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HUMAN FACTORS ASPECTS OF TEAM COGNITION

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THE PROMISED VALUE OF TEAM COGNITION

Teams think. That is, they assess the situation, plan, solve problems, design, and make decisions as an integrated unit. We refer to these collaborative thinking activities as *team cognition*.

Why is team cognition important? A growing number of tasks take place in the context of complex sociotechnical systems. The cognitive requirements associated with emergency response, software development, transportation, factory and power plant operation, military operations, medicine, and a variety of other tasks exceed the limits of individual cognition. Teams are a natural solution to this problem, and so the emphasis on teams in these domains is increasing.

Since team tasks are widely varied, it follows that human factors applications involving team cognition are also widely varied. Of particular relevance to the topic of this book are the numerous software applications that involve collaborative activities. With the rapid growth of the World Wide Web, many of these applications are intended for Web-based collaboration. In the computer supported collaborative work (CSCW) domain, team cognition is relevant to the design of groupware applications (i.e., software intended for use by groups), such as group decision support systems (GDSSs) and collaborative writing environments. Web applications include chat groups, remote team decision aids, and broad multiple tool-multiple function software, such as Microsoft's Netmeeting (Web applications for team collaboration are more thoroughly addressed by van Tilburg and Briggs (chap. 30, this volume).

Why is team cognition relevant to human factors? First, measures of team cognition provide a window to some of the factors underlying team acquisition and performance of a complex

skill and can thus be valuable in diagnosing team performance successes and failures. Second, with an understanding of team cognition, training and design interventions can target the cognitive underpinnings of team performance. The ability to assess team cognition and predict team performance has far reaching implications for evaluating progress in training programs and diagnosing remediation needs during training. If one can measure the cognitive structures and processes that support task performance, then one can use this information to predict the time course of skill acquisition and the asymptotic levels of performance once skill has been acquired. Finally, understanding the cognition underlying team performance has implications for the design of technological aids to improve team performance not only in training but, more important, in actual task environments.

The use of teams to resolve task complexity is a mixed blessing, however, as teams create their own brand of complexity. In addition to ensuring that each team member knows and performs his or her own task, it is now important to ensure that the needed information is distributed appropriately among team members. The amount and type of information that needs to be distributed among team members depends on the task and the type of team.

SOME CHARACTERISTICS OF TEAMS

This leads us to our definition of *team*. A dictionary entry from www.webster.com defines team as "a number of persons associated together in work or activity." In the research literature, there exists a smorgasbord of overlapping definitions for the terms *team* and *group* (Fisher & Ellis, 1990, pp. 12–22), and

small group behavior has been studied for decades (e.g., Shaw, 1981; Steiner, 1972). Usually, *team* has been defined as a subset of the larger category *group*, where added stipulations may be made by the author. Minimally, a team is defined as a special type of group, in which members work interdependently toward a common aim (e.g., Beebe & Masterson, 1997, p. 338; Hare, 1992; Kiekel, Cooke, Foltz, & Shope, 2001; van Tilburg & Briggs, chap. 30, this volume).

A large body of the human factors team literature defines *team* to include the additional characteristics of heterogeneous individual roles and limited life span (e.g., Cannon-Bowers, Salas, & Converse, 1993; Cooke, Kiekel, & Helm, 2001). For instance, Salas, Dickinson, Converse, and Tannenbaum (1992) define team as “a distinguishable set of two or more people who interact dynamically, interdependently, and adaptively toward a common and valued goal/object/mission, who have each been assigned specific roles or functions to perform, and who have a limited life span of membership” (p. 4).

As seen in the latter definition, *team* has often been used as shorthand for *heterogeneous team*, in that team members have predefined, heterogeneous roles. For the purposes of this chapter, we shall continue in this tradition, by using the Salas et al. (1992) definition. When it becomes critical to distinguish interdependent groups that do not have specific team member roles, we shall refer to them as *homogeneous interdependent groups*. The value of this shorthand is that, in our research, we have primarily focused on interdependent groups that *do* have heterogeneous roles.

Heterogeneity

The term team is important not as jargon, but in defining the scope of one’s work and its relation to others. The restriction of teams to mean *heterogeneous* interdependent groups is important for team cognition, because knowledge or cognitive processing may or may not be homogeneously distributed among members of a team. For *homogeneous* interdependent groups, it is assumed that task-related knowledge or cognitive processing is homogeneously distributed. That is, since everyone has the same role in a homogeneous group, the ideal is for every group member to know all aspects of the task. No individual emphases are required, and individual skill levels and knowledge levels are randomly dispersed among group members.

Once the distinction of cognitive heterogeneity is introduced, however, specialization becomes a possibility and, in many instances, a likely scenario. This is the motivation for much of the recent work on team cognition measurement (Cooke, Salas, Cannon-Bowers, & Stout, 2000). Earlier efforts to measure team cognition have revolved around some sort of averaging of individual knowledge (Langan-Fox, Code, & Langfield-Smith, 2000), which is most appropriate when knowledge is homogeneously distributed. Knowledge accuracy is often scored on the basis of a single referent, thereby assuming that shared mental models are identical or nearly identical among team members. Team cognition measurement has been weaker at addressing the needs of heterogeneous groups, although work has been done on measuring the extent to which team members are able to

catalog their knowledge of who knows what and how to interact with one another (e.g., transactive memory: Hollingshead, 1998; Wegner, 1986; teamwork knowledge: Cannon-Bowers, Tannenbaum, Salas, & Volpe, 1995).

For the purposes of research on the behavior of interdependent groups, teams are generally much more interesting than homogeneous groups. Since there is no role distinction for the latter, the kind of information that has to pass among group members is also homogeneous. For instance, there is no particular reason to assume that any specific person would serve as a leader (or other focal point) for the group. This is essentially a set of individuals plus small group dynamics.

In addition to individual behavior and group dynamics, teams may be characterized by a third element, which is specialization with regard to expertise or cognition. For example, in a heterogeneous group of company officers, everyone may need to talk to the treasurer to see if his or her plans are within a realistic budget. This added layer of role knowledge is critical for dividing the cognitive labor in complex tasks. However, it also makes heterogeneous groups more vulnerable to performance failures, because there is less redundancy in the system. In a completely heterogeneous group, each task or cognitive activity is handled by only one person. If that task is critical, then a failure of that one person to perform it is also critical. However, role heterogeneity also ensures that no single team member has to know everything. This is a trade-off of heterogeneity. In most instances, teams will not be completely heterogeneous with respect to role, but will have some degree of specialization, along with some degree of overlap.

Finally, the presence of heterogeneous knowledge distribution raises questions such as how teams should be trained. Is it better if all team members are fully trained on their own role as well as the roles of other team members (i.e., full cross-training; Blickensderfer, Stout, Cannon-Bowers, & Salas, 1993; Cannon-Bowers, Salas, Blickensderfer, & Bowers, 1998; Cooke, Kiekel, et al., 2003; Volpe, Cannon-Bowers, Salas, & Spector, 1996. What if team members are only fully trained on their own roles and given a general overview of other team members’ roles? Alternatively, what if team members are only trained on their own roles, so that complexity and training time can be minimized in complementary tasks? The answers to these and other questions are dependent on understanding team cognition in groups with different roles.

Team Size

Apart from role heterogeneity, another interesting aspect of Salas et al.’s (1992) definition is that “two or more” team members “interact dynamically.” This would require that teams be small enough for team members to directly impact one another. This creates another interesting question. How much impact is required for a team to still be a team?

Social network research (e.g., Festinger, Schachter, & Back, 1964; Fisher & Ellis, 1990; Friedkin, 1998; Steiner, 1972) focuses on evaluating the impact of different interaction patterns among team members. Influence among team members is determined on a pairwise basis, such as by determining which

team members are allowed to speak to which other team members. The global pattern of influence for the team is represented in a matrix or graphical network form. Topics of interest include evolution of gross patterns over time, effectiveness of various interaction patterns for particular task types, and so on.

Team size plays an import role in addressing these issues. For instance, conflict between dyads is more likely to result in a stalemate than is conflict among larger teams. Starting with triads, larger teams permit clique formation, majority decisions, disproportionate peer influence, and so on (Fisher & Ellis, 1990). Amount of input by individual team members decreases with team size (Steiner, 1972). This is both because communication time is more limited and because of diffusion of responsibility in larger teams (Shaw, 1981).

Steiner (1972) outlines a taxonomy of types of teams and tasks, whereby individual contribution is combined in different ways to form a holistic outcome. Work of this nature is extended in the social decision schemes literature (SDS; Davis, 1973; Gillett, 1980a, 1980b; Kerr, Davis, Meek, & Rissman, 1975; SDS for quantities, SDS-Q; Hinsz, 1999). SD Schemes research involves predicting how a team will combine its input to form a decision (e.g., by majority rule, single leader). Researchers create distributions of possible decisions under different decision schemes. Then they identify the team's decision scheme by selecting the scheme whose distribution makes the observed team decision most probable.

Research areas such as these allow us to consider the ways in which individual and team cognition differ. For individual cognition, one does not address questions such as team size or heterogeneity. It is important to ask which aspects of individual cognition carry over to teams and which aspects of team cognition carry over to individuals. The answer depends on which characteristics one is interested in. Individuals cannot encounter team conflict (though they can encounter indecision); this requires a team of at least two members. Dyads cannot encounter disproportionate peer influence (though they can encounter disproportionate power roles); this requires a team of at least three. Triads cannot encounter subteam formation (though they can encounter a majority); this requires a team of at least four. So the number of team members required to interact dynamically depends on the dynamics of interest.

PERSPECTIVES ON TEAM COGNITION

Now, armed with a definition of teams, we can proceed to more precisely define and conceptualize team cognition. The definition of team cognition starts with the definition of individual cognition. Let us succinctly define *cognition* as "the understanding, acquisition and processing of knowledge, or, more loosely, thought processes" (Stuart-Hamilton, 1995). Team cognition would have to be the team's ability to do the same. This raises the question of whether teams really have cognition or not, since the team's mental faculties do not arise from a single, connected unit, such as a brain.

The what and where of the individual mind has long been a topic of debate. Perhaps an individual mind is not a single

connected unit, regardless of whether or not a brain is. Our argument for teams having cognition is the same as our argument for an individual having cognition. One can only infer individuals' cognition from the observable actions that they display.

Similarly, teams take actions as unified wholes that reflect cognition at this level. That is, teams process, store, and retrieve information (Smith, 1994; Wegner, 1986). Teams behave in a coordinated manner, even if they do not intend to do so (e.g., Schmidt, Carello, & Turvey, 1990; Sebanz, Knoblich, & Prinz, 2003). These holistic, cognitive behaviors that occur at the team level lead us to question whether team cognition must be considered an aggregate of individual cognition or if the thinking team can truly be treated as a distinct cognitive unit. The latter view of team cognition suggests that cognition exists external to a person's mind.

Collective vs. Holistic Perspectives on Team Cognition

More attention to context is needed when we start to look at team cognition. This is partly because team tasks tend to take place in complex environments, in which outcomes, actions, and interactions take on numerous possibilities. This holds not only for team cognition, but is generally true when researchers look at all complex systems and real-world applications.

But the need to pay greater attention to context is especially germane to team cognition, because it is not reasonable to consider a single information processor. Rather, we are forced to consider that the environment now includes other people—who are themselves information processors. If the team is to be thought of as a cognitive unit, then it is necessary to include a larger system in the account of cognition. Several theories of cognition would also include nonhuman aspects of the human-machine environment, such as computers, notepads, and control panels (e.g., Hutchins, 1995).

How external influences can be incorporated into cognitive theory is a question of heated debate. One major point of dispute is between symbolic information processing theories (e.g., Anderson, 1995; Newell, 1990; Smith, 1994) and situated action/situated cognition theories (Clancey, 1993, 1997; Green, Davies, & Gilmore, 1996; Hutchins, 1991; Nardi, 1996; Rogers & Ellis, 1994; Suchman, 1993; Vera & Simon, 1993a, 1993b, 1993c for a human-computer interaction example). In the former, the primary focus is on information processing, which is confined to the individual. In contrast, for situated action (SA) theorists, the focus is improvisational reaction to cues in a very rich environment (Rumelhart & Norman, 1988). The distinction lies mostly in the locus of information processing and degree of control given to individual goals versus the environment. According to SA theories, much of what symbolic theorists assign to the individual's head takes place outside of the confines of the individual and is directed by a world that is a much richer place than symbolic theories tend to suggest. However, both camps have proposed solutions to the problem of context (often similar solutions, e.g., Neisser, 1982; Schneider & Shiffrin, 1977). As a result of this distinction, information processing research tends to isolate psychological principles from a generic

context, such as a laboratory (e.g., Schneider & Shiffrin, 1977), while SA research focuses on understanding the specific contextual constraints of the environment. The relevance of SA for team cognition is that it extends the definition of cognition beyond a single individual into a richer context, including other team members.

There are other approaches in human factors that have a flavor similar to SA. Cognitive engineering (Hutchins, 1991, 1996; Norman, 1986) is a field of human factors that addresses cognition within complete environments as much as possible (see also Flach, Bennett, Stappers, & Saakes, chap. 22, this volume). Ecological psychology (Gibson, 1979; Rasmussen, 2000a, 2000b; Torenvliet & Vicente, 2000; discussion of affordances in Gibson, 1977; Norman, 1988) suggests that perception and cognition are contextually determined, so that few principles will generalize across situations. The implication this makes for team cognition is that we need to consider the entire work domain as the unit, complete with all of the other people and machines. Work domain analysis (Hajdukiewicz, Doyle, Milgram, Vicente, & Burns, 1998; Vicente, 1999, 2000) is a data collection method that supports this notion. In the case of teams, this would mean providing awareness of the goals and constraints that each team member places on each other, but no instructions to perform the team task. Dynamical systems theory (Guastello & Guastello, 1998; Kelso, 1999; Schmidt, Carello, & Turvey, 1990; Vallacher & Nowak, 1994; Watt & VanLear, 1996) would argue that team behavior is an emergent property of the self-organizing system of individual behaviors. Finally, several writers have argued against exclusively choosing cognitive processes or sociocultural interactionism (e.g., SA, ecological psychology) as a theoretical bent (Clancey, 1997; Greeno & Moore, 1993; Norman, 1993; Rogers & Ellis, 1994).

In terms of team cognition, we would define information processing views of team cognition as collective (Cooke et al., 2000), in that they would treat a team as a summation of cognitive units. On the other hand, perspectives that extend the cognitive unit into a broader context would support a holistic view of team cognition. They would view the team as a cognitive unit all its own. On the one hand, collective approaches to team cognition are more appropriate when knowledge or information processing is distributed homogeneously among individuals. On the other hand, when cognitive specialization is part of the team's structure, holistic approaches are more appropriate.

Implications of Perspectives on Team Cognition

So why is the distinction between collective and holistic perspectives on team cognition important? Beyond the implications for measuring team cognition, which are discussed in the following section, there are also implications for applying the concept to design or training applications. For instance, design implications for the collective information processing perspective (i.e., team as a summation of individual cognitive units) would be centered on providing tools to facilitate planning and symbolic representation. Elements of the task might be represented at a gross level, reflecting the user's (in this case, the team's) need

to support top-down processing. Task phases might be treated as distinct, and supported as separate modules, permitting the team to make conscious shifts in activities. Modularization of individual team member actions might be supported by enforcing prescribed team member roles fairly strictly, to support role distinctions as part of the team's plan of action.

Design strategies based on the ecological perspective have been posited as more appropriate for complex systems and for environments in which rare, novel scenarios (such as disasters) are critical (Rasmussen, 2000b; Vicente, 2000; see Flach et al., chap. 22, this volume). Team tasks tend to be of this nature, because they tend to be too complex or dangerous for an individual to perform alone. Design implications (Rasmussen, 2000a, 2000b; Torenvliet & Vicente, 2000) are to reject a single rational model of good team behavior, in favor of displaying the system state, and the natural constraints of the workspace. System information flow is more important than individual actors. Rather than designing an interface to fit a preexisting mental model of the users, an ecological psychologist would design to constrain the team's mental model of the system. The lack of guidance to behavior is intended to facilitate adaptation and, in the case of teams, establish idiosyncratic norms by social interaction.

A GDSS is a particularly well-suited example to answer the question of design implications made by holistic-situated versus collective-symbolic theories. It is fairly solidly demonstrated that problem-solving groups go through distinct phases, along the lines of orientation, conflict, resolution, and action (Shaw, 1981, especially citing Tuckman, 1965). So a collective view might say that these are different types of information that need to be conveyed and processed at different points in the task. The group would plan to finish one stage and move on (i.e., there is some degree of intentional choice to change subtasks). For design, this theoretical position implies relatively rigid GDSS to formally structure the group task (e.g., George & Jessup, 1997).

A holistic approach would assume that the group just moves on and does not know it. Group members follow the cues provided to them by the system and each other, which leads them down a natural path toward the goal. They would use tools they value or need as the situation warrants. GDSS design from such a position would insist on allowing the group to take action on their own terms. Conversely, it would not permit any guidance to the team as to how they should progress through the task. Specific designs would be appropriate for specific groups-in-situations. The system would have to be made more flexibly or else designed specifically for a group at a task.

MEASURING TEAM COGNITION

How individuals measure team cognition is driven by their conceptualization of the construct as well as the perspective they take. Regardless, measurement is critical to an understanding of team cognition and to applications relevant to team cognition. For instance, assessment of team cognition—whether for purposes of training or design—presumes reliable, valid, and practical measures. In this section we distinguish between elicitation of team cognition and assessment and diagnosis activities based on information elicited.

Cannon-Bowers et al. (1995) distinguished between taskwork and teamwork knowledge. Taskwork knowledge is knowledge about the individual and team task, and teamwork knowledge is knowledge about the roles, requirements, and responsibilities of team members. Others have distinguished between strategic, procedural, and declarative knowledge (Stout, Cannon-Bowers, & Salas, 1996). These theoretical distinctions have yet to be captured by measures of team knowledge. When adequate measures exist to capture the constructs, we will be in a better position to test the validity of these theoretical distinctions.

Examples of Elicitation Methods

How do we elicit data regarding team cognition from a team? Can the whole system of a team of people and set of machines be effectively treated as a unit? Is such a treatment too complex? A researcher is not going to observe and attend to every detail of such a complex set of behaviors. So how can one tell if one has abstracted and retained the right information? This problem is really not different from that encountered when the individual is the unit of measurement. Both research environments are noisy and complex, and both assume that the researcher knows what behaviors *really matter*.

In fact, measurement of team behavior is easier in some ways than measurement of individual behavior. For instance, abstraction is actually more stable in a unit of measurement with more components. That is, within the system as a whole, some actions are repeated by all components of the system. If one component tries to deviate from the norm, then other components will try to bring that piece back into agreement. It is the individuals within the group that are noisier to measure. There will be more small unpredictable actions, but the group will tend to wash out those effects.

Decisions about units of measurement bring us to another issue: that of what methods the elicitor should employ. Team cognition data can be collected and used in much the same way that individual cognition data can be used in human factors. For example, walk-throughs are employed to predict user behavior in a typical task and sometimes involve walking an actual user through a rapid prototype or paper mock-up (Nielsen, 1993). This method can be adapted to a team version. Here teams would be walked through the task, and all team members express their expectations and needs at each step. Interviews can be conducted with team members, either individually or in a group. Think-aloud protocols (Ericsson & Simon, 1993) have their analogy in team dialogue, in that teams necessarily think aloud when they talk to each other during the team task. In either case, these think-aloud data can be used to identify what the users are thinking as they go through the task and what misconceptions or expectations they have.

There have been numerous calls for faster, more descriptive, and more contextual methods (such as those discussed in the previous paragraph) (Nielsen, 1993; Wickens, 1998). Some of these descriptive methods are already widely used, such as those discussed in the previous paragraph, data rich ethnographic methods (Harper, 2000; see Volk & Wang, chap. 17,

this volume), or the purely descriptive task analysis methods (Jeffries, 1997). Cooke (1994) catalogs a number of methods that have been used to elicit knowledge from individual experts. Three methods for eliciting team cognition are discussed in the next section as examples. Mapping conceptual structure was chosen because it is a method that was developed to address individual cognition and has been altered to apply it to team cognition. Ethnography was included because of its popularity in CSCW design. Finally, communication research was included because communication can be thought of as the conscious thought of a team. Hence, these methods were selected for their relevance to team cognition.

Mapping Conceptual Structure. One method of eliciting individual knowledge is to focus on domain-related concepts and their relations. There are a variety of methods to elicit such conceptual structures (Cooke, 1994). One that has been commonly used involves collecting from individuals' judgments of proximity for pairs of task-related concepts. Then a scaling algorithm is applied to reduce these ratings to a graphical representation of conceptual relatedness. This procedure highlights the rater's underlying conceptual structure and hence represents a view of the domain in question. Common scaling algorithms to map the proximity matrix include Pathfinder network scaling (Schvaneveldt, 1990), multidimensional scaling (e.g., Anderson, 1986), and cluster analysis (e.g., Everitt, 1993).

Different approaches have been discussed for modifying this scaling procedure to assess team cognition (Cooke, Salas, Kiekkel, & Bell, 2004), such as the collective methods of averaging (or otherwise aggregating) individual pairwise ratings across team members. One alternative, more holistic, method is to have the team members discuss their ratings and only make proximity judgments after a consensus is reached. With this method, one assumes that the consensus-building process is an important part of the team's cognition. It incorporates all the group biases and intrateam ranking that one would expect from such a decision-making process. But including these processes in the ratings can be considered a more legitimate way of incorporating the cognition of a team in practice than simple aggregation schemes.

Ethnography. Ethnography comes from the fields of anthropology and sociology (Harper, 2000). The main idea is to make careful observations of people interacting in their natural environment, in order to learn what meaning the observees assign to their actions. It is a program of study aimed at capturing the meaningful context in which actions are taken. In the case of a team task environment, one would trace the life cycle of information as it is passed among different team members. Artifacts that the team members use are of key importance, because they influence what the team members will do and what their actions mean. The method involves open-ended interviews of relevant personnel and enough engrossment in the context in question to be taken seriously by the interviewees.

An example team application of ethnographic methods would be to interview actual team members to determine what impact their individual roles have on the team task. This would also mean observing what artifacts team members pass

among themselves and how they manipulate these artifacts. An ethnographic study of a collaborative writing team might entail recording what materials the expert on topic A uses to do research (e.g., does the expert prefer Web sources to print because they are more immediately updated?). Then the ethnographer would investigate the impact of writer A's decisions on writer B's input (e.g., does writer B write in a less formal style, because the references from section A are not as formal?). This process would go on throughout the life of the document to establish the team's writing process.

Communication Data. Another holistic method of eliciting team cognition is to use team task dialogue, and other communication data, as a window to team cognition. Individuals express their thoughts to themselves during task performance by subvocal speech. Human factors practitioners try to elicit these thoughts by getting individuals to think aloud during task performance. This think-aloud protocol (Ericsson & Simon, 1993) is used as a window to the underlying cognition of an individual, because subvocalization is a form of cognition, and the think-aloud procedure is intended to amplify the subvocalization. In the case of team tasks, there is less need to amplify the subvocalization, because team members naturally speak to one another during the task. This can be thought of as one form of team cognition. It can be directly observed and collected more easily than the awkward task of getting people to (supposedly) say everything they are thinking. These dialogue data can be analyzed in a variety of ways, both qualitatively (e.g., "are they arguing?" "are they on task?") and quantitatively (e.g., "how long do speech turns tend to last?" "who speaks the most?"). Because communication data are taken in the rich context of an ongoing stream of interaction, they can provide much deeper detail to the team's cognition than is available with most other methods.

Assessment and Diagnosis

The other side of measurement, apart from elicitation, is assessment and diagnosis. Elicitation should be seen as a precursor to assessment and diagnosis, as the latter depends on the former. Assessment means measuring how well teams meet a criterion. Diagnosis means trying to identify a cause underlying a set of symptoms or actions, such as identifying a common explanation for the fact that specific actions fall short of their respective criteria. Diagnosis therefore involves looking for patterns of behaviors that can be summarily explained by a single cause (e.g., poor team situation awareness and poor leadership both being caused by an uninformed team member in a leadership position). It is during assessment that one judges whether team behavior is adequate, and it is during diagnosis that specific causes behind shortcomings or strengths are postulated and identified.

In both assessment and diagnosis, one first defines some set of criteria for acceptable team behavior. Often the formal definition of acceptability can only apply to gross outcome measures, rather than to microscopic behaviors. Individual behaviors occur in the context of a complex stream of interactions, so it is more difficult to specify all of these criteria beforehand. A

selection of specific actions that should apply to all teams can be defined, but it is unlikely to be exhaustive.

The particular approach to assessment and diagnosis one wishes to perform is tied to the types of measures one has taken. Ideally, the desired assessment and diagnosis strategy determines the measures, but there are often cases where the reverse is true. This happens either when an ergonomist is unfamiliar with measures that better serve the desired purpose, or when such methods are unavailable. Suppose one wishes to assess what aspects of team communication are impacting the team's global performance. If the communication data are recorded only as frequency and duration of speech acts, then one cannot assess aspects of communication that involve content. Particularly for the case of heterogeneous teams, there are many measurement issues that remain to be resolved (Cooke et al., 2004). They primarily revolve around how to scale up individual cognitive measures to the team level. For example, holistic elicitation of a pairwise concept mapping structure may or may not be accessible by taking team consensus ratings.

There are many dimensions on which to classify measurement strategies. One of interest here is whether the measures are quantitative, qualitative, or some combination of the two. The decision should be based on the types of questions a researcher wishes to pose. Quantitative measures of team performance apply to relatively objective criteria, such as a final performance score (e.g., number of bugs fixed in a software team), or the number of ideas generated by a decision-making team. More qualitative criteria will require (or be implied by) richer, more context-dependent data, such as interview or observational data. The qualitative-quantitative distinction is softened by the fact that qualitative measures are often ultimately converted to a quantitative criterion. For instance, in a set of unstructured interviews, the researcher may count the number of respondents who expressed a popular idea. The distinction is still an important one, because it helps determine what data a researcher collects and how the researcher interprets the findings.

So, for example, we may discover that an uninhabited air vehicle (UAV) team is missing most of its surveillance targets. This is an unfavorable assessment of the team, which warrants further investigation into why they are missing targets. The closer inspection will often consist of observation, interviews, reviewing transcripts, and so on. But the investigator does so with an idea in mind of what might go wrong on a team of this sort. If an investigator is examining the transcripts of the uninhabited air vehicle in question, then he or she should have a set of qualitative criteria in mind that the navigator must tell the pilot where to go, the photographer must know where to take pictures, and so on. The measures for these consist of reading transcripts to see if the needed information is adequately discussed. The investigator will also have some quantitative criteria in mind, such as the fact that better teams tend to speak less during high tension situations (e.g., Achille, Schulze, & Schmidt-Nielsen, 1995). The measures that correspond to this diagnostic criterion would be relatively quantitative in nature, such as number of utterances made during tense periods.

There are also some challenges regarding assessment and diagnosis of team cognition that are related to some specific team task domains. Many team tasks that human factors specialists

study are those in dynamic, fast tempo, high-risk environments (e.g., air traffic control, flight, mission control, process control in nuclear power plants). Whereas in other domains one may have the luxury of assessment and diagnosis apart from and subsequent to task performance, in the more dynamic and time-critical domains it is often necessary to be able to assess and diagnose team cognition in near real time. In other cases, real time is not timely enough. For instance, we would like to be able to predict loss of an air crew's situation awareness before it happens with potentially disastrous consequences. This challenge requires measures of team cognition that can be administered and automatically scored in real time as the task is performed.

The other aspect of teams that presents unique challenges to assessment is not specific to the task, but inherent in the heterogeneous character of teams. For teams, the part about assessment that is most relevant to team cognition is accounting for the heterogeneity of roles. When one assesses a team member's knowledge using a single, global referent or gold standard, one is assuming homogeneity. If team knowledge is heterogeneously distributed, then team cognition needs to be assessed using role-specific referents.

USING TEAM COGNITION DATA IN HUMAN FACTORS

Three applications for the kind of information elicited from team cognition can be informing design, designing real-time assistance and intervention applications, and designing training routines. We will discuss each of these in the following.

Informing Design

If team usability methods are employed before the new interface is set in stone, then the data can indicate user needs, typical user errors, unclear elements of the current system, areas in which the current system particularly excels, and so on. For example, if a team is trying to steer a vehicle toward a remote destination, then team members should know their current distance to that destination. If their dialogue consistently shows that they refer to their distance in the wrong units, then designers may choose to change the vehicle's distance units, make the display more salient, or otherwise match the environment to the users' expectations.

Also, by understanding team cognition and its ups and downs in a task setting, one can design technology to facilitate team cognition. For example, if a team appears to excel only when team members exchange ideas in an egalitarian manner, then a voting software application employed at periodic intervals may facilitate this style of interaction.

Finally, the methods used to assess team cognition can also be used in the context of two or more design alternatives and would thus serve as an evaluation metric. In the case of the earlier example, different methods of representing distance units in the interface could be compared using team situation awareness or communication content as the criteria.

Real-Time Intervention

If the team cognition data can be analyzed quickly enough to diagnose problems in real time, then automatic system interventions can be designed to operate in real time. For example, suppose that the same vehicle-operation team has hidden part of the distance display behind another window, so that its distance units are not salient. If the system can analyze the team's dialogue in time to determine this problem, then it can move the offending window, or pop up a cute paper clip with helpful pointers, or use some other real-time attempt to correct the problem. With real-time interventions, as with other automatic system behaviors, it is important that the actual users not be superseded to the extent that they are unable to override (Parasuraman & Riley, 1997). With teams, as opposed to individuals, designers have a leg up on monitoring and real-time intervention, due to the rich communication data available for analysis in real time. As is the case for the design example previously discussed, team cognition data can also serve as a metric upon which we can evaluate the usefulness of the real-time intervention.

Training

Cognitive data are particularly important in training, since training is about learning. One can generate training content through a thorough understanding of the team cognition (including knowledge, skills, and abilities) involved in a task.

Many aspects of using team cognition data for training applications are no different from using individual cognition for individual training. For instance, in designing training regimes, it is important to collect data on what aspects of training can be shown to be more effective than others. This is true both for overall task performance and for subtask performance. For example, if trainers wish to determine whether the benefits of full cross-training justify the added time it requires (e.g., Cooke, Kiekkel, et al., 2003), then they would have to experimentally isolate those characteristics.

Diagnostic data can be used to identify what is left to be learned or relearned. Teams can provide a special advantage here, in that their task dialogue can be used to assess what misconceptions they have about the task. If, for example, a flight crew in a simulator talks about adjusting airspeed as if there were no lag time, then the trainers know that this is a misconception in the team's knowledge. Diagnosis requires the measurement of diverse aspects of team cognition, such as fleeting situational knowledge, the ability to manipulate incoming data, and latent knowledge structure representation (Cooke et al., 2000).

Comparison of learning curves can help identify teams who are learning more slowly or where a given team is expected to asymptote. The data plotted may be outcome measures for task performance, in which case increased knowledge will be inferred from performance increases. If knowledge data can be collected at repeated intervals, then learning curves can be plotted of actual knowledge increase. Knowledge can be broken down into further components, such as the knowledge of technical task requirements for all team members (i.e., *taskwork*)

versus knowledge of how team members are required to interact with one another in order to perform the task (i.e., *teamwork*: Cannon-Bowers et al., 1995).

Research across several studies has shown (Cooke et al., 2001; Cooke, Salas, et al., 2004) that taskwork knowledge is predictive of team performance, and teamwork knowledge does improve with experience, along a learning curve. There is also evidence that formation of teamwork knowledge is dependent upon first forming taskwork knowledge. It has also been found that fleeting, dynamically updated knowledge (i.e., team situation awareness) is predictive of team performance.

EXAMPLES OF TEAM APPLICATIONS

In this section we begin by discussing computer-mediated communication (CMC), a prominent Web-based domain application for team cognition. Then we discuss two specific examples of team applications and describe how team cognition can be useful for designing those applications. First we consider a collaborative writing example and then an example of vehicle operation. The first example is treated from a conventional collective perspective, and the second is treated from a cognitive engineering, or more holistic, perspective.

Application to Computer-Mediated Communication

CMC makes for a very general topic for the discussion of team cognition, particularly team communication. There is a large body of literature on computer-mediated communication. This is because interconnected computers are so ubiquitous, especially since the explosion of the Web. Much of the literature is not on groups who share interdependence toward a common goal, but much CMC research has been conducted on interdependent groups as well.

All of the points addressed in this chapter apply to CMC research. CMC may either involve heterogeneous groups (e.g., a team of experts collaborating on a book) or homogeneous groups (e.g., a committee of engineers deciding on designs). CMC can involve anything from dyads e-mailing one another to bulletin boards and mass Web-based communication. Similar diversity exists in the CMC literature on communication data elicitation, assessment, diagnosis, and how those data are applied. We will focus on one aspect of CMC, that of collective versus holistic interpretations of CMC research. Research and design methods for groupware rely more on anthropological methods than on traditional psychological methods (Green et al., 1996; Harper, 2000; Sanderson & Fisher, 1994, 1997), which, as described earlier in the chapter, tend to be more holistic and to rely more on qualitative and observational techniques.

One important finding in CMC research is that, under certain conditions, anonymity effects can be achieved, leading to either reduced pressure to conform and an enhanced awareness of impersonal task details (e.g., Rogers & Horton, 1992; Selfe, 1992; Sproull & Kiesler, 1986) or pressure to conform to norms that differ from those for face-to-face communication (e.g., Postmes, Spears, & Lea, 1998). One theory to account for

the former effect of anonymity is media richness theory (MRT; Daft & Lengel, 1986). Other, more contextual theories have been proposed to account for the latter effect of anonymity. We address this juxtaposition in the following.

In the context of CMC, MRT (Daft & Lengel, 1986) has been linked to a symbolic framework (Fulk, Schmitz, & Ryu, 1995). Medium richness/leanness is defined by its ability to convey strong cues of copresence. The theory states that, for tasks of a simple factual nature—in which lots of data need to be passed for very uncontroversial interpretations—*lean* media are most appropriate. For tasks requiring creation of new meaning (i.e., complex symbol manipulations), *rich* media are required. MRT has been related to symbolic theories because of the claim that users rationally formulate the appropriate plan (what medium to choose) and execute it. Further, all tasks can be defined by what symbols need to be conveyed to collaborators. The design implication of MRT is that one can maximize the task-team fit by incorporating media into the design that are appropriate for the task being performed. The team cognition data collected for MRT-based design would involve determining how equivocal the team members feel each communication task is.

MRT has been challenged repeatedly, in favor of more social and situational theories (Postmes et al., 1998; El-Shinnawy & Markus, 1997). One interesting attempt to combine these two apparently disparate perspectives was by Walther (1996). Walther made a compelling argument to treat MRT as a special case of the more social-situational theories. He argued that rational theories of media use, such as MRT, are adequately supported in ad hoc groups. But when groups get to know one another, they overcome technological boundaries, and their behavior is more driven by social factors. He cites couples who have met online as an example of overcoming these media boundaries. Hence, more contextual-social theories are needed for ongoing groups. Correspondingly, different design implications are in order, and media incorporation into the task environment will be dependent upon richness, only for newly formed teams.

Harmon, Schneer, and Hoffman (1995) support this premise with a study of GDSSs. They find that ad hoc groups exhibit the oft-cited anonymity effects (e.g., Anonymous, 1998; Sproull & Kiesler, 1986), but long-term groups are more influenced by norms of use than by media themselves. Postmes and Spears (1998) used a similar argument to explain the apparent tendency of computer-mediated groups to violate social norms. For example, *flaming* can be characterized as conformity to local norms of the immediate group, rather than as deviance from global norms of society at large.

The design implication of this is that the incorporation of media into the task environment is dependent not only on what the team task is like, but also on how familiar team members are with one another. So groupware that is intended to be used by strangers would be designed to fit media richness to task equivocality. Groupware for use by friends would be designed with less emphasis on media choice. The team cognition data collected for a design based on a more social theoretical bent than MRT would involve determining such factors as how conformist team communication patterns are (e.g., by measuring position shift), team member familiarity (e.g., by measuring the amount of shared terminology in their speech patterns), and so on.

This broad example of a domain application for team cognition highlights the importance of how one approaches team cognition. Based on the accounts cited previously (e.g., Walther, 1996), a collective-symbolic approach to team cognition is relevant for certain teams and situations, in this case, when teams do not know one another well. However, a holistic approach is more appropriate for other situations, in this case, when teams have interacted with another for a longer time. We now turn to two more specific examples of team cognition applications. Among other things, these examples illustrate the issue of role heterogeneity and group size.

Collaborative Writing

The first example is in the domain of Web-based collaborative writing software. Kiekel (2000) investigated the necessity of incorporating an audio-video channel in a collaborative writing task. All interdependent groups worked with a groupware word processor plus chat window, while some also had an open audio-video channel. In the task, interdependent groups of two persons (i.e. dyads) with homogeneous roles were expected to write an essay on a controversial topic. The question of interest was how effectively interdependent dyads could communicate emotion in a purely text-based communication environment. This is a way to assess user needs, where the users are actually interdependent groups.

These dyads were homogeneous with regard to roles, so we refer to them as interdependent groups. There were only two members for each interdependent group, which prevents characteristics such as clique formation or an arbitrator for dispute resolution. Because of the role homogeneity, measurement and interpretation were taken from a collective stance. That is, each member's cognition was compared against the same criteria, measures were taken to be averages, and so on.

How can the interdependent group's cognition be assessed in this context, and how is the assessment useful? We begin by deciding what criteria to use in assessment and diagnosis and use that decision to guide elicitation measures.

One might be interested in how effectively information is passed between members. Because the interdependent groups are homogeneous, there is no expectation of specialized knowledge. It would therefore be reasonable to measure each member's cognition according to the same criteria. A researcher might therefore conclude that each member should ideally contribute more or less equally because the essay was purely an opinion piece and because there are no specific contributions expected from either member. Differential knowledge about the topic would be randomly distributed among members, so differential contribution would be expected to balance out over multiple dyads. Hence, the passage of information between members can be simply measured by the amount of text typed into the chat window or spoken into the audio-video channel.

Another question, more important for the purposes of this specific research, would be the effectiveness of emotional communication. Ideally, good interdependent groups on a task like this should clearly communicate their emotional reactions to

each other. Again, because there is no heterogeneity among roles, it is reasonable to take individual measures and aggregate them. Emotional communication accuracy can be measured by having each member privately record his or her own emotional reaction (by a rating scale or by an interview) and then speculate about the feelings of the partner through similar ratings. Then accuracy can be calculated by comparing what each partner said he or she felt to what the partner said he or she felt. Although essay quality would be an important criterion for some applications, it is only tangentially related to the effectiveness of emotional communication. So it would not be a major criterion for this study, though it may be a secondary one.

Having elicited the interdependent group's cognition, and compared it against an ideal criterion, the next step is to diagnose shortcomings. In this case, emotional communication accuracy was measured based on ratings assigned to a list of emotions. These were separated out into positive and negative emotions for diagnostic purposes. It was concluded that the audio-video channel was helpful for communicating positive emotions, but neither helpful nor hurtful for communicating negative emotions. Hence, designers of a collaborative writing package to serve an emotional purpose of this sort would want to include more interpersonal cues, such as an audio channel. This added expense may not be necessary for tasks in which one does not expect to communicate positive emotions.

Other, more specific aspects of the interface could have been addressed with team cognition data as well. For example, a collaborative writing task will require that members of the interdependent group are able to take turns writing and not to inadvertently eradicate each other's writing. If their dialogue indicated a great deal of argument over how to pass control of the document, then the human factors researcher would be able to identify potential solutions. The researcher would examine their dialogue to identify particular misconceptions interdependent groups tend to have and redesign the control passing mechanism according to this diagnosis. Data can similarly be gathered from group interviews, observation, consensus ratings of the similarity ratings of different aspects of the interface, and so on.

This first example involves a simple environment, with homogeneous interdependent groups (dyads). It is therefore addressed from a collective perspective of team cognition. The main variable of interest (i.e., emotional communication accuracy) is isolated and measured as a single construct (with multiple dimensions). For example, there was no need to consider teamwork knowledge versus taskwork. This collective treatment had the advantage of being a simple experimental manipulation, making causal inference more clear-cut.

Uninhabited Air Vehicle Operation

The second example is treated from a more holistic, cognitive engineering perspective. The research aim was focused on team cognition and addressed the complete environments as much as possible. The team members had heterogeneous role assignments, and there were three team members. These two

expansions upon the previous example allow for more complex social dynamics.

Rich data were collected in great detail, including observational data. Several varieties of cognitive data were collected. Though these measures were related to normative definitions of ideal team knowledge, those definitions came in several diverse forms, addressing different aspects of knowledge. For example, individual taskwork knowledge was defined for each team member's global task knowledge, knowledge of that member's own task, and knowledge of other team members' tasks. In order to take more holistic measures, consensus metrics and communication data were also collected to capture team knowledge.

Cooke et al. (2001) and Cooke et al. (2004) have done several studies on team operation in a simulated ground control station of a UAV. This task involves heterogeneous teams of three members collaborating via six networked computers. The team flies the plane to different locations on a map and takes photographs.

Each role brings specific skills to the team and places particular constraints on the way the UAV can fly. The pilot controls airspeed, heading, and altitude and monitors UAV systems. The photographer adjusts camera settings, takes photos, and monitors the camera equipment. The navigator oversees the mission and determines flight paths under various constraints. Most communication is done via microphones and headsets, although some involves computer messaging. Information and rules specific to each role are only available to the team member filling that role, though team members may communicate their role knowledge.

This is a complex task, and there are hence many criteria on which to assess and diagnose team performance. Foremost are the various performance measures. These include an overall performance score made up of a weighted average of the number of targets photographed, total mission time, fuel used, and so on. This being a heterogeneous task, we cannot apply one measure to all team members and expect to aggregate. Therefore other, more diagnostic performance measures include the three individual performance scores, each comprised of similar weighted averages, but of individual behavior. Acceptability criteria are loosely defined for each of these variables, based on the asymptote of numerous teams as they learn the task. These performance measures represent acceptability criteria for other measures.

Because team members each have their own knowledge and their own knowledge dependencies, it is important to measure how well they each know their own role and how well they know each other's roles. We can call this knowledge of what to do during the task *taskwork knowledge*. In team tasks, it is also important to know how each team member is expected to interact with the others. We will call this *teamwork knowledge*. We discuss these in turn.

In our studies, teamwork knowledge is measured with questionnaires with predefined correct answers. Individual team members are asked for a given scenario what information is passed and between which team members. The correct answers were separated out by individual role as well as by basic information that all team members should have. The tests were administered to each individual, and each individual's accuracy score

was calculated according to that person's own role. The scores now properly scaled, the proportion of accurate answers could then be aggregated. In addition, teams were asked to complete this questionnaire as a group, coming to consensus on the answers. This gives us an estimate of teamwork knowledge elicited at a more holistic level.

For taskwork knowledge, a criterion was first defined in the form of a network of pairwise links among domain relevant concepts. Then team networks could be collected and compared against this criterion. Like teamwork, taskwork knowledge was measured two ways. First, each individual rated his or her own pairwise proximities. Then teams were asked to give group ratings, in which they engage in group discussion and reach consensus before rating any concepts. Again, this latter measure is more of a holistic measure of team cognition. The networks derived from Pathfinder analysis of the pairwise ratings (Schvaneveldt, 1990) could be scored for accuracy by calculating the similarity of the teams' (or individuals') networks to an expert, referent network.

Since both the taskwork and the teamwork measures yielded quantitative measures of fit to criterion, the accuracy could be used to predict team performance scores. This allows researchers to diagnose what may be wrong with a team that performs poorly. For example, a team for which the taskwork scores are low would indicate that a training regime should concentrate on taskwork knowledge. Specific taskwork weaknesses can further be assessed by determining whether team members are weak in knowledge of their own role or on each other's roles. This diagnosis can go even further by examining specific links in the network that do not match up to the ideal referent. All of this information can be incorporated into a training regime or converted to interface design recommendations.

Another form of knowledge that was measured in the UAV task context was team situation awareness. This was measured using a query-based approach (Durso et al., 1998; for discussion of retrospective queries, e.g., Endsley, 1990) in which individuals, and then the team as a whole, were asked during the course of a mission to answer projective questions regarding the current situation (e.g., how many targets will you get photos of by the end of the mission?). The responses were scored for accuracy as well as intrateam similarity.

Communication data were furthermore collected and analyzed extensively. Transcripts were taken to record actual utterances, and latent semantic analysis (Landauer, Foltz, & Laham, 1998) was applied to analyze the content of the discourse. Speech acts were preserved in a raw form by specialized software to record quantity of verbal communication by each team member and to each team member.

These communication data were used in a wide array of measures, all aimed at predicting performance (Kiekel, Cooke, Foltz, Gorman, & Martin, 2002; Kiekel et al., 2001). For example, examining the transcripts revealed that a number of teams did not realize that they could photograph the target as long as they were within a specific range of it. Kiekel et al. (2001) also used the communication log data to define speech events as discrete units and then modeled the behavior of those units to determine complexity of team communication patterns. Teams that

exhibited many diverse communication patterns were shown to be poorer performers. This was thought to indicate that the teams had not established a stable dialogue pattern and would perhaps imply more clear teamwork knowledge training.

As this detail shows, this task involved a great deal of diverse measurement, both to assess multiple team cognition constructs and to assess individual and holistic team knowledge. Training or design recommendations based on these data would be very specific to the diagnostic findings. For example, the finding that better performing teams tended to have more stable communication patterns might imply a training regime aimed at stabilizing team discourse (of course, we must be cautious, in that we must avoid drawing causal implications from correlational data). Specificity of this sort was not needed for the first example, because the task was so much simpler.

Another use of team cognition in this research context would be to design a real-time system monitor to assess the need to intervene. So, for example, suppose a communication monitor is running in the background, and it determines a point at which the team communication pattern becomes erratic and unusually terse. This might indicate a red flag that something is wrong in the task. An appropriate intervention would then be called in to correct the problem.

This was a small-scale simulation task on an intranet. Similar real-world tasks occur in the context of network-centric warfare and distributed mission training, in which a critical issue is assessing team cognition and performance in distributed Web-based applications. The metrics of team cognition discussed in this example can be applied for that purpose and for real-time intervention.

CONCLUDING REMARKS

As noted at the beginning of this chapter, team tasks are extremely common and are being given increasing greater focus within organizations. In particular, computer-mediated communication and decision-making applications for teams are extremely varied and ubiquitous, ranging from e-mail to shared bulletin boards for classrooms to remote conferencing. As the potential to put these applications onto the Web becomes better exploited, computer-mediated communication and coordination of teams of individuals will become even more widespread. Although the Web is normally thought of as an individual-to-mass form of communication, it actually has a great deal of potential to serve team collaboration. This is largely due to the cross-platform nature of Web design. It is also partly due to the fact that Web-based applets do not require the team members to have specialized software installed on their machines in advance.

With the growth of collaborative Web applications, an interesting ramification for team cognition will be the greater possibility of anonymity. Web-based applications make it much more possible for teams to form, interact, and perform tasks without ever having met. Certainly, this is not a prerequisite for Web collaboration, since teams using Web-based groupware generally do know one another. But it creates a possibility to dramatically amplify issues such as interpersonal awareness, teamwork

knowledge, task focus, telepresence, and so on. Issues of this nature will have to be addressed much more thoroughly than they are now, and more researchers will be interested in doing so.

As team tasks become an increasingly important part of life, it will become increasingly important to consider the needs of teams. The interaction patterns among team members, including the cognitive processes that occur at the team level, add a second layer to behavior that is not present in individuals. However, human factors has long been addressing systems in which the human and the environment are treated as interacting factors. When this principle is extended to include other humans and increased technological complexity, we can see that much of the groundwork already exists for designing to meet the needs of teams. Many of the tools that have been applied to individuals in the cognitive engineering framework can be adapted to meet the needs of team cognition in human factors.

Considerations of team cognition can be important in designing team tasks and environments, in much the same way that individual cognition is used in design for individuals. Team characteristics and abilities must be assessed, team task environments must be understood, and so on. The complexity is introduced when team cognition must account for the knowledge individuals have of their team members and the influence team members have on one another. Two major approaches to this are to conceive of teams either as a collection of individuals, in which each person's cognition is considered separately (collective team cognition), or as a single cognitive unit (holistic team cognition). The two approaches are not mutually exclusive and some scenarios are better fitted to collective or holistic approaches, respectively.

In order to treat teams as holistic units, we transfer what is known from individual cognition and incorporate those features that individuals do not possess. For instance, team size and heterogeneity are issues that do not exist for individuals. When we treat teams holistically, say by using team communication data as our measure of cognition, we automatically incorporate the social dynamics intrinsic in team size, because the types of interaction we observe are inherently determined by this factor. Likewise, individual role expertise is incorporated in holistic measures such as consensus interviews, because team members with differential role expertise or influence will contribute differentially to the consensus formation. But issues unique to teams may also have their analogy in individual cognition. For instance, ambivalent deliberation during decision making appears analogous to team conflict.

As team cognition measurement becomes more adept at incorporating the added dimensions that teams bring, some of this advantage should transfer back to the measurement of individual cognition. For example, although individual cognition may have no such distinction as teamwork versus taskwork knowledge, methods developed to account for these constructs in teams may transfer back to individuals. It may, at least, help to enrich the complexity of our view of individual cognition. Hence, teams may raise new issues of complexity that exist in parallel for individual cognition, but which might not have been addressed otherwise.

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