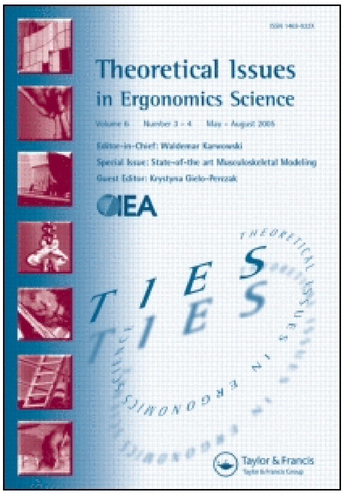

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Towards an understanding of macrocognition in teams: developing and defining complex collaborative processes and products

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Towards an understanding of macrocognition in teams: developing and defining complex collaborative processes and products

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One of the significant challenges for the burgeoning field of macrocognition is the development of more sophisticated models that are able to adequately explain and predict complex cognitive processes. This is even more critical when specifying research questions involving cognition unfolding across interacting individuals, that is, macrocognition in teams. In this article, we provide a foundation for developing a model of macrocognition focusing on collaborating problem-solving teams with a measurement framework for studying macrocognitive processes in this context. We first discuss an important set of key assumptions from team measurement theory that form a critical foundation for this model. We then describe the core definitions we suggest are foundational to the conceptualisation of macrocognition in teams. We conclude with a description of the key dimensions and subcomponents of our model in order to lay the foundation for a principled approach to measuring and understanding macrocognition in teams.

Keywords: team performance; macrocognition in teams; collaborative problem solving; knowledge building; external cognition; team cognition

1. Introduction

In this article, we provide an overview of a model for understanding and measuring macrocognition in teams. This represents an evolution of the conceptualisation of subcomponents and dimensions of macrocognition in teams reported in earlier publications on this topic (Warner *et al.* 2005, Letsky *et al.* 2007, Fiore *et al.* 2008a). First, we describe some of the uses of the term macrocognition as it has developed in research on cognition in complex settings. Second, we discuss an important set of key assumptions from team measurement theory. These are essential to our approach and form the critical foundation for any development of a model that can adequately capture cognition dynamically unfolding in collaborative contexts. Third, we describe a set of definitions foundational to our conceptualisation of macrocognition in teams. Our goal is to clarify a number of the processes and products that have been discussed in some

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way in the team cognition literature and illustrate how they fit with our approach. Last, we describe and define the key dimensions and subcomponents of our model in order to lay the foundation for a principled approach to measuring and understanding macrocognition in teams.

1.1. *Macrocognition and its relation to understanding complex cognition*

Teams in government, industry and the military are increasingly relying on interconnected and interdependent systems, with a large degree of the cognitive work distributed among people and machines. Because of this, we see an increased need to understand how individuals and teams in these environments are able to work together to plan, think, decide, solve problems and take action as tightly coupled units. In this section, we briefly review the use of the term *macrocognition* as it has been developed to describe cognition at this more complex level. Our goal here is not to provide an exhaustive review, rather it is to illustrate the evolution of this concept and some of the subtle differences that have emerged. Our point is that, despite these subtle differences, an important similarity exists; that of recognising the need to pursue the development of theoretical models capable of capturing complex collaborative processes.

Early use of the macrocognition term arose over 20 years ago when researchers involved in the design and development of intelligent systems began to differentiate micro- from macro-level phenomena. In a discussion of what he termed 'humane intelligence', McNeese (1986) theorised about the design of intelligent aircraft cockpits that could extend human abilities. In this context, he noted that what was necessary were artificial intelligence technologies that symbiotically blended with the human operator in support of situation awareness. Specifically, McNeese argued that, in a cockpit combining human and artificial intelligence, 'macro-awareness and macro-cognition must be provided that will obviate such conditions as channelised attention, spatial disorientation and cognitive overload as well as providing perspicacious insight' (p. 6). McNeese (1986) was essentially arguing that, by developing human–machine systems that were able to complement the capacities and capabilities of each other, cognition at a more complex level could emerge (see also McNeese 2007).

Also around this time, although not specifically using the term macro-cognition, but more closely aligning with present day conceptualisations, analogous notions were developing in the study of complex decision-making environments. As described in Schraagen *et al*. (2008a), this community was distinguishing between levels of analysis at the micro- and macro-operational levels in the context of process control (Hollnagel *et al*. 1986, Woods and Roth 1986). These ideas set the stage for explorations of contextually bound cognitive work and theorising on the nested decision processes across multiple operational levels (see Schraagen *et al*. 2008a for a full discussion).

During the 1990s, the concept of macrocognition was still being used in contrast with the term microcognition as a means of illustrating differing types of cognitive processes. For example, in the cognitive and neural sciences, macrocognition was used to describe cognitive processes such as communication and reasoning, that is, processes occurring at levels greater than a single processing unit as was sometimes studied in the neurosciences (Bara 1995, Wilkes 1997). But it was also around this time that cognitive engineering theorists began to specifically use the term to describe cognition in natural environments. Based upon the work of Cacciabue and Hollnagel (1995), the term 'macrocognition' was used to describe how cognition emerges in naturalistic contexts and 'the study of the role of cognition in realistic tasks, that is, in interacting with the environment' (Cacciabue and Hollnagel 1995, p. 57). Since then, researchers in the area of naturalistic decision-making have adopted this view and expanded upon it to more fully describe complex cognition in natural settings (Klein *et al.* 2000). Specifically, naturalistic contexts are said to be environments in which complex and emergent cognitive processes arise (i.e. macrocognitive processes), as opposed to 'microcognitive' processes described as cognition used in laboratory studies (Hutton *et al.* 2003, Klein *et al.* 2003, Helander 2006). Macrocognition was offered as a means of developing 'a framework for studying and understanding cognitive processes as they directly affect performance of natural tasks,' (and representative macrocognitive functions were described as) 'decision-making, situation awareness, planning, problem detection, option generation, mental simulation, attention management, uncertainty management, expertise and so forth' (Klein *et al.* 2000, p. 173). More recently, this notion was generalised to emphasise macrocognition as knowledge-based performance (cf. Rasmussen 1983), in consideration of how expertise is utilised 'out of context' (Hoffman 2007) to deal with complex cognitive work (Schraagen *et al.* 2008b).

More recently, others have used the concept of *macrocognition in teams* to focus on this form of complex cognition in collaborative settings (Warner *et al.* 2005, Letsky *et al.* 2008) and the internalised and externalised cognitive processes occurring during team problem-solving. This is the particular instance of the more general area of team cognition research and it is the focus of this article. Specifically, team cognition theory tends to emphasise coordinating actions among individuals; for example, understanding how team members are able to sequence their actions in service of team tasks. But, consistent with the general view of macrocognition, macrocognition in teams focuses more on the *knowledge work* done by a team. Within this area, the knowledge work is described as the transformation of data and informational inputs arising in unique contexts to build knowledge that enables the team to develop problem representations and candidate solutions for the problem at hand. As such, our approach to macrocognition in teams represents a particular aspect of team cognition where the emphasis is on building knowledge in the context of collaborative problem-solving. Note that, although team cognition theory does include 'knowledge' in areas such as shared mental models and related forms of overlapping knowledge structures (Cannon-Bowers *et al.* 1993, Marks *et al.* 2000, Mathieu *et al.* 2000, Mathieu *et al.* 2005, Salas and Fiore 2004, Rentsch and Davenport 2006), that work focuses more on coordination processes and how such knowledge supports teams in their execution of previously learned task procedures in familiar environments. For example, team cognition research studies how to understand and train for situations such as an aircrew encountering a problem due to an engine failure and how they interact to diagnose the situation and generate a course of action. Importantly, recent reviews have examined factors of team cognition and shown the research impact of various measurement techniques of shared mental models (DeChurch and Mesmer-Magnus 2010a), as well as outlined critical distinctions between compositional and compilational conceptualisations of cognition within teams (see DeChurch and Mesmer-Magnus 2010b) and how these all relate to process and performance outcomes. Nonetheless, macrocognition in teams is distinguished from the broader area of team cognition research in that it *does not* involve selecting and executing 'a set of possible procedures or rules, but [rather] involves the generation or adaptation of rules to novel situations. This is the focus of macrocognition in teams, understanding the process by which individuals and teams generate new knowledge for addressing unique problems' (Rosen *et al.* 2008, p. 15).

Our approach, then, aligns with extant theorising on macrocognition as a form of knowledge-based work with an emphasis on an adaptation to complexity (Klein *et al.* 2003, Schraagen *et al.* 2008a). Furthermore, fitting with what others have described as the conditions under which macrocognition functions and processes are performed, our focus is on teams operating in uncertain and time-stressed situations, with ill-defined goals, and high stakes, and working to solve one-of-a-kind problems (Schraagen *et al.* 2008b). But, while Klein *et al.* (2003) do note that the 'emphasis in macrocognition is on cognitive functions, and teams can perform these' (p. 82), their definition more broadly encompasses complex cognitive activity as it arises in context and through the use of information technologies and does not specify the nature of the team interaction involved. Thus, when considering this theoretical context, that is, collaboration to generate solutions for rare problems, we have a unique but critically important area of naturalistic decision-making (NDM) research. As such, our focus on macrocognition is narrowly defined to macrocognition in teams to address this gap. Our goal, then, is to augment this broader area of inquiry by better specifying the processes and products associated with macrocognition in teams so as to complement developing conceptualisations of macrocognition.

1.1.1. *Parsing the macrocognition research space*

We close this section by pointing out that, across the more recent uses of this term, what we see are arguments having to do with both the realisation of cognition in the real world (cf. Hoffman and Deffenbacher 1993) as well as a need to address varied levels of analysis in understanding cognitive processes. As discussed by Fiore (2006, 2007), if we look more closely at these distinctions, we can find that there are three somewhat inter-related issues arising from the usage of the term macrocognition (see Table 1 for a conceptual breakdown of these issues).

First, there is a factor having to do with levels of complexity. This is manifest in distinctions comparing and contrasting the cognitive processes required, for example, in solving simple puzzle problems versus those involved in complex reasoning. Second, there is a contextual factor. This arises when comparisons are made between research examining cognition in the laboratory versus research assessing it in the field. The last is a distinction having to do with cognition emerging in individuals versus in teams and how team interaction both drives and is driven by individual cognition. Further, these levels of analysis have with them concomitant differences in time scale (Klein *et al.* 2003, see also Liljenström and Svedin 2005). At the microcognitive level, responses generally occur in a timeframe of milliseconds to seconds. But at the macrocognitive level, responses generally occur at the rate of minutes to tens of minutes. Thus, when addressing how to

Table 1. Conceptual breakdown of issues associated with usage of macrocognition term.

	Microcognition		Macrocognition	
	Individual	Team	Individual	Team
Laboratory settings				
Field settings				

conceptualise and measure complex cognition, we see that it is critical to identify both the differing levels and varied time scales.

In short, we bring out these distinctions because they are foundational to clarifying how the concept of macrocognition can be more efficaciously pursued (see Shraagen *et al.* 2008b for a fuller discussion of the epistemological and ecological issues associated with these distinctions). As Table 1 demonstrates, it is conceivable to cross each of these (e.g. study complex team problem-solving in the lab) and clarity in specifying what exactly is being examined, and at what level, will enable a better discussion of macrocognition in the literature. Thus, the benefit of these distinctions is that we can now better use concepts that provide a number of boundary conditions for understanding the emergence and use of complex cognition in collaborative environments. What is necessary, then, is a multilevel approach where researchers theorise about multiple levels of analysis (e.g. individuals, groups and organisations) in order to better specify how they are conceptualising construct(s) that can cut across levels (Klein and Kozlowski 2000a,b, Dansereau and Yamarino 2002). In the absence of a multilevel theoretical approach, one might not only miss relationships, but also inaccurately specify the relations they are attempting to address (Mumford *et al.* 2002, Hackman 2003).

With these broader theoretical issues as our stepping off point, in the next section we more specifically present our approach for examining *macrocognition in teams*. Our purpose here is to take the necessary first steps to more clearly define and measure dynamic, cognitive and collaborative processes in complex environments; that is, to better examine the nature of macrocognition in teams. We have drawn from the literature in team cognition (e.g. Salas and Fiore 2004) as well as recent thinking in macrocognition (Letsky *et al.* 2008) and, from these, we put forth a candidate set of preliminary processes. We hope to motivate discussion and debate, as well as empirical examination, so as to determine the viability and the uniqueness of these ideas within the broader literature on cognition and collaboration.

2. Key assumptions in studying macrocognition in teams

The theory and measurement of macrocognition in teams is a multidisciplinary endeavour. As such, many terms can have different meanings depending upon their disciplinary origin. In an attempt to establish common ground and centre these within team measurement theory, our initial description of theory and measurement primarily adopts terminology from psychology. In this section, we briefly enumerate a set of assumptions that lay the foundation for what we argue is a principled approach to understanding this form of complex cognition in collaborative contexts.

As noted, the general focus of macrocognition in teams is on the building of knowledge within a problem-solving context, that is, new knowledge as a product of collaboration. Related to this, it focuses on the process of building new knowledge at *both* the individual and team levels in service of problem-solving. From the theoretical standpoint, then, this involves the transformation of team knowledge into externalised knowledge through individual and team knowledge building processes. Our interest is in developing a theoretical approach capable of understanding and predicting performance in one-of-a-kind problem-solving situations that arise in teams quickly assembled to solve problems (i.e. in ad hoc teams put together to perform in complex operational environments). As such, we specifically focus on knowledge building as that is a core element of problem-solving in these contexts. We suggest that, in order to test this notion, we must measure knowledge and knowledge building separately. Further, data on internalised knowledge and individual knowledge building processes need to be assessed at the individual level and aggregated in some fashion to the team level. Nonetheless, we recognise that, depending on how individual results are aggregated to the team level, care must be taken that individual effects not be lost. But, because such research is developed to understand and predict team level outcomes, pertinent variables in our model must ultimately be indexed at the team level of analysis.

At a more fine-grained level, data on internalised knowledge is appropriately modelled through both introspective methods and inference based on observation (e.g. measuring intent via gaze using eye tracking; using facial expressions). But individual knowledge building may be captured by introspective methods or by direct observation. Data on externalised team knowledge and team knowledge building are collected directly at the team level of analysis. Specifically, data on externalised team knowledge is captured through communications and the artefacts created by the team. Related to this, data on team knowledge building are captured through communications data, and non-discourse communications (e.g. gestures, facial expressions and artefacts) and may be indexed in terms of both content and flow. Thus, the content can be indicative of what is being constructed while how it is communicated is informative as to process.

Given the above, we recognise that, when we measure internalised and externalised knowledge, we are capturing a snapshot or 'state' of knowing at a given point in time. Further, in an iterative fashion, internalised and externalised knowledge serve as both antecedents and consequents of individual and team processes. Thus, internalised and externalised knowledge and knowledge building processes need to be measured over time. Similarly, in an iterative fashion, internalised team knowledge interacts with individual and team processes to predict externalised team knowledge. And externalised team knowledge interacts with individual and team level processes to predict problem-solving outcomes.

Last, we recognise that a number of the dimensions associated with macrocognition in teams have been studied in the team research field. Nonetheless, they have often been studied using different terminology. For example, shared mental model and transactive memory theories address some of the dimensions associated with what we are referring to as internalised knowledge and team knowledge building categories. Research on problem-solving and NDM has investigated dimensions associated with what we are referring to as individual and team knowledge building. Nonetheless, we argue that the model of macrocognition in teams we are developing is unique in that we specify the manner in which internalised individual knowledge, externalised team knowledge, and individual and team knowledge building processes may influence each other and how these dimensions change at different phases of the collaborative problem-solving task. Prior theories address only certain pieces of this puzzle (e.g. impact of shared knowledge on process but not the reverse). Furthermore, few models have fully integrated notions of externalised team knowledge, and how this iteratively influences the problem-solving process and changes as problem-solving proceeds, with most standard team interaction measures coming out of the team performance literature. We acknowledge that these ideas are preliminary and that these notions of macrocognition in teams are also nascent. Nonetheless, we are taking the necessary first steps forward to gain a more comprehensive and potentially predictive view of this area of inquiry. The definitions, measures and measurement model described and depicted in the following sections explain the expected relations between five major types of measures that we argue must be collected to help develop, test and refine a model of macrocognition in teams.

3. Foundational definitions in studying macrocognition in teams

In this section, we first briefly describe some of the core elements of our view of knowledge building in teams and present representative definitions of data, information and knowledge, and how these instantiate the knowledge building process. We conclude with a formal definition of knowledge building and macrocognition in teams in order to illustrate how these fit together in support of research to understand complex collaborative problem-solving.

First, we consider the transformation of data, to information, to knowledge, and how this can be construed of as a *product* of the collaborative process (cf. Rowley 2007). We suggest that, in the context of collaborative problem-solving, data are what is provided by the task itself (e.g. the problem givens). Data are transformed to information when structured and contextually grounded, that is, it becomes information when it is organised to provide meaning within a particular context. Information becomes knowledge when it is integrated with other task-related information and/or experience and made useful for action via synthesisation with the problem-solving context. Thus, knowledge can be considered as emergent in that it has been *created* through the team's interaction. With this as our foundation, we state that knowledge building is generally defined as the transformation of data, to information, to knowledge. More formally, we suggest that context represents a critical component of this process and that knowledge building requires an increasingly tight connection to the problem-solving context. Furthermore, we specifically define process, in our conceptualisation of knowledge building, as a series of related actions engaged by individuals or the team, and measured over time, that bring about some outcome, result or product. In this sense, then, knowledge building is a *process* that leads to the *product* of *knowledge*; it is a process where isolated bits of data are organised and then integrated into a tightly coupled network of actionable knowledge for use within a particular problem-solving context. Thus, for data to become information, it must be organised and related to the problem-solving. For information to become knowledge, it must be integrated in such a way that it is actionable. It is the expanding volume of problem-relevant knowledge, when taken as a whole, which enables action towards solving a problem.

Second, while we note that collaborative problem-solving involves more than just knowledge building, as discussed earlier, this activity is at the core of macrocognition in teams. Thus, to ground our conceptualisation of knowledge building within the larger context of collaborative problem-solving, we state that macrocognition in teams is the process of transforming internalised team knowledge into externalised team knowledge through individual and team knowledge building processes. Internalised knowledge refers to the collective knowledge held in the individual minds of team members. With respect to this knowledge, we are interested in the amount held and the degree to which this knowledge is overlapping or specialised/non-overlapping. Externalised team knowledge refers to the integrated information that has been made actionable *and* explicitly agreed upon, or not openly challenged or disagreed upon, by a single or multiple team members. In other words, externalised knowledge is an emergent property resulting from individual and team processes. Team knowledge building includes actions taken by teammates to process data and disseminate information, and to transform that information into actionable knowledge for team members. Individual knowledge building includes actions taken by individuals in order to process and organise data in the context of the problem, and integrate information to create their own knowledge. These processes can take place inside the head (e.g. reading and mentally

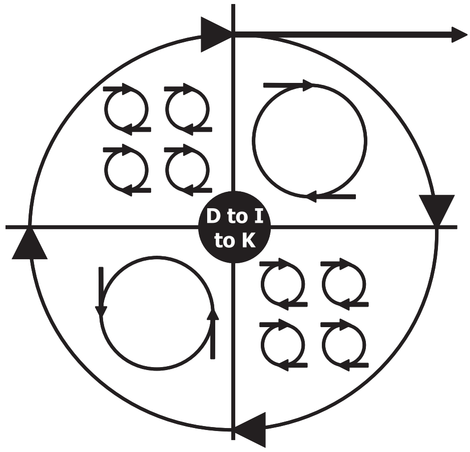

Figure 1. Qualitative representation of macrocognitive processes occurring across individuals and the team within a particular stage of problem-solving.

rotating objects) or may involve overt actions (e.g. accessing a screenshot, creating graphs and making tables).

Third, to help ground these ideas, we present a qualitative representation of macrocognition in teams. Although prior conceptualisations of macrocognition in teams presented concepts sequentially (Warner *et al.* 2005), our view is meant to capture how the *parallel*, *interdependent* and *iterative* nature of these processes unfold in the context of collaboration. As initially described in Fiore *et al.* (2008a), Figure 1 illustrates this conceptual representation developed to reify the *nested structures* invariant in multilevel phenomena. Specifically, this illustrates the iterative processes engaged by a four-person team interacting to build knowledge and solve problems. The figure shows two sets of four circular arrows, representing individuals in the team, and two sets of larger circular arrows, representing the team as a whole. The arrows are used to represent the iterative nature of the macrocognitive processes as they unfold individually and collectively. Next, the team is encompassed by a larger circular arrow to illustrate the overall iterative nature of this knowledge building effort as it unfolds within and across the individuals. Finally, the arrow leaving the circle illustrates movement *through* stages of problem-solving. Thus, the overall process occurs across the stages of collaboration. Essentially, this is a conceptual representation of how individuals and teams iteratively interact to move from data, to information, to knowledge in service of problem-solving.

Finally, Table 2 presents the formal definition and characteristics of macrocognition in teams. As we noted earlier, although theories of team cognition has discussed elements of the ideas we have just articulated (see Salas and Fiore 2004 for a discussion of these theories), these prior approaches have not, in total, specified the interactive influence of these dimensions within phases of problem-solving, nor across the phases. In particular, we take into account the somewhat discrete activities engaged by a team in service of problem-solving. These include phases such as problem model development and solution generation (Fiore and Schooler 2004, Warner *et al.* 2005, Fiore *et al.* 2008a for a discussion of problem-solving stages engaged during collaboration). Further, earlier approaches have not fully addressed knowledge building at the individual *and* team level while investigating macrocognition in teams as an emergent cognitive property of the team's interaction.

Table 2. Definition and characteristics of macrocognition in teams.

Definition	Macrocognition in teams is the process of transforming internalised team knowledge into externalised team knowledge through individual and team knowledge building processes
Unit of analysis	Both the individual team member and the whole team are appropriate units of analysis
Cognitive process focus	The focus is on individual and team knowledge building; it incorporates internalised and externalised cognitive processes
Empirically studied	It can be studied in operational field settings and in the lab given domain rich collaborative problem-solving scenarios
Summary	Macrocognition in teams is collaboratively mediated occurring within and across individuals during team interaction; it is influenced by artefacts in the environment and/or created by the team; it is an emergent cognitive property and it develops and changes over time; it is domain and collaboration environment dependent

4. Dimensions of macrocognition in teams

In this section, we more specifically describe the dimensions of macrocognition in teams as we conceptualise them in a measurement framework designed to help us capture these dynamic processes of collaboration (refer to Figure 2). As noted earlier, our focus of macrocognition in teams is 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 planning context. Stated simply, macrocognition in teams focuses on the process of building new knowledge at the individual and team levels. Overall, these dimensions represent an attempt to capture the multidimensional nature of macrocognition in teams rather than focusing on a single component as is sometimes done in the team cognition literature (e.g. shared mental models). These dimensions were culled from prior research and theory on macrocognition (Klein *et al*. 2000, 2003), team cognition in general (Salas and Fiore 2004), and collaborative problem-solving in particular (Warner *et al*. 2005, Stahl 2006). Thus, we have integrated elements of prior theories and are putting them forward as our initial thinking on how to build a model that describes collaborative problem-solving arising in complex planning situations and which emphasises the creation of new knowledge.

For illustrative purposes, as we describe our model, we use examples from recent research in macrocognition, specifically, the non-combatant evacuation operation (NEO) scenario (Letsky *et al*. 2008). The 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 organisational and agency backgrounds along with varied levels of expertise. In this task, an ad hoc team must gather and synthesise information to develop their solution, that is, an evacuation plan for the hostages (Rosen *et al*. 2008). We first describe *Individual Knowledge Building* processes along with its subcomponents and associated measurement methods. Second, we discuss *Team Knowledge Building* and its component processes along with what we suggest are methods appropriate for measuring these concepts. Third, we discuss *Internalised Knowledge* and follow this with a discussion of *Externalised Knowledge*. We conclude with a description of *Problem-solving Outcomes*, that is, the means through which effective and ineffective team performance can be evaluated.

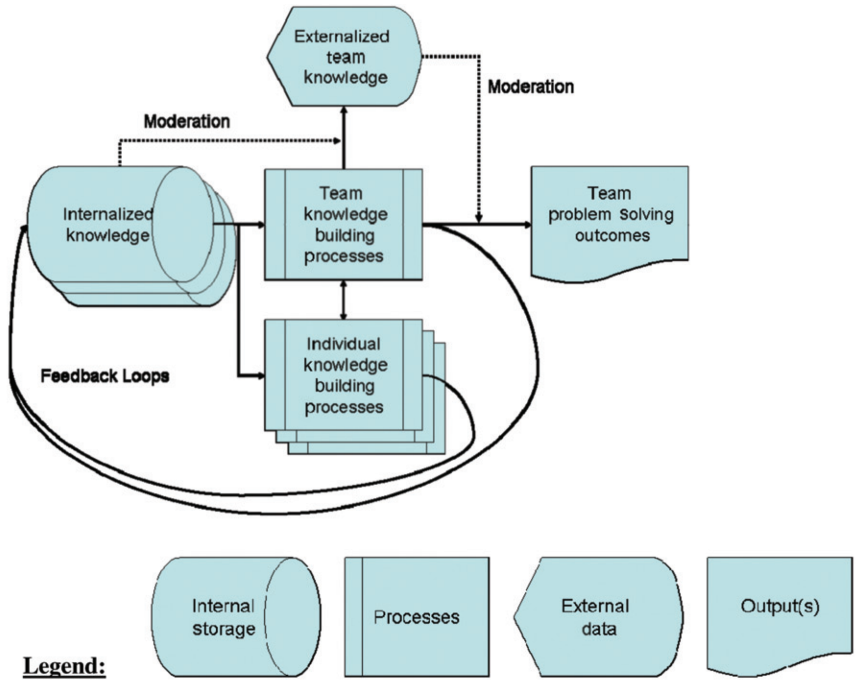

Figure 2. Measurement model for research on macrocognition in teams.
Note: Multiple overlapping symbols indicate representations for multiple team members.

These are all discussed along with candidate measurement methods appropriate for the processes along with representative indices for measurement to more fully assess macrocognition in teams.

5. Individual Knowledge Building processes

Individual Knowledge Building is a process which includes actions taken by individuals in order to build their own knowledge. These processes can take place inside the head (e.g. comprehending text) or may involve overt actions (e.g. accessing a screenshot). Raw data on individual knowledge building are captured using methods, such as eye tracking, keystroke analysis and coding of verbal or written transcripts. These data are then aggregated in some way to the team level of analysis. Below we list the specific subcomponents making up this dimension.

The first is the process of *Individual Information Gathering*. Here the process involves actions individuals engage in to add to their existing knowledge, actions such as reading, asking questions, accessing displays, etc. Next is the process of *Individual Information Synthesis*. This involves comparing relationships among information, context, and artefacts to develop actionable knowledge. Last is the process of *Knowledge Object Development*. Here the process involves creation of cognitive artefacts that support the creation of actionable knowledge for the task. Table 3 lists the particular measurement methods we suggest are appropriate for the processes associated with *Individual Knowledge Building* along with candidate indices and an example of each in the context of the NEO scenario.

Table 3. Measurement methods, indices and example of *Individual Knowledge Building*.

Individual information gathering	
Measurement methods	Eye-tracking, communication audio, computer-generated messages and searches, asking behaviour logged by experimenter on collaboration logger
Indices	Possible indices include the 'depth and breadth' of information seeking behaviours (e.g. searching for an appropriate vehicle for a given objective or searching for the location of needed personnel resource); dwell times in 'areas of interest'
Example	Team member studies the personal as well as collaborative maps which display the waypoints where resources may be held
Individual information synthesis	
Measurement methods	Information relationship density, nodal linkages, concept maps, similarity among knowledge objects; post-performance debrief/questionnaire, written or verbal probes during scenario
Indices	Possible indices include nature of connectedness between concepts, quantity of connections between concepts
Example	The Humanitarian Personnel Specialist synthesises information about the different personnel he is in charge of and about the objective of the first operation into a set of criteria of what resources he should send to which grid
Knowledge object development	
Measurement methods	Analysis of created notes, diagrams, tables and sketches
Indices	Quantity of diagrams/tables, structure of diagrams/tables and number of pushpins created, relation between pushpins
Example	The Air Vehicle Specialist creates a table on a document outlining the three most appropriate means for moving parcels to a given zone and provides it to the Humanitarian Personnel Specialist so that they may refer to it when planning how to get parcels to pickup zones

6. Team Knowledge Building processes

Team Knowledge Building is a process which includes actions taken by teammates to disseminate information and to transform that information into actionable knowledge for team members. Raw data on team knowledge building are collected directly at the team level of analysis through the use of transcripts and other methods of logging team communications. Thus, team knowledge building processes are measured using communication transcripts, transcripts of written communication, coding of graphics and text written on shared workspaces. Next, we describe the specific subcomponents making up this dimension.

First, the process of *Team Information Exchange* involves passing relevant information to the appropriate teammates at the appropriate times. Second, the process of *Team Knowledge Sharing* involves explanations and interpretations shared between team members or with the team as a whole. These explanations may be augmented by graphic visualisations on shared workspaces. Third, *Team Solution Option Generation* involves the process of developing and offering potential solutions to a problem. Fourth, *Team Evaluation and Negotiation of Alternatives* describes a process of clarifying and discussing the pros and cons of potential solution options. This could include clarifying pieces of information, verbally

Table 4. Measurement methods, indices and example of *Team Knowledge Building*.

Team information exchange	
Measurement methods	Verbal, written, and sketched, communications between team members
Indices	Quality, amount, flow/sequencing, and timing of information exchanged; anticipation ratio (i.e. the ratio of passing to asking behaviour) collected from the collaboration logger. Components of coordinated awareness of situation by teams (Gorman *et al.* 2005)
Example	During the discussion of where to establish the land base, the Military Personnel Specialist points out that the land base location suggested by other team members is extremely far from any military personnel, which may be critical to completing a mission
Team knowledge sharing	
Measurement methods	Verbal, written, and sketched, communications between team members
Indices	Quality, amount, flow/sequencing, and timing of knowledge exchanged, percentage of teammates sharing knowledge
Example	The Humanitarian Personnel Specialist posts information memos on the shared map that highlight for all team members where resources such as pallets and humanitarian workers are located
Team solution option generation	
Measurement methods	Verbal, written, and sketched, communications between team members
Indices	Number of potential options offered, percentage of teammates offering options, timing of option generation; solutions generated in proportion to total communications
Example	The team develops specific options regarding the transportation of supplies from the base to a grid where it is needed
Team evaluation and negotiation of alternative*s*	
Measurement methods	Verbal, written, and sketched, communications between team members
Indices	Number of clarifications requested and provided, number of supporting information points and/or conflicting information points offered per solution ultimately chosen. Percentage of teammates who participated in the evaluation of alternatives. Flow pattern of communication among members regarding evaluation of alternatives. Degree of following behaviour within a team communication
Example	After the transportation specialist suggests that even though the helicopter at the base is more expensive to operate it can still deliver the supplies faster than the helicopter on the carrier, the team discusses the pros and cons of either option, such as what the impact of each option is on the refugees
Team process and plan regulation	
Measurement methods	Verbal, written, and sketched, communications between team members
Indices	Number of times a critique is offered, percentage of teammates contributing to the critique or re-evaluation of the team's plan, timing of regulation or replanning efforts
Example	After completing one operation, the team receives feedback that one of their planes was lost due to bad weather. The air vehicle specialist adamantly states that the cost of the airplane far exceeds what they would spend on higher reliability weather reports. Team members unanimously agree to purchase the highest reliability information possible in all subsequent planning

simulating the ripple effects of offered alternatives, attempting to persuade other teammates regarding the relative efficacy of alternatives. Last, the process of *Team Process and Plan Regulation* involves discussing or critiquing the team's knowledge building process or plan following feedback on its effectiveness. Table 4 lists the particular measurement methods we suggest are appropriate for the processes associated with *Team Knowledge Building* along with candidate indices and an example of each in the context of the NEO scenario.

7. Internalised Team Knowledge

Internalised Team Knowledge refers to the collective knowledge held in the individual minds of team members. With respect to this knowledge, we are interested in the amount held and the degree to which this knowledge is overlapping or specialised/non-overlapping. Raw data associated with internalised knowledge are collected from individuals and then aggregated in some fashion to form a team level score. *Internalised Team Knowledge* is measured by eliciting it from individual team members using methods, such as card sorting, concept mapping, paired comparison ratings, scenario probes (e.g. by confederates), questionnaires, bio-data (experience) or knowledge tests. These data are then aggregated to the team level to form a single score for each team under each dimension or sub-dimension. *Internalised Team Knowledge* consists of the following subcomponents.

First, *Team Knowledge Similarity* can involve the degree to which differing roles understand one another (e.g. how well a land/sea vehicle specialist understands a humanitarian specialist), or how well the team members understand the critical goals and locations of important resources (shared situation awareness). Second, *Team Knowledge Resources* involves team members' collective understanding of resources/responsibilities associated with the task. This could be examined through a performance assessment survey given to all members of the team at the end of each operation. Each individual team member would respond as to the relevant knowledge they have via paper and pencil method. Then, the whole team would be asked what relevant knowledge the team as a whole knew. This could also be examined through visual analysis of the eye tracking videos in conjunction with an assessment of the plan. If a team member did not see a critical and relevant piece of information, then that could lead them to make a plan that was not optimal and would then lead the team to receive a lower score on their plan. Table 5 lists the particular indices we suggest are appropriate for *Internalised Team Knowledge*. We additionally describe the specific forms it may take dependent upon the particular issues being assessed.

8. Externalised Team Knowledge

Externalised Team Knowledge refers to facts, relationships and concepts that have been explicitly agreed upon, or not openly challenged or disagreed upon, by factions of the team. With respect to this knowledge, we are interested in its accuracy and completeness. This is distinct from *information* in that it signifies information that has been processed by team members via some form(s) of analysis. It includes not only components of knowledge agreed upon, but also aggregations of knowledge forming a team's developing problem representation. In this regard, we are interested in the degree to which a team's problem representation(s) change during the problem-solving process, how the subcomponents of the problem that have been generated lead to particular problem solutions, and how these may differentially impact how they are negotiated. *Externalised Team Knowledge*

Table 5. Measurement methods, indices and example of *Internalised Team Knowledge*.

Team knowledge similarity	
Indices	Indexed as an average distance score, a correlation, or percentage of agreement
Specific forms	Task mental model similarity: The degree to which teammates' mental models of relatively stable task characteristics (e.g. equipment, procedures) converge (Cannon-Bowers *et al*. 1993)
	Team interaction knowledge similarity: The degree to which teammates' knowledge of their relatively stable positional roles, interdependencies and interaction patterns converge. This is referred to in the shared mental model literature as team interaction mental models (Cannon-Bowers *et al*. 1993)
	Teammate knowledge similarity: The degree to which teammates' mental models of one another's relatively stable levels of skill, knowledge, experience, dispositions and/or habits converge. This dimension is referred to in the shared mental model literature as shared mental models of teammates (Cannon-Bowers *et al*. 1993) and in the transactive memory literature as teammate knowledge consensus (Austin 2003)
	Shared situation awareness: The degree to which teammates' awareness and interpretation of moment-to-moment changes in their collective situation converge. This can also be evaluated by determining critical landmarks or by inserting perturbations and then observing team member interaction in response to this (e.g. using ASU's CAST method; Gorman *et al*. 2006). This construct has been defined previously by (Stout *et al*. 1994, Endsley 1995, Cooke *et al*. 2001b)
Team knowledge resources	
Indices	This can be indexed as a sum or average of all team members' knowledge, or as a percentage of the relevant knowledge (defined a priori as the criterion space) that is held by at least one team member
Specific forms	Task knowledge stock: accurate task-relevant knowledge held by team members. This would include knowledge about task strategy and equipment. This dimension is included within the components of transactive memory (Austin 2003) and is referred to as task mental model accuracy within the shared mental model literature (Rouse *et al*. 1992, Cooke *et al*. 2001a)
	Interpositional knowledge: Accurate knowledge regarding position-specific roles, goals, responsibilities, access to information, constraints, and interdependencies with other team positions. This dimension is referred to as team interaction mental model accuracy within the mental model literature and as interpositional knowledge within the general team literature (Volpe *et al*. 1996, Cooke *et al*. 2000)
	Recognition of teammate expertise: Total amount of accurate knowledge regarding teammates' expertise and behavioural habits. This dimension is referred to in the literature on transactive memory as teammate knowledge accuracy (Austin 2003), in the literature on shared mental models as teammate mental model accuracy (Rouse *et al*. 1992, Mathieu *et al*. 2005), and in the schema literature as teammate schema accuracy (Rentsch 1993)
	Individual situation awareness: Accurate awareness of moment to moment changes in the team's environment. The construct has been defined previously by Endsley (1995)

is measured from oral or written transcripts of team communications and shared workspaces. Specifically, raw data regarding externalised team knowledge can be captured through time stamped audio and written transcripts and through the external artefacts generated with shared workspaces during the collaboration. Next, we list the sub-components of this dimension.

Table 6. Measurement methods, indices and example of *Externalised Team Knowledge*.

Externalised cue-strategy associations	
Measurement methods	Oral or written transcripts of team communications and artifacts developed on shared workspaces
Indices	Percent or number of cues explicitly planned for and the quality of those cue-strategy associations
Example	Linkages between weather data and resources appropriate for use in certain weather conditions
Pattern recognition and trend analysis	
Measurement methods	Oral or written transcripts of team communications and artifacts developed on shared workspaces
Indices	Number or percent of trends and task-related patterns collectively agreed upon that are correct or incorrect, amount of time needed to correctly agree upon those patterns or trends
Example	There is an optimal plan that can be determined based on cost and resources moved. If the air specialists creates a route for an aircraft to leave a carrier, go over to a site to pick up personnel, and then drop them off in another location, it could be considered a pattern, especially if it is not challenged by the other members of the team
Uncertainty resolution	
Measurement methods	Oral or written transcripts of team communications and artifacts developed on shared workspaces
Indices	Number or percentage of problem variables in which a team level assessment has been agreed upon and that assessment is correct or incorrect, the amount of time needed to correctly agree upon those assessments. Nature of 'consensus' events logged by experimenter
Example	The resolution of the plan and the individual components of the plan, would be an example of uncertainty resolution. Each team member is responsible for his or her resources, but also for communicating with teammates to move those resources to their respective locations. At first, there is a certain degree of uncertainty about the best method to move those resources, and it is the job of the team members to resolve that and come to a consensus with their plan they submit

First, *Externalised Cue-strategy Associations* describe the team's collective agreement as to their task strategies and the situational cues that modify those strategies (and how). Second, *Pattern Recognition and Trend Analysis* describes the accuracy of the patterns or trends explicitly noted by members of a team that is either agreed upon or unchallenged by other team members. Third, *Uncertainty Resolution* is the degree to which a team has collectively agreed upon the status of problem variables (e.g. hostile/friendly). Table 6 lists the particular indices we suggest are appropriate for the processes associated with *Externalised Team Knowledge* along with an example in the context of the NEO scenario.

9. Team Problem Solving Outcomes

In the context of our collaborative planning situation, *Team Problem Solving Outcomes* are assessments of quality relating to a team's problem solutions or plan. In this regard, we are interested in the degree to which a team's solution effectively meets the criteria for problem resolution, the efficiency with which the plan does so, and the speed with which the team

Table 7. Measurement methods, indices and example of *Team Problem-solving Outcomes*.

Quality of plan (problem-solving solution)	
Measurement methods	Output from function hooks in the task that documents number of objectives achieved (e.g. 67 refugees out of 100 rescued) at end of operation
Indices	Number of objectives completed, quality of the resolution to a problem
Example	Each operation has an objective to complete, for example, rescuing a certain number of refugees from a particular zone. The percentage of refugees actually extracted from this zone would show the quality of a plan in regards to its problem-solving solution. If one team rescues all 100 refugees and another only 80, then the first team has a higher quality plan in terms of solving the problem. However, efficiency remains a factor (see below)
Efficiency of planning process	
Measurement methods	The operation time, anticipation ratios, number of interactions
Indices	Length of problem-solving process
Example	A team that requires 32 min for planning versus a team that quickly plans and inputs in 17 min showcases a strong difference in planning efficiency, assuming their output remains high quality
Efficiency of plan execution	
Measurement methods	Functions in the simulation that provide data on number of resources spent per planning phase and the impact on civilian population
Indices	All financial costs associated with the plan including labor (that is, time a plan becomes executed until the accomplishment of plan objectives multiplied by resources (man hours, gas, etc.)
Example	The quality of a plan utilising a high amount of unnecessary air travel to consolidate humanitarian aid parcels will likely be much lower than one that uses efficient ground travel to consolidate parcels to a single pick-up point for the expensive air vehicle. The end result of impact on civilians may be the same, but the influence of cost affects its quality

generates their plan. Raw data regarding team problem-solving outcomes can be captured through time stamped audio and written transcripts and through the external artefacts created during solution generation. This dimension is made up of the following subcomponents.

First, *Quality of Plan (Problem Solving Solution)*, involves the degree to which the solution adopted by a problem-solving team achieves a resolution to the problem (e.g. limit fatalities, limit destruction). Second, *Efficiency of Planning Process* describes the amount of time it takes a problem-solving team to arrive at a successful resolution to a problem. Third, *Efficiency of Plan Execution* describes the quality of the plan (e.g. number of lives saved) divided by the amount of resources used to accomplish this and the amount of time the plan takes to unfold. Table 7 lists the particular measurement methods we suggest are appropriate for the processes associated with *Team Problem-Solving Outcomes* along with candidate indices and an example of each in the context of the NEO scenario.

10. Conclusions

To conclude, one of the significant challenges for the burgeoning field of macrocognition is the development of approaches that are able to more fully describe complex problem-solving behaviours. This is most certainly a necessary factor for our understanding of complex cognition unfolding across individuals interacting in teams; that is, macrocognition in teams. But, though this is necessary, it is not sufficient. Any coherent approach to macrocognition in teams requires, not only an understanding of the many factors contributing to team interaction, but also models addressing the inter-relationships that emerge when individuals and teams collaborate to solve complex problems.

In this article, we have begun the process of accounting for these types of inter-relationships as they arise in the context of macrocognition in teams. As noted earlier, by more clearly identifying levels of cognition as they unfold in collaborative activity, our goal is to move the field towards a multilevel theoretical understanding of process and performance (see also Fiore *et al.* 2008b). Theoretical models with a multilevel approach can take on differing forms, for example, a 'cross-level model in which higher-level variables are hypothesised to moderate the relationship of two or more lower-level variables . . . [or] models focused . . . on the role of the individuals in shaping the organizational context' (Klein *et al.* 1999, p. 246). Such approaches support a more sophisticated understanding of how to conceptualise construct(s) cutting across levels (Klein and Kozlowski 2000a,b, Dansereau and Yamarino 2002). By developing models for cross-level cognitive research, we significantly gain explanatory power in service of diagnosing the causal factors associated with performance. But we need to additionally consider whether there are additional levels of analysis to consider, that is, levels above, below, or between our areas of inquiry. As an example, by bracketing our main level of interest, that is, collaboration, with a level above (i.e. teams of teams; organisation), and a level below (i.e. individuals), we are likely to more accurately explain the causes of effective and ineffective interactions (Hackman 2003).

Although we have drawn primarily from the team cognition and related literatures for our model development, to further such approaches, it might be warranted for researchers in collaborative cognition to adapt theory and methods from additional scientific disciplines, including complex systems theory and cognitive science in order to better understand the nature of the inter-relations emerging in complex environments (Alberts *et al.* 1999, Fiore *et al.* 2008b). The notion is that, because of the complexity inherent in collaborative environments, it might be useful to consider *Team Interaction* as a network of non-linear interactions within an open system, which produces a form of self-organisation and emergence (cf. Liljenström and Svedin 2005).

More generally, by following such an approach we may be able to explore patterns of similarity in complex interacting systems across the physical, biological or social world and do so while simultaneously accounting for different levels of analysis. For example, as noted by Liljenström and Svedin (2005), when considering systems in the biological sciences, microscopic can refer to the molecular level and macroscopic to the organ level. A conceptually similar approach is followed in organisational research where microscopic refers to the behaviour of individuals working alone and macroscopic is used to capture behaviour at the level of an entire organisation (Wagner and Hollenbeck 2004). Understanding the tightly coupled nature across such levels enables a more thorough examination of their mutual influence. Thus, our point here is that adopting such an approach might enable research on macrocognition in teams to mature in its description of the varying levels of cognition, how they interact, and how they influence each other (Fiore *et al.* 2008b). If so, complex systems theory may help the field better understand the intricacies arising from the *nested structures* invariant in multilevel phenomena.

In sum, in this article we have made steps towards describing the intricate relationships among macrocognitive processes within teams. This involved accounting for the parallel, interdependent and iterative nature of these processes as they unfold in the context of collaboration, as well as examining how these processes drive specific problem-solving outcomes. Our goal is to move the field closer to capturing both micro- and macrolevel phenomena, along with the inter-relations among these levels, as teams work to solve complex problems. We encourage debate and empirical examination of these ideas to help determine the degree to which this represents a unique approach within the broader literature on cognition and collaboration.

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