving outcomes	Proposition 5.1	Proposition 5.2	Proposition 5.3	Proposition 5.4

building, internalized and externalized knowledge, and team problem solving outcomes. For a more detailed description of these processes, see Fiore, Smith-Jentsch, et al. (2010). Along with this review, a set of propositions rooted in the preceding review is advanced. Because these propositions are derived from an extensive literature base, some of these propositions do have empirical support. As such, when appropriate, we provide relevant representative citations to these works. However, the main contribution of this article involves the integration of these propositions into a coherent framework. Consequently, this article represents the instantiation of a theoretical framework meant to offer research guidance in the area of complex collaborative problem solving and to provide suggestions for more systematic empirical testing.

*Individual knowledge building* involves the particular actions taken at the intraindividual level for the purpose of building one’s own knowledge. This process may involve reading task-relevant content, therefore taking place in the head of the individual, or it may involve interactions with a system. At a more specific level, this process is hypothesized to involve individual information gathering, individual information synthesis, and knowledge object development. These processes involve a number of activities ranging from reading to question asking to accessing displays. Furthermore, individuals will begin to compare relationships among the acquired information, and with the

problem context, as well as begin to develop cognitive artifacts supporting the creation of actionable knowledge for the task. The following theoretical propositions predict a change in the type of individual knowledge-building processes engaged as teams move through the problem-solving process. Specifically, it is hypothesized that a differential interplay between internalization and externalization of information and knowledge will arise as team members move through the problem-solving phases.

*Proposition 1.1:* During the knowledge construction phase, individual knowledge building involves internalization of data and information (e.g., Moreland & Myaskovsky, 2000). The emphasis is on information gathering as members work to understand their own unique task information as it relates to the goals at hand.

*Proposition 1.2:* During the problem model development phase, with the process of individual knowledge building, there will be an increase in the interaction of internalization and externalization but with more of an emphasis on externalizations as individuals begin the process of knowledge object construction (e.g., Zhang & Norman, 1994, 1995). The focal activity of individual knowledge building will shift to information synthesis and knowledge object construction, wherein subsets of information are connected in ways meaningful to the problem-solving context.

*Proposition 1.3:* During the team consensus phase, individual knowledge building will involve

additional information seeking as team members work toward clarification or modification of their generated knowledge. The solutions that have been externalized become the focal point (e.g., Suthers et al., 2001), but there will be a relatively equal occurrence of internalization and externalization. More specifically, internalization will involve gathering additional information in support of particular solutions or will involve accepting knowledge proffered by teammates as one works to understand another's point. Externalizations will serve to support particular arguments or solutions either self-generated or generated by other members with whom one agrees.

*Proposition 1.4:* During the outcome evaluation and revision phase, individual knowledge building will involve modification of one's generated knowledge based on feedback following a plan's implementation. This involves primarily internalization as individuals modify their understanding on the basis of the nature of the feedback.

*Team knowledge building* involves the particular actions taken at the interindividual level for the purpose of building knowledge across the team. This process may involve actions to disseminate information or to transform information into actionable knowledge. More specifically, this process involves team information exchange and team knowledge sharing; the former involves passing relevant information, and the latter involves sharing explanations and interpretations based on synthesis of the information. This process also involves solution option generation as well as evaluation and negotiation of alternatives, whereby team members discuss and clarify the positive and negative aspects of potential solutions. Here, there may be instances in which team members draw from prior experience with analogous situations to support or refute candidate solutions that are on the table. This action may serve to reduce uncertainty, and it is in such instances that the evaluation of negative consequences will interact with prior knowledge.

For example, for a team to speculate on the potential negative consequences of a solution, prior knowledge of similar experiences may be relied on. Finally, teams will engage in process and plan regulation, whereby they critique their

knowledge-building process or, when feedback has been received, the effectiveness of their plan. The following theoretical propositions predict changes in quantity of a particular type, or to a particular type, of knowledge building as teams move through the problem-solving process. Whereas a differential interplay between internalization and externalization of information and knowledge is predicted in the prior phase, team knowledge building is necessarily a phase primarily involving externalizations, as information and knowledge are shared among the team members.

*Proposition 2.1:* During knowledge construction, team knowledge building will emphasize *problem analysis*, involving externalizations of what individual team members know or have acquired. This process will involve exchange of information (cf. Smith-Jentsch, Zeisig, Acton, & McPherson, 1998) to integrate it with the problem context (i.e., build knowledge) and develop an understanding of the problem (e.g., problem elements, task resources, sense of goals).

*Proposition 2.2:* During the problem model development phase, team knowledge building will primarily focus on externalizations of cognition to support creation of a broader representation of the constructed knowledge. Here, the team works to integrate its externalized knowledge into a larger problem space (e.g., Suthers, 2006) to see how solutions can be created (e.g., diagramming how resources can be shared or used with particular vehicles to achieve a given objective).

*Proposition 2.3:* During the team consensus phase, team knowledge building will emphasize the refinement of the already developed knowledge. This involves assimilation or accretion of knowledge (cf. Anderson, 1984; Rumelhart & Norman, 1981) as teams focus on clarifying or discarding solutions.

*Proposition 2.4:* During the outcome evaluation and revision phase, team knowledge building will focus on integrating feedback from a plan's execution. A team's externalizations will involve discussion of how to adapt knowledge and replan on the basis of the effectiveness of the solutions they had generated.

*Internalized team knowledge* describes the knowledge team members hold individually.

Macro cognition in teams involves performance in situations in which at least some components of the task are novel to some members and in which team members likely have not previously worked together. Consequently, each team member will be bringing a unique expertise to the team; in terms of shared mental model theory and related work on team knowledge, this means that the overlap or congruence of individual team member knowledge may be low. Thus, from the collaborative problem-solving standpoint, what matters is *team knowledge similarity*, that is, the degree to which team members with differing roles understand one another or how well the team members understand problem goals. Also important is the individual members' understanding of *team knowledge resources*. This component pertains to the collective understanding of resources and responsibilities associated with the task and with the team members. This knowledge may converge as team members interact, and the degree to which internalized team knowledge converges is a function of the quality of the interaction processes. The following propositions summarize these relationships.

*Proposition 3.1:* During knowledge construction, given the novel nature of the particular problem situation considered here, internalized knowledge will be primarily unique for each of the team members (cf. Campbell & Stasser, 2006). Because members at this phase are only in the initial stages of comprehending their problem situation, there will be little overlap in team knowledge.

*Proposition 3.2:* During problem model development, team members have begun sharing information to integrate it with the problem context, thus creating knowledge. Therefore, internalized knowledge structures about the task and team members will become more common (e.g., McComb, 2007).

*Proposition 3.3:* During team consensus development, solution alternatives are evaluated via team discussion (e.g., Orlitzky & Hirokawa, 2001). Thus, the degree of uncertainty individuals hold about their internalized knowledge will decrease depending on the quality of interaction processes (e.g., the evaluation of negative outcomes).

*Proposition 3.4:* During the outcome evaluation and revision phase, internalized team knowledge is

modified on the basis of feedback. Knowledge modification is dependent on the nature of the team interaction on that feedback (e.g., changes in internalized team knowledge are dependent on the quality of one's understanding of feedback effectiveness).

*Externalized team knowledge* describes relationships constructed from gathered information and the specific task-relevant concepts the team has explicitly agreed on or not openly challenged or disagreed on. Note that this is distinct from *information* in that it signifies information that has been processed by team members via some form of analysis. It includes not only components of knowledge agreed on but also aggregations of knowledge forming a team's developing problem representation. As described, the nature of the problem representation used by a team is critical to the effectiveness of the solution developed.

As team members progress through a performance episode, they must come to a shared understanding of critical aspects of the task. This process involves the use of communication as well as the construction of physical artifacts. The process consists of *externalized cue-strategy associations*, which have to do with the team's collective agreement as to their task strategies and the situational cues that modify those strategies. It also includes *pattern recognition and trend analysis*, which has to do with the accuracy of the patterns or trends explicitly noted by members of a team that are either agreed on or unchallenged by other team members. Finally, it includes *uncertainty resolution*, which is described as the degree to which a team has collectively agreed on the status of problem variables.

Essentially, as teams engage in knowledge-building processes, both communication and the development of knowledge objects or cognitive artifacts will be involved in the collaborative process. Initially, teams rely more heavily on verbal communication to reach agreement on facts, relationships, and concepts. As this agreement is developed, team members may create cognitive artifacts to physically represent the products of group discussion. This process results in the development of a structured knowledge

environment that can later be used to aid problem-solving processes. More specifically, in later phases of problem solving, team members can refer to cognitive artifacts in developing and evaluating solution alternatives. As with team knowledge building, this phase is necessarily one involving primarily externalizations as information and knowledge are shared among the team members. The following propositions summarize these relationships.

*Proposition 4.1:* During the knowledge construction phase, team members will be working to primarily share initially acquired knowledge and to inform each other of this knowledge (e.g., Dwyer & Suthers, 2005). Externalizations of knowledge will be primarily conceptual (i.e., notes, annotations) as team members lay out their understanding of task elements and constraints.

*Proposition 4.2:* During problem model development, externalized team knowledge will involve combination of team and task-relevant knowledge with cognitive artifacts (e.g., Fiore & Schooler, 2004; Suthers, Vatrappu, Medina, Joseph, & Dwyer, 2008). Teams will use cognitive artifacts (e.g., shared notes, graphs, tables) to externalize cognition and anchor development of solution alternatives within the model of the overall problem they are developing.

*Proposition 4.3:* During *TEAM CONSENSUS DEVELOPMENT*, the emphasis will be on referring to externalizations; that is, the focus is on the developed knowledge (e.g., Lu & Lajoie, 2008; Orlitzky & Hirokawa, 2001). Team members work to reduce uncertainty by communicating about plausibility of externalized knowledge and hone in on viable solutions the team has developed.

*Proposition 4.4:* During the outcome evaluation and revision phase, the emphasis will be on modifying externalized knowledge dependent on feedback. Here, the teams will alter cognitive artifacts when solution elements were ineffective or reinforce such artifacts when plans were effective.

*Team problem-solving outcomes* pertain to the effectiveness of the chosen solutions. Addressing the quality of the team's problem solutions or plan involves assessing the degree to which the solution meets all of the criteria for problem resolution. Additionally, this process

can address the efficiency of a solution (e.g., costs, speed). Whereas the aforementioned propositions more generally described the expected processes within and across phases based on collaborative problem solving and team cognition research, in this final section, the following propositions related to problem-solving outcomes are offered.

*Proposition 5.1:* The proportion of time spent on the differing phases will be related to problem-solving outcomes. When the proportion of time spent on construction and representation is less than that spent on solution generation and evaluation, that is, when teams have not been "problem minded" (cf. Chi, Glaser, & Rees, 1982; Maier, 1967), outcomes will be inferior (as measured by either incomplete coverage of the problem criteria or more expensive or slower resolution of the problem).

*Proposition 5.2:* The degree of externalizations will be related to problem-solving effectiveness (e.g., Suthers et al., 2008). During problem model development, given the complexity of the problems faced, teams producing fewer externalizations for information or knowledge related to the problem (i.e., teams have not externalized problem representation) will produce inferior outcomes.

*Proposition 5.3:* Sharedness of the problem model will be related to solution effectiveness. During problem model development, teams showing less convergence of problem conceptualization (e.g., measured via shared mental models; cf. McComb, 2007) will produce inferior outcomes.

*Proposition 5.4:* The nature of the team's evaluation process will affect solution effectiveness. During team consensus development, teams that do not evaluate the negative consequences of solutions (cf. Orlitzky & Hirokawa, 2001) will produce inferior outcomes.

## CONCLUSION

This article has presented a preliminary theoretical framework and associated propositions describing and predicting collaborative problem-solving processes. The perspective presented here is consistent with theories across the organizational and cognitive sciences. For example, Russell, Stefik, Pirolli, and Card (1993) describe the procedures followed within sensemaking as



cyclic and iterative, whereby problem solvers act to develop and shift representations as they gather information and, in our terms, build knowledge (see also G. Klein, Moon, & Hoffman, 2006; Weick, 1995). Similarly, Hackman and Woolley (2004) focused on the social nature of intelligence analysis and outlined a descriptive model of types of "collaborative analysis" teams in different industries based on differences in scope of information being processed, temporal urgency, and interdependence of collaborators. Last, Herbsleb and colleagues (Herbsleb, et al., 1995; Herbsleb & Mockus, 2003) have presented and tested models of collaboration in software design teams. These examples illustrate the application of the macrocognition-in-teams concept beyond the more limited range of military planning teams discussed here.

As noted by Huey and Wickens (1993), the field of human factors must reach to understand analogous domains when particular phenomena of interest are understudied. Fitting with this suggestion, the approach taken here to understanding collaborative problem solving in complex and dynamic environments has been multidisciplinary. By relying on theoretical underpinnings from the cognitive and organizational sciences, integrated with naturalistic decision making, we have developed an innovative framework to understand collaboration. The need for such an integrative framework addressing the core aspects of collaborative performance is supported by a number of studies documenting that effective problem solving is attributable to differences in cognitive and collaborative processes (e.g., Simmons & Lunetta, 1993; Sonnentag, 1998).

In sum, this article outlined how teams engage in processes that help them construct knowledge, represent a problem, and evaluate candidate solutions. The nature of the interrelationships of these processes was described so as to identify differing levels of cognition as they unfold in collaborative activity. By developing models for cross-level cognitive research, one can realize greater explanatory power in service of diagnosing the causal factors associated with team performance (see Dansereau & Yamarino, 2002; K. J. Klein & Kozlowski, 2000a, 2000b).

Because of the complexity inherent in collaborative environments, drawing from additional literatures investigating *interaction* on multiple levels—across brains, bodies, systems, and environment—and with multiple methods of analysis is warranted.

Our goal is to encourage researchers to use an interdisciplinary approach to understand the interrelations among levels of interactions, the processes that arise, and how these drive outcomes.

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## NOTE

1. The traditional hierarchy includes "wisdom" at the end of this chain. Given the complexity inherent in operationalizing what can be construed of as wisdom in the context of collaborative problem solving, we have not included it in our discussion.

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