# Metrics for Evaluation of Cognitive-Based Collaboration Tools

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**Abstract**

Collaboration metrics are key for developing effective collaboration tools. By measuring the impact of collaboration tools on team effectiveness, collaboration metrics provide the feedback necessary for testing new types of tools. The cognitive-focused metrics described in this paper provide especially powerful support to developing better collaboration tools. By measuring the impact of the tools on team members' knowledge and mental information processing, they provide insight on the fundamental reasons for tool effectiveness, and thus support a systematic theory-based search for increasingly powerful tools.

This paper describes four categories of collaboration metrics. These address respectively product quality and team efficiency, team behaviors, group understandings, and individual team member understandings. Product and team efficiency metrics are the "bottom line" measurements for collaboration, for they measure how well a team achieves its goals. Team behavior metrics measure how team members exchange information, synchronize, adapt to new circumstances, negotiate, and perform other functions associated with effective teamwork. Group understanding metrics measure the overall completeness and consistency of team members' understanding of the external task and of team dynamics. Metrics for individual team member understanding measure how well each team member understands those aspects of the team and tasks necessary for his effectiveness as a member of the team.

In addition to describing metrics, the paper also describes collaboration models and taxonomies. The models help link the different categories of metrics in order to explain the connection between individual cognitive processes and effective collaboration. The taxonomies define spaces of tasks, teams, and tools. They provide structure for examining the particular circumstances when different kinds of tools are likely to be most effective.

## INTRODUCTION

Collaboration, as used in this paper, is the methods and interactions of people actively sharing data, information, knowledge, perceptions, or concepts when working together toward a common purpose[*]. Cognitive-focused investigations of collaboration address collaborations where cognitive processes predominate. Examples are teams tasked to generate and evaluate courses of action or teams that interpret situations.

[*] Information Superiority Working Group

Two goals of cognitive-focused collaboration research are to understand what people need to know in order to collaborate effectively and to understand what mental information processing people employ in obtaining that knowledge. Cognitive-focused collaboration metrics support these goals. They provide a way to measure what people know and they help researchers infer how people acquired that knowledge. In conjunction with collaboration and cognitive models, these measurements support efforts to understand the connection between mental information processing, knowledge, and team effectiveness. This understanding in turn helps illuminate the critical bottlenecks to effective collaboration and helps suggest means to eliminate these bottlenecks.

Figure 1 is a simple example illustrating the connection between team effectiveness and team member understandings. This example contrasts effective and ineffective collaboration for the case when individual team members generate product components that must then be combined into an overall product. In the case of effective collaboration, the pieces are finished when needed and fit together smoothly. In the case of ineffective collaboration, the pieces are not available when needed and do not fit together smoothly. We hypothesize that in the case of effective collaboration, each team member knows when the various pieces are needed and knows the qualities these pieces need in order to fit together well. In contrast, we would hypothesize that when the pieces do not fit together smoothly, the individual team members either did not have the skill to create the pieces or did not know what was needed.

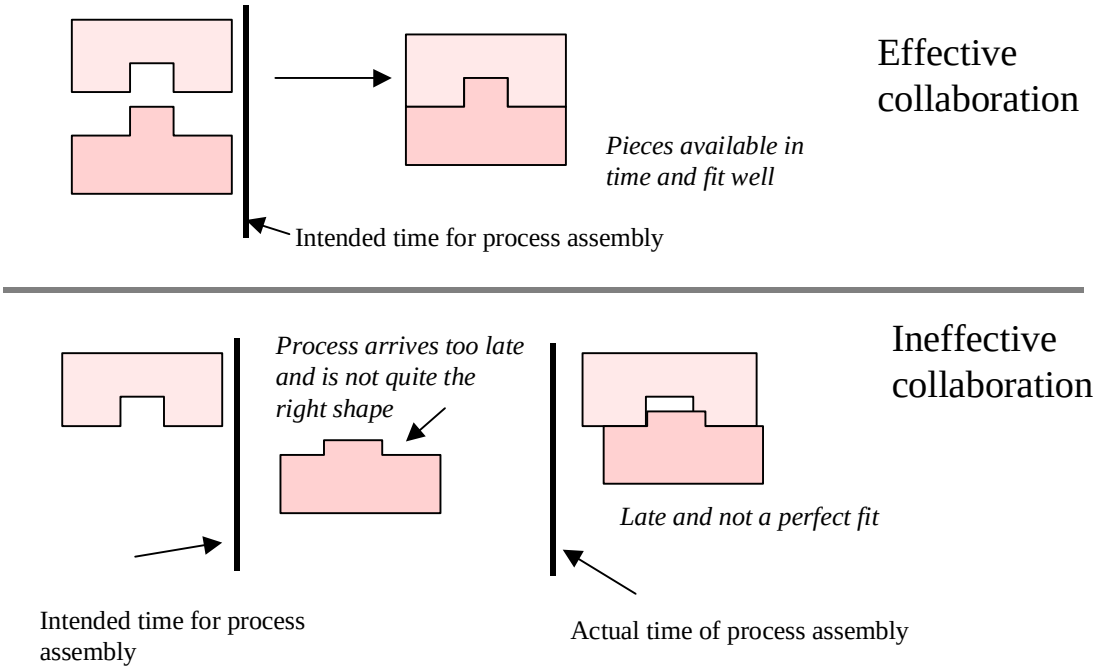


**Figure 1. Effective and Ineffective Collaboration**

The remainder of this paper describes the elements most important for developing this understanding of what people need to know in order to collaborate effectively and what mental information processing people employ in obtaining this knowledge. These elements are cognitive-oriented collaboration models; team, task, and tool taxonomies; and the metrics themselves. The models help link individual cognitive processes to team effectiveness. The

taxonomies help define the range of environments in which collaboration can occur, so that the collaboration theory can be both specialized and generalized to address these many environments. The metrics identify the broad range of processes and products whose measurement is important for evaluating team effectiveness and for understanding its causes.

## COLLABORATION MODELS

Collaboration models describe the mechanisms through which collaboration works. They clarify the relationships among individual cognitive processes and team processes, support predictions of the consequences of changing the collaboration environment or processes, and suggest tool features able to increase collaboration effectiveness. Good models capture the key drivers that account for both the advantages and costs of collaboration. They reflect such advantages as the ability to share workload, augment expertise, provide backup and redundancy, increase reach, and increase impact from resources. They reflect collaboration costs such as the overhead from the need for synchronization and integration, and decreased agility and ability to adapt.

Because collaboration can be complex, no single model can describe all of the processes important to collaboration. This paper presents two. The first emphasizes the importance of feedback in both the explicit team mission task and also the implicit team maintenance task. The second emphasizes the interplay between individual work and team member interactions.

### *The Dual Feedback Model*

This model (Figure 2) emphasizes two important features of collaboration. First, collaborating teams work simultaneously in two different domains: team and mission. Second, execution monitoring, feedback, and adjustment are central in both domains.

The dual feedback model divides team activities using two dimensions. The first, corresponding to the labels at the top of Figure 2, is the team vs. mission domain. The second, corresponding to the labels at the left edge of the figure, is the phase of team activity: planning and execution. In the mission domain teams are working to accomplish the tasks that the team was formed to do. In the team domain, the teams carry out additional activities required to maintain effectiveness as a team. These additional activities are the source of much of the collaboration overhead. They include allocating and adjusting roles, coordination, meetings, and negotiation. Note that though teams are not formed to maintain themselves, they cannot achieve their mission goals without doing so.

Monitoring, problem diagnosis, and adjustment are important in both domains. In the mission domain, these processes are part of the well-known C2 cycle: teams formulate a plan to achieve their goals, begin executing the plan, monitor execution progress to determine if the plan will still work as intended, and make adjustments if it will not. In the team domain, the team makes a plan that describes how the work will be allocated and how the team members will work together to accomplish their goals. In performing their tasks, the team monitors its teamwork to ensure that the team members can work together as planned. If the team is not functioning well, the team (or team leader) diagnoses the problem, such as a poor allocation of workload among team members, and makes the needed adjustments.

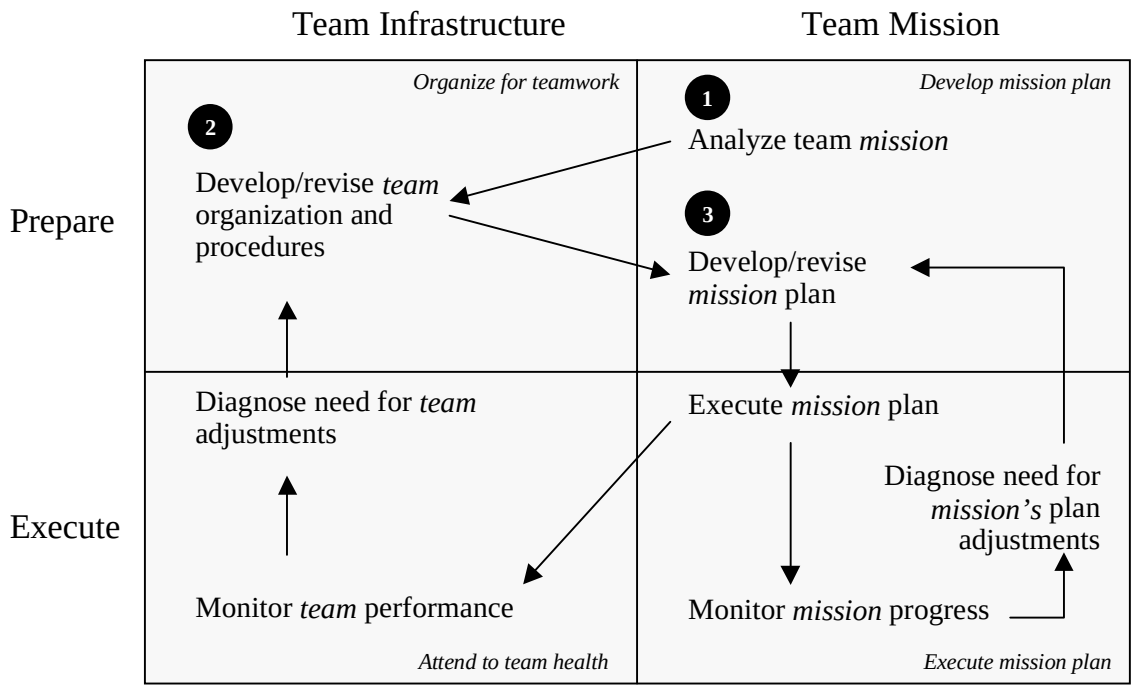


**Figure 2. Dual Feedback Collaboration Model**

### *The Individual-Team Interplay Model*

The second model (Figure 3) describes the interactions between individual members. It applies to those collaboration tasks where team members spend much of their time performing individual subtasks and creating individual component products that are then reassembled into an overall team product. Collaborative planning usually occurs this way.

In this model, the team assembles (not necessarily physically) to allocate, review, adjust, and assemble individual contributions. After meeting, the team members separate to carry out their individual tasks, possibly asynchronously. For decision focused tasks, the team members perform the seven types of cognitive functions (e.g, goal formulation) listed to the left of Figure 3. Though working individually, team members continue to coordinate through shared documents and visualizations and by requesting and providing information to each other. Occasionally, the team members notice the need for synchronous dialog within the overall team. Team members then coordinate to establish a meeting time and prepare for the meeting; e.g., members create their PowerPoint presentations. In the meeting itself the team members engage in the various group activities (e.g., negotiation) to critique, enrich, and adjust the product and the team collaboration process. If the team's task is accomplished, the team provides the finished product. Otherwise, they continue the cycle by adjourning to perform their individual assignments.

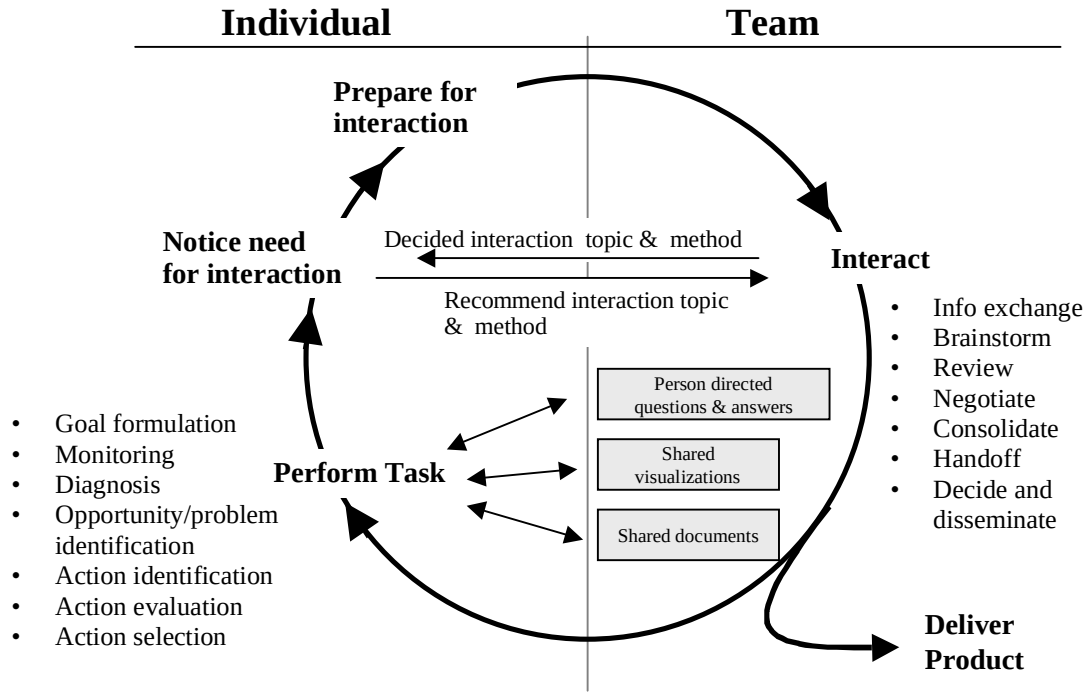


**Figure 3. The Individual-Team Interplay Model**

## TEAM, TASK, AND TOOL TAXONOMIES

These taxonomies structure different kinds of collaboration environments. They provide an orderly way to specify the circumstances in which various collaboration tools work best.

### *Team Taxonomy*

The team taxonomy (Table 1) organizes types of teams along six dimensions: distribution, roles and functions, team structure, team member dependencies, information and information flow, and decision making.

- **Distribution** addresses how people, expertise, and information are distributed in time and space.
- **Team roles and functions** concern the stability of roles, familiarity of team members with their own and others' roles, and the expertise required to perform a role.
- **Team structure** is concerned with team size, organization, and permanence.
- **Team member dependencies** address the nature of the coupling among team member tasks, emphasizing the extent to which team members need to synchronize.
- **Information and information flow** deal with the inherent complexities of sharing information.
- **Decision making** addresses the distribution of decision making authority, the magnitude of stakes and time pressure, and the prevalence of proactive or reactive decisions.

**Table 1. Taxonomy of Collaboration Teams**

| Team Dimension | Dimension Subcategories |
|---|---|
| Distribution | • Physical—spatial separation<br>• Temporal—e.g., working different shifts<br>• Expertise—spatial and temporal distribution of experts and expertise<br>• Information—spatial distribution of information |
| Roles and Functions | • Stability of definition—whether roles are clearly defined or become defined in process of performing work<br>• Experience--extent that each team member is experienced with assigned roles and collaboration tools<br>• Familiarity—extent each team member is familiar with roles and functions of other team members<br>• Team member expertise—extent that individual team members have specialized expertise needed for their assigned tasks |
| Team Structure | • Hierarchical vs. flat—extent that team has designated leader in charge or is peer-to-peer<br>• Size—number of members<br>• Permanent vs. ad hoc—extent team works together over extended period of time, or is brought together for one task<br>• Single vs. team-of-teams—extent that teams can be decomposed into collaborating sub-teams<br>• Turn-over—stability of team membership |
| Team member dependencies | • Independence—extent that each team member depends on other team members to perform his or her task<br>• Interaction frequency--how often team members must interact<br>• Synchronization—requirement for and schedule tolerance of temporal sequencing of tasks performed by different members<br>• Cognitive—extent that team members must understand each others' tasks<br>• Task sharing—extent to which each team member has own task or all team members share the same tasks<br>• Processing flow-- individual/parallel or sequential |
| Information and Information Flow | • Information sharing—degree to which team members need to share information<br>• Information processing complexity--number of handoffs required to produce an information product<br>• Team expertise--extent that expertise the team needs resides somewhere within the team so that team members need not go outside of team to retrieve needed expertise |
| Decision Making | • Group makes decision vs. leader makes decision<br>• Reactive vs. proactive—extent that tasks require team to react to uncontrollable events<br>• Degree of time pressure<br>• Stakes--degree of risk and responsibility |

### *Task Taxonomy*

The task taxonomy (Table 2) characterizes the different types of tasks that teams do. Taxonomy dimensions are the cognitive domain, workload, divisibility, and difficulty.

- **Cognitive domain** identifies the decision-focused and collaboration-focused tasks, as listed in the Individual-Team Interplay Model (Figure 3).
- **Workload** is the amount of effort, expertise, time, and distribution that the task requires.
- **Divisibility** is the extent and ease with which the overall task may be partitioned among the team members.
- **Difficulty** concerns numerous issues, such as goal clarity, known to impact the difficulty the team is likely to encounter in carrying out its tasks.

**Table 2. Taxonomy of Collaboration Tasks**

| Task Dimension | Dimension Subcategories |
|---|---|
| Cognitive domain | • Stage(s) of decision making emphasized--goal specification, monitoring, situation diagnosis, opportunity/problem ID, alternative ID, alternative evaluation, selection<br>• Interaction focus--info exchange, brainstorming, review, negotiation, consolidation, handoff |
| Workload | • Effort--amount of work required to carry out team assignment<br>• Duration--length of time over which work must be performed<br>• Expertise—amount of expertise requires for successful task completion (extent that work require specialists)<br>• Degree of reach--extent that assigned work requires tasks carried out at different places and at different times |
| Divisibility | • Partition granularity--size of tasks into which work may be partitioned<br>• Partition flexibility--different ways that work can be partitioned among team members<br>• Order--extent that the different tasks must be performed in a particular order<br>• Logical dependencies--extent that the different task elements depend on one another |
| Difficulty | • Goal clarity--extent that objectives are well defined<br>• Resource clarity--extent that available resources are well specified<br>• Stakes--importance of the outcome<br>• Familiarity—extent that tasks are routine or novel<br>• Information availability--extent that needed information is readily available<br>• Time pressure--extent that task has hard real or perceived deadlines<br>• Transparency--the ease or difficulty required to monitor task status or progress<br>• Stability—extent that tasks, resources, and information requirements may change in response to new opportunities and problems |

### *Tool Taxonomy*

Our taxonomy groups collaboration tools in four classes: general purpose communication tools, special purpose facilitators of group processes, shared work and group sense making tools, and process support tools.

The first class, **general purpose communication tools**, are widely available today. They enable people to collaborate over distances. These include e-mail, video and audio conferencing, shared white board, shared documents and databases, bulletin boards, news groups, and web pages. Some of these, like e-mail, support asynchronous collaboration while others, such as video conferencing require team members to meet at the same time.

The second class, **facilitators of group processes**, addresses some of the obstacles to successful collaboration that exist even when people meet face to face. These include electronic meeting systems, brainstorming, negotiation, review and editing, idea enrichment tools. Many tools in this class are commercially available. One example is the Microsoft Word change tracking capability.

The third class, **shared work and group sense making tools**, provides tailored interactive visualizations of shared data. These tools advance shared white boards using advanced visualization techniques. They depict information to each team member in ways that help that team member contribute to collaboration goals. The DARPA CPOF program and ACOA ACDT are developing tools of this type.

The final class, **process support tools**, helps team members synchronize their activities. These include workflow managers, electronic document management, calendar support, collaborative planning, and plan monitors.

## COLLABORATION METRICS

Collaboration metrics provide the scales for measuring the end result of a collaboration and the many processes that contribute to that end result. This paper organizes these metrics into two main groups, cognitive and non-cognitive (Table 3). Each of these are subdivided into several additional groups.

**Table 3. Cognitive and Non-Cognitive Collaboration Metrics**

| NON-COGNITIVE | COGNITIVE |
|---|---|
| Overall utility<br>Product quality<br>Team efficiency<br>Team behaviors | Team level<br>Alignment<br>Roll-up<br>Individual<br>Task focused<br>Team behavior focused |

Because metrics, to be relevant, must bear on the efficient and timely development of quality products, this discussion begins with the overall utility metrics, those that measure product quality and team efficiency. Subsequent material describes and illustrates the metrics

for the key team behaviors, team level cognitive metrics, and individual cognitive metrics. The EBR Final Report, "Metrics for Evaluation of Cognitive Architecture-Based Collaboration Tools" describes these collaboration metrics in greater detail.

### *Overall utility metrics*

These are the bottom line "proof of the pudding" metrics. They measure the quality and timeliness of team products and overall team efficiency. A team that consistently scores well on these metrics is an effective team, for they are accomplishing their purposes efficiently. Note that these metrics apply irrespective of how the products are created. They would be equally relevant whether produced by a single person or by a team. Table 4 provides examples of some of the overall utility metrics.

**Table 4. Examples of Overall Utility Metrics**

| Metric type | Examples |
|---|---|
| Product timeliness | • Timeliness of product production--product completion time relative to deadline<br>• Product completion time relative to a norm or benchmark |
| Product quality metrics (plan example) | • Useful life of plan compared to its intended useful life. No plan "survives contact with the enemy," but better plans last longer<br>• Number of major changes required before plan can be executed<br>• Fraction of commander's objectives that plan addresses<br>• Fraction of plausible contingencies covered by plan<br>• Number of possible significant adverse unintended consequences, including excessive collateral damage, adversary responses, or undesirable coalition or international reactions |
| Team efficiency | • Total amount of time required to complete the product<br>• Person hours to complete product |

### *Team Behavior Metrics*

Team behaviors are the second category of non-cognitive metrics. These metrics measure how well the team functions as a team; e.g., the extent to which a team can adapt to new circumstances. Team behaviors directly impact the product and team efficiency metrics discussed previously and are directly impacted by the more fundamental cognitive processes to be described later. Team behaviors are important to measure because they can provide insight into how the various cognitive processes actually impact team effectiveness.

Successful teams are effective in adapting to new circumstances, maintaining common goals and team members' buy in, maintaining shared understanding, synchronizing tasks and

products, sharing work and information, leveraging expertise, detecting problems early, adapting to new circumstances, and maintaining "common ground."

This last behavior, maintaining common ground, may be the core skill that is required to do the others well. Common ground is what each collaboration participant assumes about each other in order to have effective interactions. It includes each team member's assumptions about other team members: their goals; their skills, expertise, and information; their status, to include workload, fatigue, distraction, and level of engagement; their degree of commitment and buy-in; and their cognitive strategies and approach to problem solving.

Some example of team behavior metrics are:

- Time needed to disseminate messages
- Fraction of messages received that are relevant
- Number of cases where sub-teams refuse to share information relevant to others
- For synchronous collaboration, number of incidents requiring participation by team members not at the meeting
- Extent that homogeneous, conventional speech patterns used

### *Team Level Cognitive Metrics*

The team level cognitive metrics abstract and aggregate the metrics for individual cognitive processes described later. These team level cognitive metrics measure the overall level of task and team awareness within the team, the extent to which team members' understandings are aligned and consistent, and the extent to which each team member is aware of other team members' tasks, skills, commitment, perceptions, workload, and progress.

Team level cognitive metrics are divided into two groups: 1) roll-ups (usually averages) of individual cognitive processes, and 2) the extent to which team members' perceptions are aligned.metrics. Both groups are computed from the individual cognitive metrics.

Some examples of roll up metrics are:

- Hierarchical sensitivity: "the degree to which the team leader effectively weights staff members' judgment in arriving at the team decision"
- Average accuracy of each team member's estimates of information needed by other team members

Some alignment examples are:

- Degree team members' individual goals align with team goals
- Consistency and overlap of shared understanding of problem, goals, information cues, and strategies

### *Metrics for Individual Team Member Cognition*

The Individual Cognitive Metrics measure the level of team member awareness and understandings. They can be inferred from the information that people provide or seek, from the products that they produce, or from the actions that they take. When data collection constraints permit, they may also be estimated by asking people questions about what they know and understand.

These metrics are measured for each individual separately. Because individual cognitive processes are the processes directly affected by collaboration support tools, these metrics are essential to any systematic cognitive-based investigation of collaboration tool effectiveness.

Individual cognitive metrics are divided into two broad groups, task-focused and team focused, as suggested by the Dual Feedback Collaboration Model (Figure 2). Examples of individual cognitive metrics for these two categories are:

For achievement of team mission:

- Correctness of team member understanding of commander's intent
- In monitoring, the fraction of significant observables overlooked
- In situation diagnosis, the fraction of monitor-reported situation observables requiring attention that receive attention
- Correctness of reasons why plan needs adjusting
- Correctness of specification of own and adversary centers of gravity
- Correctness of knowledge of deadlines of decisions

For maintenance of team health

- Fraction of monitor-reported team status observables requiring attention that receive attention
- Accuracy of assessment of team member roles, tasks, workload, capabilities, buy in, and goals
- Fraction of opportunities for team improvement noted or overlooked
- Correctness of knowledge of deadlines of decisions

## SUMMARY

Because they measure the immediate effects of collaboration tools on individual team members, cognitive-focused collaboration metrics are very important for developing effective collaboration tools,. The metrics described in this paper measure team products and efficiency, team behaviors key to effective collaboration, team level reflections of individual team member cognitive processes, and individual cognition. These metrics support analyses that seek to identify critical bottlenecks to effective collaboration and to suggest means to minimize bottlenecks.

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