The Relationship Between e-Collaboration and Cognition

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Recent research has proposed that groupware performance may be affected by two factors, the strongest of which is the fit between the task and the groupware structures selected for use. We suggest that the link is deeper; there needs to be a fit between the task and the group's cognitive structures as mapped to the groupware structures. In this paper we address this shortcoming by integrating recent theories of cognition (distributed cognition, transactive memory and template theory) from the perspective of electronic collaboration. We refine the concept of cognitive fit as applied to group work and offer propositions for further study. We show that template core data is used during situation assessment and that slot data refines response selection. Finally, we propose several techniques by which the group cognitive effort can be minimized, thereby leaving more capacity for the collective task. This approach is especially applicable to naturalistic group decision situations.

Keywords: e-Collaboration, Transactive Memory, Template Theory, Stimulating Structures

1. INTRODUCTION

An emerging theme in today's workplace is the pressure to do more with less. For example, the US economy continues to expand even though the numbers of people employed remains fairly static: resulting in remarkable productivity gains (Bureau of Labor Statistics, 2004). In the public sector, schools, universities, governments, police, hospitals, and firemen are all under pressure to reduce their overhead while maintaining levels of service. The military is not immune to these trends, retention and recruitment are serious issues for the military at a time when major operations are taking place in several areas of the world. This pressure to increase

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productivity creates a stressful work environment for employees, and places a premium on the ability to discover ways to work more effectively.

Most work involves some kind of group activity rather than individual activity (Thompson and Fine, 1999). Work groups have many forms, including project teams, boards of directors, management teams, planning teams, juries, and committees of various types. Most important economic, political, legal, scientific, cultural, and military decisions are made by groups, not individuals (Keltner, 1989).

As the pace of work continues to increase, many work groups must face situations that routinely have high stakes, time-pressure, and uncertainty. In this challenging task environment, group members are often pushed to their limits of performance. Humans have limited cognitive resources of memory, attention and perception; availability of these resources directly impacts our task performance (Wickens, 1984).

To address some of these limitations, tools have been developed to support specific cognitive strategies for individual decision makers (Kaempf, Klein, & Wolf, 1996). Performance has been shown to improve when there is a good cognitive fit between the task and the tool (Dunn & Grabski, 2001; Vessey, 1991). Software support for group decision-making has been a central research area of information systems in the last 30 years (for reviews, see Dennis and Williams, 2005; DeSanctis & Gallupe, 1987; Jessup & Valacich, 1993; McGrath & Hollingshead, 1994; Nunamaker, 1997). This electronic collaboration (e-collaboration) can be broadly defined as collaboration among individuals engaged in a common task using electronic technologies. While some meta-analyses have shown mixed results (Benbasat and Lim, 1993; McLeod, 1992; Pinsonneault and Kraemer, 1990), many studies have shown that e-collaborative teams can outperform face-to-face teams (Schmidt, Montoya-Weiss & Massey, 2001 as merely one example). However, within the large body of literature on e-collaboration, we are not aware of any software that is specifically designed to optimize the utilization of human cognitive resources in collaborative situations. Most systems have addressed behavioral issues associated with human interaction or have implemented algorithms designed to increase decision or communication efficiency.

Most recently, Dennis, Wixon and Vandenberg (2001) have suggested that groupware performance may be affected by two factors, the strongest of which is the fit between the task and the groupware structures selected for use. We suggest that the link is deeper; there needs to be a fit between the task and the group's cognitive structures as mapped to the groupware structures. In this paper we address this shortcoming by integrating recent cognitive theory with collaboration and put forward several propositions for further study.

2. THEORETICAL FOUNDATION

Groups can accomplish larger and more complex tasks than individuals. Yet, there are many factors affecting group effectiveness that have been categorized into process losses and process gains (Jessup and Valacich, 1993; Nunamaker, 1997). While this simple model has an intuitive appeal, it begs the question, "how does one maximize gain or minimize loss?" From the perspective of cognition, we believe the answer to this question requires the integration of at least three broad areas of study:

- Individual cognitive psychology, including abilities and limitations,
- Groups and social interactions, including communications and motivations, and
- The role of software artifacts as stimulating structures for human interactions.

A complete review of any one of these topics is beyond the scope of this paper, so we will limit our review to a subset of these topics that apply most directly to collaboration and cognition. For our purposes, we assume that each group member understands their role in the group, and the roles of the other group members. We assume that the members are motivated to achieve the stated objectives of the group. We restrict ourselves to decision domains having high stakes, time pressure, and some uncertainty. And, finally, we presume that the group has some kind of e-collaboration or groupware support, e.g. a shared workspace.

There are many tasks that fit within the limitations of our assumptions: tasks having a sufficiently large scope to require group effort, and presenting a significant cognitive challenge. Consider the case of a financial services firm seeking to choose investments for their clients' retirement portfolios. One such financial services firm, TIAA-CREF (2004) has stated that one of their three key investment philosophies is "collaborative expertise". Each type of investment requires different kinds of experts and decisions must be made quickly in the marketplace. For example, decisions about what kinds of bonds to purchase for fixed-income portfolios depend on the work of *credit analysts, sector analysts, acquisition specialists, portfolio managers* and *quantitative managers*. In a nutshell, their collective task is to identify stocks to purchase, to decide how much to weight them in the portfolio and when to make the trades. To be successful, these different kinds of investment professionals must work together in a way that makes the most of each skill set, and their firm wants this to happen not just within an asset class, but also throughout their entire organization. Firms like TIAA-CREF may manage as much as US$100 billion; we suggest that collaborative portfolio management involves high-stakes, time pressure and some uncertainty. We will use this example throughout the paper.

In the following sub-sections, we review the limitations of individual cognition, theories of group-level cognition related to transactive memory, shared mental models, and distributed cognition as integrated with template theory. Each topic is summarized with a group cognitive proposition.

2.1. Model Human Processor

Our goal is to specify a set of prescriptions for designers of collaborative systems that will provide mechanisms to improve group performance by reducing the cognitive effort required to perform group tasks. The importance of reducing cognitive effort stems from the notion that humans have limited cognitive resources. The capacity or resource models (e.g., Kahneman, 1973; Navon & Gopher, 1979; Wickens, 1984) view the human system as having a limited reservoir of resources that are quantifiable, divisible, allocatable, and scarce. To the extent that the cognitive effort to perform some task can be reduced, then people will be likely to make fewer errors, and to have more residual effort available for other task-related activities; in our case, group oriented tasks.

Multiple resource theory proposes that there are separate and finite reservoirs of cognitive resource (Wickens, 1984; 2002), some of which are potentially available simultaneously for different purposes. Figure 1 shows the Model Human Processor proposed by Card, Moran, and Newell (1986). The model shows various cognitive resources, including different types of memory (long-term and separate working memory stores for visual and auditory working memory), separate processors for perception, motor control, and an executive "cognitive" processor. Working memory refers to temporary or "short-term" memory that humans use to buffer our recent perceptions, or to gather our recollections from "long-term" memory.

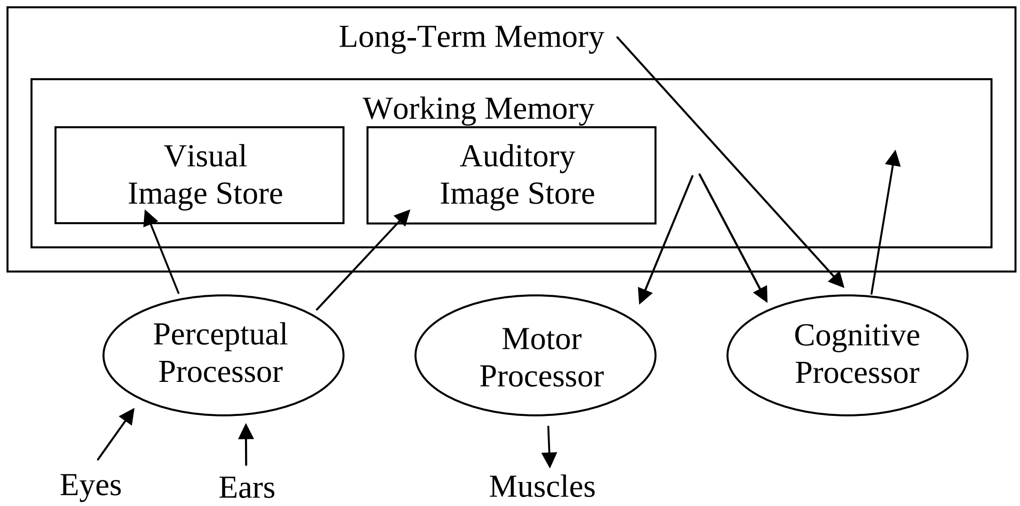

Figure 1. Model of the Human Information Processor from Card, Moran, and Newell, 1986.

It requires some cognitive effort to retrieve memories from long-term storage. Once those long-term memories are "active" in short-term memory, it also takes some ongoing effort to keep them active. These efforts are expended by the cognitive processor, and are generally referred to as "attention." Humans have a finite amount of attention resource, which can be consciously directed to a variety of tasks, such as retrieving memories from long-term storage, maintaining memories in short-term storage, directing sensory activities (e.g. looking or listening carefully), and controlling motor processes. We have difficulty dividing attention among several tasks, or attending to all the information provided by the senses (Broadbent, 1958; Treisman 1969). As a result, we often do not perceive most of the information that is available to us (Lavie, 1995). As Nobel Laureate Herb Simon has said, "a wealth of information creates a poverty of attention (Varian, 1995)." The "perceptual" and "motor" processors also have limitations, i.e., the eyes and ears can detect a limited range of light and sound.

Short-term memory is limited to two separate stores of relatively small capacity (see Figure 1). The presence of separate memory stores has received significant recent support (Baddeley, 1992, 1998; Baddeley, Chincotta & Adlam, 2001; Wickens, 2002; Wickens & Liu, 1988; Winn, 1990). Baddeley's (1992) terminology has been generally adopted as the standard; he refers to these separate resources as "visio-spatial" and "articulatory-loop" memory. While Chase and Simon (1973a, 1973b) adopted Miller's (1956) estimate for the size of each short-term memory store as about 7 ± 2 items, more recently, the size of the visio-spatial store has been estimated as a maximum of 4 items (Zhang and Simon, 1985; Gobet and Clarkson, 2004; Gobet and Simon, 2000). These limitations are additive; it is possible to simultaneously hold about 4 items in visio-spatial memory while holding approximately 7 items in articulatory-loop memory.

Up to this point, we have described the construct of "cognitive effort" as it applies to individual persons rather than groups of persons. In the next sections, we assimilate Hutchins (1991) construct of distributed cognition, and Wegner's (1987) theory of transactive memory which allow us to bridge the unit of analysis from individuals to groups.

2.2. Distributed Cognition

Not only do individuals have cognitive limitations, groups are also limited in their capacity to remember everything required to accomplish the task. Hutchins (1991) introduced distributed cognition as a mechanism to explain how high-performing teams create a distributed socio-technical system. Socio-technical systems refer to groups of people, and the technologies they use to interact. Hutchins asserts that a distributed socio-technical system engages in two kinds of cognitive work: the cognition that is the task, and the cognition that governs the coordination of the elements of the task. The cognitive properties of this socio-technical system are produced by an interaction between the structures internal to individuals and structures external to individuals.

The technologies used by a socio-technical system may be as simple as paper and pencil, or as complex as a jet cockpit. Hutchins (1995) describes the complex process by which a commercial jet aircraft transitions from cruise flight to landing: there are several steps, each requiring careful consideration of aircraft weight, speed, and configuration of airfoils. The task requires the crew to perform complex computational tasks while simultaneously monitoring the performance of the aircraft, as well as remembering the appropriate sequence of actions that result in a safe landing. The task creates a high cognitive load, and is prone to errors. Aircraft systems designers have found that placing a "bug" on the airspeed indicator (an external representation) reduces cognitive effort.

Distributed cognition allows us to consider that cognitive effort can be distributed among group members and external representations. That is, elements of a task might be represented in the external environment, and be available to the group for inspection. By making a representation "public", the group can share it. External representations (at the least) serve to expand the amount of available memory for the group (see Figure 2).

Proposition 1: External representations increase the memory available to the group.

Group memory, in this case, could be defined as:

$$N * (4 + 7) + i + j - (N * k)$$

where N is the group size, 4 and 7 being the established estimates for the capacity of the separate channels of short term memory, i is the number of visio-spatial external representations and j is the number of articulatory-loop external representations and k is a function of the amount of attention each team member has. Attention is a scarce resource and impacts the ability to maintain items in short-term memory. Note that these external representations can be technical artifacts that extend the memory (and cognitive) capacity of socio-technical systems, without directly affecting the communications (behaviors) of the group members.

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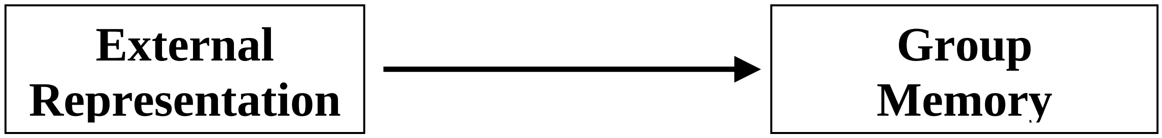

Figure 2: Distributed Cognition Increases the Size of Group Memory

In our TIAA-CREF example, if the team is supported with a shared workspace, the quantitative manager could display the expected risk characteristics (beta) of a particular portfolio. This would be the external representation and could take the form of an electronic "post-it" note, or symbol. All the other group members could refer to that representation as they conduct their analyses and thus not have to store this data in their memory.

2.3. Transactive Memory

Group memory may now be larger, but not everyone in the group has access to it. For these memories (including external representations) to be available to the group, one or more members of the group must remember where to find the information they need. In order to achieve the benefits of collective recall, the individual group members will require a system for encoding, storing, retrieving, and communicating their own and other's representations. This system has been called a transactive memory system (Wegner, 1987) and includes the cognitive abilities of the individuals as well as meta-memory, that is, the beliefs that the members have about their memories. Members of a group have access to the collective memory by virtue of knowing which person remembers which information (see Figure 3).

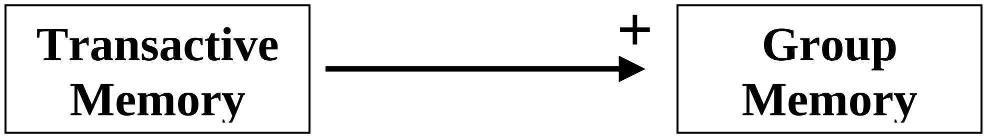

Figure 3: Transactive Memory Increases the Size of Group Memory

By having a shared awareness of who knows what information, cognitive load is reduced because each individual only has to remember "who knows what" in the group and not the information itself. Greater access to expertise can be achieved, and there is less redundancy of effort (Wegner, Erber, and Raymond, 1991). Mohammed and Dumville (2001) point out that developing a transactive memory system reduces the rehashing of shared information and allows for the pooling of unshared information. Moreland (1999) also showed that transactive memory systems improved performance and that training people together allowed for the development of such a system. Moreland and Myaskovsky (2000) investigated the possibility of whether performance benefits from being trained together were due to transactive memory or just improved communication. They found that communication itself was not responsible for improved performance; groups that had handouts of each other's skills, yet did not communicate with each other, performed as well as the members of the group who were trained together.

To integrate distributed cognition with transactive memory, the group socio-technical system must develop meta-memories regarding the distribution of knowledge and expertise within the group. And, if these meta-memory structures are placed into the external environment, the effort required recalling "who knows what" is reduced, thus increasing the groups' cognitive processing capacity.

Proposition 2: Transactive memory systems increase the cognitive capacity of groups.

Returning to the financial management example, the skill sets and sector responsibilities of the sector analysts (and all other group members) should be made publicly available. When a new or existing group member wishes to know the forecast profile for a particular company, if they don't find it as an external representation, they can search the transactive memory system, to find out who to ask. The group would not have to build or hold this knowledge in their memories.

2.4. Stimulating Structures and Coordination

Public representations have been studied before in other contexts. Grassé (1959) coined the term stigmergy, referring to a class of mechanisms, or stimulating structures, that mediate animal-animal interactions. The concept has been used to explain the emergence, regulation, and control of collective activities of social insects (Susi and Ziemke, 2001). Social insects exhibit a coordination paradox: they seem to be cooperating in an organized way. However, when looking at any individual insect, they appear to be working independently as though they were not involved in any collective task. The explanation of the paradox provided by stigmergy is that the insects interact indirectly by placing stimulating structures in their environments. These stimulating structures trigger specific actions in other individuals (Theraulaz and Bonabeau, 1999). Stigmergy appears to be the ultimate example of reduction of cognitive effort because social insects, having essentially no cognitive capability, are able to perform complex collaborative tasks.

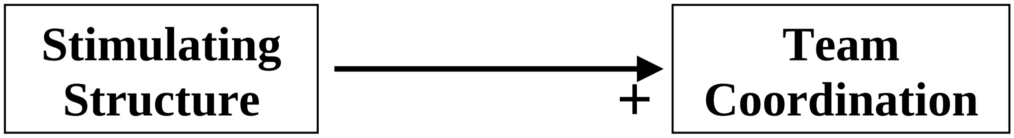

Figure 4: Stimulating Structures Improve Team Coordination

We suggest that this concept can be applied to human teams, i.e. when a stimulating structure is placed in the external environment by an individual, other team members can interpret it and take appropriate action, without the need for specific communication or coordination (see Figure 4). Stigmergy in its current form is complementary to distributed cognition, because the stimulating structure may or may not have any cognitive properties. However, we suggest that if a stimulating structure (artifact) is mapped to a cognitive memory construct (chunk or template as discussed later), the cognitive effort required for coordination and collaboration can be significantly reduced (Hayne, Smith, Vijayasarathy, 2004).

Proposition 3: Stimulating structures reduce the effort required for cognition that governs the group's coordination on the elements of a task.

Continuing with our TIAA-CREF example, acquisition specialists would display a "recommend buy at *X*" for a particular stock on the shared workspace. Once this stimulating structure is represented on the screen, portfolio and quantitative managers would immediately take whatever action they deemed appropriate without the need for further coordination or communication. We will recommend a format for display of this information in the next section.

2.5. Template Theory and Memory Chunks

While we have shown that various types of external representations are important, we suggest it is critical that they be mapped directly to the right cognitive memory construct, chunks or more specifically, templates. Experts in various domains vastly outperform novices in the recall of meaningful material coming from their domain of expertise. To account for this result, Chase and Simon (1973a, 1973b) proposed that experts acquire a vast database of chunks, containing, as a first estimate, 50,000 chunks. When presented with material from their domain of expertise, experts recognize chunks and place a pointer to them in short-term memory. These chunks, each of which contains several elements that novices see as units, allow experts to recall information well beyond what non-experts can recall (Simon, 1974).

However, recent Intensive research in skilled memory has shown that parts of the original chunking model must be incorrect. For example, in contrast to the usual assumptions about short-term memory, chess masters are relatively insensitive to interference tasks (Charness, 1976; Frey & Adesman, 1976) and can recall several boards that have been presented successively (Cooke, Atlas, Lane & Berger, 1993; Gobet & Simon, 1996a). In addition, Chase and Ericsson (1982) and Staszewski (1990) have shown that highly trained subjects can memorize up to 100 digits dictated at a brisk rate (1 second per digit). Experts can also increase the size of their chunks based on new information; effectively increasing short-term memory (Gobet & Simon, 1998). Because an explanation of this performance based on chunking requires learning far too many chunks, Chase, Ericsson and Staszewski proposed that these subjects have developed structures ("retrieval structures") that allow them to encode information rapidly into long-term memory (LTM). Such structures have been used at least since classical times, when rhetoricians would link parts of a speech to a well-known architectural feature of the hall in which the speech was to take place, to facilitate recall (Yates, 1966). Retrieval structures are an essential aid to expert memory performance. Gobet and Simon (1996b) went on to demonstrate that the time required to encode and retrieve chunks is much shorter than previously believed. These results lead to the development of template theory.

Template theory assumes that many chunks develop into more complex structures (templates), having a “core” of data to represent a known pattern of information, and slots for variable data to enhance the core (Gobet and Simon, 1996a; Gobet and Simon, 2000). Templates have been referred to by various other names in other non-cognitive domains, i.e. schemas

(Bartlett, 1932), frames (Minsky, 1977), prototypes (Goldin, 1978; Hartston & Wason, 1983), etc. In the domain of chess, templates allow rapid encoding and retrieval from long-term memory of more data than chunks (10-15 items as opposed to 4-5 items). For example, when a chess position pattern is recognized (say, as a King's Indian defense), the corresponding stored representation of the chess board provides specific information about the location of a number of core pieces (perhaps a dozen) together with slot data which may possess default values ("usual" placements in that opening) that may be quickly revised. Templates are cued by salient characteristics of the position, and are retrieved from long-term memory in a fraction of the time than other memory structures.

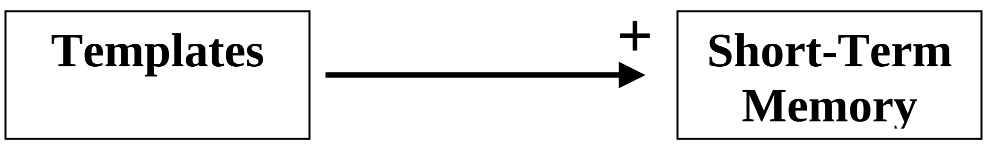

Figure 5: The Use of Templates Expands the Capacity of Short-Term Memory

If a template can be retrieved from long-term memory in essentially the same time as other constructs from short-term memory, the team can significantly increase memory capacity by representing templates in the external environment, for all to see, attend to and retrieve (see Figure 5).

Proposition 4: Templates increase the effective size of group short term memory.

Framed in our financial services example, we suggest that the "buy" simulating structure from the previous section be displayed in a form that matches the memory structure in which the group has been trained. This might be some kind of icon in the shared workspace, with a ticker symbol and limit price embedded within the icon. The icon serves as an external representation of the “buy” template. The core data about the firm will be retrieved from the individual’s memory and the slot memory for limit price will be overwritten by the data on the screen. Group members do not have to keep all this information in short-term memory because it can be so effortlessly retrieved when needed.

The network of templates is grown by two learning mechanisms, familiarization and discrimination. When a new object is presented, it is sorted through a hierarchical discrimination net. When a template node in the discrimination net is reached, the new object is compared with the image at the node. If the existing image underrepresents the new object, features are added to the stored image (familiarization). If the information in the existing image and the new object differ on some feature, the new object is stored as a new node in the discrimination net (discrimination). Gobet and Jackson (2002) have demonstrated this process with complete novice subjects when learning chess.

Thus, template theory offers a major advantage over previous representations of short-term memory. Template theory offers the possibility that we may discover ways to improve human performance by taking advantage of the distinctions between the cognitive structures of core and slot memory.

2.6. Situation Assessment, Response Selection and Template Core/Slot

While template theory describes an innovative way to retrieve memories, we need decision theory to act upon them. Klein (1993) developed the theory of Recognition-Primed Decision Making (RPD) to describe how individual experts make decisions in naturalistic environments and suggested that experts make decisions by recognizing patterns in a developing situation. According to RPD, tactical decision makers recognize the current situation in so far as it is similar to some recalled and similar situation stored in their memory. This situation assessment, and its associated plan of action (or response selection), is retrieved from memory for use in the current situation. RPD has been validated by Kaempf, Klein, and Wolf (1996) when they found that experts make almost 90% of their decisions by “feature matching” between the current situation and one from prior experience. Experts spent most of their time scanning the environment and developing their situation assessments. Relatively little time was spent selecting and implementing responses. Because of the similar results from the domain of chess (Gobet, 1997; Gobet and Simon 1998; Gobet and Simon, 2000), we argue that from a cognitive perspective, experts build discrimination nets of templates to enable this feature matching.

It is at this point where template theory provides insight to the cognitive mechanisms behind situation assessment and response selection for individuals. As a decision maker scans their environment they are directing attention to their perceptual processes. The information they perceive is sorted through their template discrimination net, and when core items are noticed, the appropriate templates are retrieved. In other words, core data items activate recognition of familiar patterns, thus creating situation awareness (see Figure 6a). As templates are retrieved, the slot data are made available in short-term memory. These slot data provide additional information to the decision maker regarding variants of the patterns, and potential strategies for action. In other words, the slot data provide the key to successful responses (see Figure 6b).

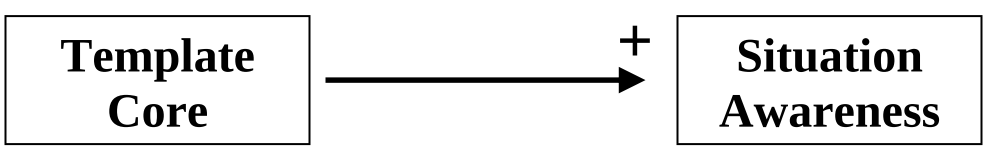

Figure 6a: Template Core Data Improves Situation Awareness

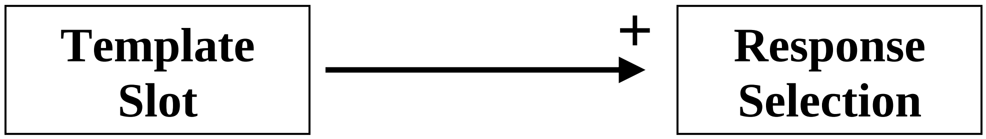

Figure 6b: Template Slot Data Improves Response Selection

Evidence suggests that teams perform essentially the same steps as individual experts, with some additional executive functions (Hayne, Smith, Turk, 2003; Hayne, Smith, Vijayasarathy, 2004). Similar to individual experts, teams assess the situation and perform “feature-matching” tasks which trigger recall of similar situations from their collective memory. The “core” of the template appears to be retrieved first by team members (Hayne, Smith, Vijayasarathy, 2005). Then, teams select a response by adapting a strategy from their previous experience and slot data is used to refine the response.

Proposition 5: Template core data enables group situation assessment.

Proposition 6: Template slot data enables group response selection.

In our final portfolio management example, when the “buy” icon is displayed on the shared workspace, all team members who attend to this stimulating structure, retrieve the core data associated with the “buy” template. This retrieval is effortless, and the team members know exactly what response is appropriate. While this significantly increases e-collaboration, we suggest that if slot data is also represented, i.e. the date/time by which a trade needs to be completed, a more detailed response can be motivated in the other group members.

3. COGNITIVE STRATEGIES

In the previous sections we have described the general limitations of cognitive capacity for attention, perception, and memory. We have explained in some detail the mechanisms that facilitate individual and group recall and how they impact e-collaboration. Based on these fundamental properties of cognition, we now put forward three strategies that can be applied to any task. These global strategies should reduce individual cognitive effort and thus improve group work.

3.1. Minimize the net cognitive effort required for a collaborative task.

Remember, the total cognitive effort required for collaboration is comprised of two components, one associated with task-related cognition, and another associated with coordination-related cognition. These separate efforts draw from the same pool of available cognitive resources. Thus effort expended on coordination activities reduces the cognitive effort available for task-related activities.

Keeping an item "active" in short-term memory requires effort from our cognitive processor. The cognitive processor also directs attention to perceptual processes and activates motor processes. In socio-technical systems, the cognitive processor for each group member must devote some available effort to coordination-cognition. Coordination cognition may include reserving some perceptual capacity for intra-group communications, some short-term memory for the current status of other group members' activities, and some cognitive processor capacity for noticing when coordination actions are required. So, for groups engaged in e-collaboration, the members' cognitive processors must perform several tasks: maintaining information active in short-term memory, retrieving-from and storing-to long-term memory, directing perceptual processes, and activating motor responses. If a cognitive processor becomes overloaded, there may be insufficient attention resources available to maintain information active in short-term memory. In other words, we may forget things because we are busy, rather than because the demands on our short-term memory are excessive. Strictly speaking, this is not a failure of short-term memory. Rather it represents a limitation of the collective cognitive resources available for perception, attention, *and* memory. This distinction is important. In order to make a task easier, we must understand why it is hard. Collaboration tasks are especially difficult, because each group member must reserve some cognitive capacity for coordination-cognition, leaving less available for task-cognition.

We propose that e-collaboration systems should seek to minimize the net cognitive effort required by a group in the performance of a task. The system should promote load-sharing so that any member of the group is not forced to exceed their individual limitations for attention, memory, or perception. The net cognitive effort includes the efforts expended by group members to coordinate their actions. We have discussed how the stigmergy strategy can reduce the cognitive effort required for coordination. Every collaborative task is likely to have some optimum amount of coordination which permits the group members to achieve their collective goals without expending unnecessary effort on the coordination process.

Beyond these basic prescriptions for reducing effort, we offer an additional insight. As mentioned earlier, most naturalistic tasks involve situation assessment and response selection (Kaempf, Klein, and Wolf, 1996). Templates are discriminated by their core data items; retrieval of matching templates provides the initial options for situation assessment. Response selection is based primarily on the slot data: once a pattern is recognized by virtue of the core data, the response depends on the state of the ancillary information. This provides an opportunity to reduce cognitive effort by tailoring e-collaboration tools for the task: situation assessment or response selection. During situation assessment, core data items should be perceptually salient. Furthermore, if different templates share some core items but not others, then the discrimination task can be made less effortful by drawing the users' attention to the non-shared core items. In other words, draw the users' attention to the core items that are most diagnostic of the situation. When situation assessment has been completed, the information presentation can be altered to make the slot data items more salient, as an aid to response selection.

3.2. Transform computational tasks to perceptual tasks to increase performance

In the example of the "airspeed bug" on the airspeed indicator (above), the crew transforms an effortful cognitive task into a simple perceptual task (see Figure 7): when the airspeed needle points at the bug, the pilots perform the next action in their landing procedure. The airspeed bug provides a simple visual cue to the current state of the landing procedure. The external representation frees up short-term memory and cognitive capability in the crew members.

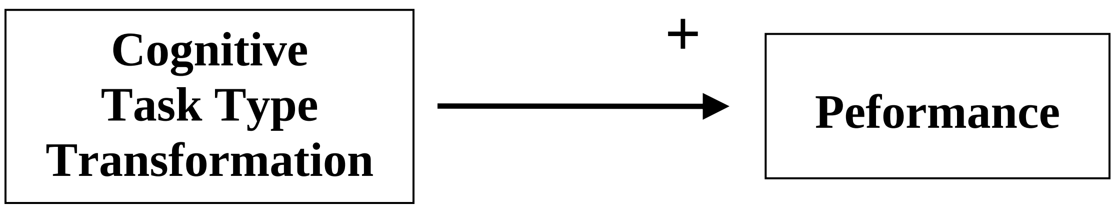

Figure 7: Cognitive Task Type Transformation Improves Performance

For humans, stigmergy is especially effective under conditions of time pressure. The limitations of short-term memory are exacerbated by the stress of time pressure: it has been shown that stress causes the release of a cortical steroid that interferes with memory (de Quervain, Roozendaal, Nitsch, McGaugh, and Hock, 2000; Kirschbaum, Wolf, and Hellhammer, 1996). In complex multi-tasking environments, it is not uncommon for decision groups to be interrupted in the middle of a process. After dealing with the interruption, the group may find it difficult to resume the process. Often, this results in restarting from the beginning. Using stigmergy, systems designers can provide stimulating structures (perceptual cues) to the point in a process at which execution was interrupted. Transforming the effortful task of remembering where to resume to a simple perceptual task can reduce errors and save time. This is especially useful under time pressure, when saving time is critical and the stress of time pressure further degrades our already limited memory capacity.

3.3. Transform task modality to reduce effort

When the demands of a task exceed the capacity of either short-term memory store (visio-spatial or articulatory-loop), task performance degrades. Thus the mode by which information is presented can affect task performance. Consider an e-collaboration system that presents information to a group in the performance of their task: if the task is visually intensive, presentation of any additional information in visual form may exceed the capacity of the members' visio-spatial stores. However, in the same visually intensive task, if additional information is presented aurally, then the additional information may be maintained in the members' articulatory-loop memory, and not interfere with their task performance. For optimal performance, we suggest that each group member's cognitive load be balanced between both visio-spatial and articulatory-loop. Tasks should be transformed between task modes as necessary (see Figure 8) to accomplish this goal.

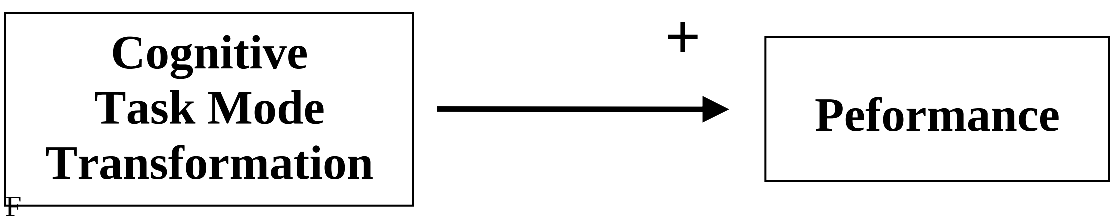

Figure 8: Cognitive Task Mode Transformation Improves Performance

In summary, balancing the load between visio-spatial and articulatory-loop memory is an effective strategy for improving task performance.

4. IMPLICATIONS FOR PRACTITIONERS

There are several benefits that may result from the approach described here. We expect that it is possible to:

1. Reduce the amount of overt supervision and coordinating actions required for groups engaged in complex collaborative tasks,
2. Improve organizational memory for “who knows what,”
3. Make decisions faster, and
4. Reduce errors of situation assessment.

To illustrate these advantages, we refer to a recent article by Talbot (2004) which describes military operations in Afghanistan. Talbot describes an operation that occurred in the fall of 2001 in which an insurgent convoy was detected, surveilled, and interdicted. What makes the example unusual is that the forces involved were collaborating outside their formal chains of command in an ad-hoc team.

> “The scene was a cold night in 2001… A U.S. Air force pilot en route from Uzbekistan noticed flashing lights in the mountains below, near the Pakistan border… he radioed his observation to the webmaster. The webmaster relayed the message across a secure network accessible to special forces in the region. One team replied that it was near the position and would investigate. The team identified a convoy of trucks carrying Taliban fighters and got on the radio to ask if any bombers were in range. One U.S. Navy plane was not far off. Within minutes, the plane bombed the front and rear of the convoy, sealing off the possibility of escape. Not long after, a gunship arrived and destroyed the crippled Taliban column.” (Talbot, p. 44)

The example above illustrates the advantages of a distributed socio-technical system having access to the cognitive aids described in this article. In this case, the operation was triggered by the application of good transactive memory: the pilot of the first aircraft notices something unusual, and he knows “who needs to know this?” The webmaster uses a technical artifact to place a stimulating structure on a publicly available external representation: he posts the observation on a web page. All the special forces in the area are scanning their environment – they notice the stimulating structure placed on the public representation. Without requiring any external supervision, the nearest special forces team immediately understands the implication of the stimulating structure. In contrast, other teams in the region also know that the stimulating structure has no relevance to *their* missions. Thus the stimulating structure has made it possible to reduce the effort expended for coordination. This example also illustrates the reductions in time-to-decision that can be achieved by minimizing the degree of overt supervision. Furthermore, by virtue of having the nearest team make a visual identification of the convoy, the possibility of a tragic mistake is minimized.

While this example is in the military domain, we believe the benefits are equally applicable to other complex collaborative tasks. For example, the collaboration by multiple public agencies in their responses to natural disasters such as hurricanes or earthquakes could be improved through application of the principles outlined in this article. On a more mundane scale, many businesses charge their employees to work on cross-functional teams for projects ranging from strategic planning to employee parking. Achieving these outcomes in less time and with less overt coordination would be beneficial.

5. CONCLUSIONS

We have integrated recent cognitive theory of individual decision-making and applied it to collaboration. Vessey (1991) coined the term "cognitive fit" to describe individual enhanced performance when there is a good match between the information emphasized in the representation type and that required by the task type. We offer an extension to Vessey's findings and give propositions for further study. We have proposed several techniques by which collective cognitive effort may be minimized. We believe that our prescriptions, grounded in cognition, have wide applicability and offer significant opportunities to improve group performance.

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