COGNITIVE MODEL OF TEAM COLLABORATION: MACRO-COGNITIVE FOCUS

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The purpose of this paper is to describe a cognitive model of team collaboration emphasizing the human decision-making processes used during team collaboration. The descriptive model includes the domain characteristics, collaboration stages, meta- and macro cognitive processes and the mechanisms for achieving the stages and cognitive processes. Two experiments were designed to provide empirical data on the validity of the collaboration stages and cognitive processes of the model. Both face-to-face and asynchronous, distributed teams demonstrated behavior that supports the existence of the collaboration stages along with seven cognitive processes.

INTRODUCTION

The purpose of this paper is to describe a cognitive model of team collaboration emphasizing the human decision-making processes used during team collaboration. The descriptive model includes the domain characteristics, collaboration stages, meta- and macro cognitive processes and the mechanisms for achieving the stages and cognitive processes. There have been several models of team collaboration (Orasanu & Salas, 1992; McNeese, Rentsch, Perusich, 2000; Cooke, 2005) each focusing on various aspects of human decision-making while describing those aspects at different levels of detail. The cognitive mechanisms in this model are described at a *macro level* (e.g. knowledge building, knowledge interoperability, team shared understanding, team negotiation to reach team consensus) rather than at the *micro level* (e.g. information processing, neural-cognitive) because of the limited metrics for measuring the micro-cognitive team processes. The model's macro level definition of the cognitive processes permits empirical assessment of these cognitive processes using our current measurement techniques (e.g. verbal protocol analysis, communication analysis).

It is important to understand the scope of the problem area that the collaborative model will be addressing. Major factors impacting military collaborative teams include the *Collaborative Problem Environment*, *Operational Tasks*, *Collaborative Situation Parameters,* and *Team Types*. Military problems are becoming more complex, requiring teams to address problems, rather than relying solely on individuals (Jensen, 2002). In addition, problems are addressed at an international level requiring agile coalition operations. Developments in information and communication technologies have provided greater communication between coalitions, but because of a lack of information management, information overload remains a problem. There are many operational tasks, which involve team collaboration (Jensen, 2002). To gain an understanding of the team collaboration process, the model will focus on three of these tasks: (1) team decision-making, course of action selection, (2) developing shared understanding, and (3) intelligence analysis (team data processing). During team collaboration there are various collaborative situation parameters that influence collaboration performance (Letsky, 2004). Time pressure, information and knowledge uncertainty, large amounts of information, and dynamic information were chosen as critical parameters to focus our collaboration domain because of their significance to current military requirements (Jensen, 2002). The final factor is team types, the most complex factor influencing collaboration performance. The seven-team type characteristics (asynchronous, distributed, cultural diversity, heterogeneous knowledge, unique roles, rotating teams and hierarchical vs. flat command structure) were selected based on the common characteristics of today's military collaborative teams (Jensen, 2002).

Figure 1 presents the cognitive model of team collaboration. The model's domain is defined by the *problem area characteristics*, which were described earlier. The model consists of general *inputs* (e.g. task description), *collaboration stages* that the team goes through during the problem-solving task, the *cognitive processes* used by the team and final team output(s) (e.g. selected course of action). The cognitive processes include the meta-cognitive and the macro-cognitive processes. Also described are the communication mechanisms for achieving the meta- and macro-cognitive processes. The model is a *synthesis* of the literature in team collaboration, human information processing and team communication together with the results obtained during the annual workshops on Collaboration and Knowledge Management. During the 2003 Collaboration and Knowledge Management workshop 12 initial conceptual models were produced each providing some unique and overlapping information. The models varied in their approach and included information-processing, team recognition primed decision making, transactive memory, discovery and innovation, and hybrids such as multi-stage and process models. The final selection of the specific stages and processes was made based on the ability to empirically measure the cognitive process.

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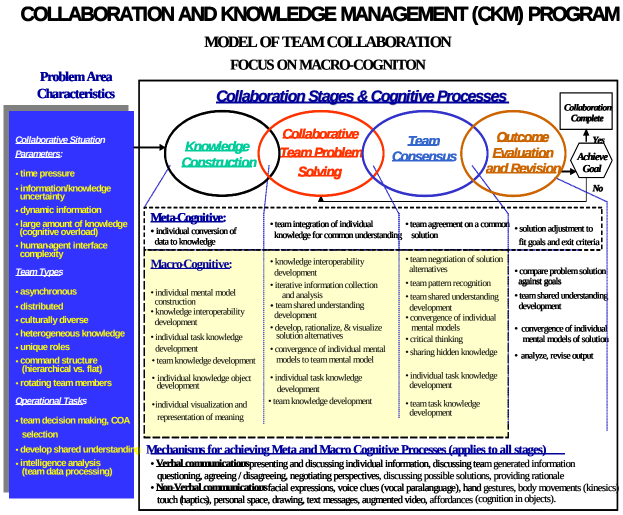

Figure 1: Cognitive Model of Team Collaboration

Model Components

Model Inputs. This information includes such items as: (1) a description of the problem (2) team member expertise, (3) organizational structure, (4) roles and responsibilities of each team member and (5) projected events and future information. This representative domain information is provided to the team during team formation.

Collaboration Stages and Cognitive Processes. The model has four unique but interdependent stages of team collaboration. The stages are: Knowledge Construction, Collaborative Team Problem Solving, Team Consensus and Outcome, Evaluation & Revision. There is also a feedback loop for revising team solutions. Teams will typically start in the Knowledge Construction stage and proceed into Collaborative Team Problem Solving, Team Consensus and finally Outcome, Evaluation & Revision. The stages are not sequential as they appear in Figure 1. Because team communication is very dynamic, the flow of communication can follow virtually any path. The cognitive processes within each stage are represented at two levels: *meta-cognitive*, which guides the overall problem solving process, and *macro-cognitive*, which supports team members activities within the respective collaboration stage. In addition, there are Communication Mechanisms (i.e. verbal and non-verbal) for developing the meta-cognitive and macro-cognitive processes.

Knowledge Construction, the first stage in team collaboration, begins with team members building individual task knowledge and the construction of team knowledge. In this model, data, information, knowledge and understanding are defined and used according to the definitions and principles of Bellinger, 2004. *Data* represents a fact or statement of event without relation to other things. *Information* embodies the understanding of a relationship of some sort, possibly cause and effect. *Knowledge* represents a pattern that connects and generally provides a high level of predictability as what is described or what will happen next. *Understanding* is a cognitive, analytical and probabilistic process that takes current knowledge and synthesizes new knowledge from previously held knowledge. It is understanding that supports the transition from data, to information, to knowledge. The meta-cognitive process during Knowledge Construction is the awareness by each team member that knowledge needs to be developed from data and information in order to solve the collaborative problem. The focus of all the macro-cognitive processes in the Knowledge Construction stage is to support individual and team knowledge development. This knowledge will be used during Collaborative Team Problem Solving to develop solution alternatives to the problem.

During Collaborative Team Problem Solving, team members communicate data, information and knowledge to develop solution options to the problem. The majority of collaboration occurs during this stage. The meta-cognitive process during this stage is the awareness by the team that individual knowledge needs to be integrated for common team representation of the problem. Team mental representation can change during the course of solving the problem. Changes can occur as the team gains more complete understanding of the problem elements, goals or overlooked information (McComb, 2005). The focus of the macro-cognitive processes in this stage is to support development of solution options for the collaborative problem. Some of the macro-cognitive processes under this stage are the same as found in the Knowledge Construction stage, although the focus of these processes differs. For example, knowledge interoperability under Knowledge Construction centers on the exchange of knowledge for the creation of new knowledge among the team. In the Collaborative Problem Solving stage, the emphasis is on exchanging knowledge to develop solution options.

Team Consensus is the stage where the team negotiates solution options and reaches final agreement by all team members on a particular option. During team consensus, the meta-cognitive process is the team's awareness to reach agreement on a common solution. The macro-cognitive processes support the team in reaching total agreement on the final solution to the problem.

During the Outcome, Evaluation and Revision stage, the team evaluates the selected solution option against the problem-solving goal and revises the solution option if that option does not meet the goal. The meta-cognitive process is the team's awareness to have the final solution option meet the problem solving goals. The team as a whole compares the complete solution option against the goal. The focus of the macro-cognitive processes in Outcome, Evaluation and Revision is to support the team in comparing the final solution option against problem goals and to revise the solution, if necessary.

Definitions of the specific macro-cognitive processes are as follows:

Individual mental model construction. Individual team members use available information and knowledge to develop their mental picture of the problem situation.

Knowledge interoperability. The act of exchanging useful, actionable knowledge among team members.

Individual task knowledge development. Individual team members ask for clarification of data or information, or respond to clarification requested by other team members.

Team knowledge development. All team members participate in clarifying information to build team knowledge.

Individual knowledge object development. Pictures, icons, or standard text developed by an individual team member or the whole team to represent a standard meaning.

Individual visualization and representation of meaning. Visualizations (e.g. graphs, pictures) are used by individual team members to transfer meaning to other team members. Representations are methods (e.g. note pads) used by individual team members to sort data and information into meaningful chunks.

Iterative information collection and analysis. Collecting and analyzing information to come up with a solution with no specific solution mentioned.

Team shared understanding. The synthesis of essential data, information or knowledge, held collectively by some (complementary understanding) and/or all (congruent understanding) team members working together to achieve a common task.

Develop, rationalize and visualize solution alternatives. Using knowledge to justify a solution.

Convergence of individual mental models to team mental model. Convincing other team members to accept specific data, information or knowledge.

Team negotiation. Team negotiation of solution alternatives ending in a final solution option.

Team pattern recognition. The team as a whole identifies a pattern of data, information or knowledge.

Critical thinking. The team works together toward a common goal, whereby goal accomplishment requires an active exchange of ideas, self-regulatory judgment, and systematic consideration of evidence, counterevidence and context in an environment where judgments are made under uncertainty, limited knowledge and time constraints.

Shared hidden knowledge. Individual team members share their knowledge through prompting by other team members.

Compare problem solution against goals. Team members discuss solution option against the goal.

Analyze and revise solution options. Team members analyze final solution options and revise them if necessary.

Model Outputs. The product output will vary depending on the problem domain addressed by the team. This model focuses on three types of products: (1) team decision-making, course of action selection, (2) developing shared understanding, and (3) intelligence analysis (team data processing).

The following two experiments provide empirical data on the validity of the collaboration stages and cognitive processes.

EXPERIMENT I

Method

Participants. Eighty-four undergraduate students from a local community college served as participants in this study.

Design. The experimental design used in this experiment was a two by two randomized factorial with two levels of collaboration mode (face-to-face and asynchronous, distributed) and two levels of knowledge distribution (homogeneous and heterogeneous). Each team consisted of three students. There were a total of 28 teams. Face-to-face is where the teams interacted synchronously with each other through speech. Asynchronous, distributed is where teams interacted with each other at different times and from different locations through a text-based web forum. All members of the homogeneous team were given the same information of the murder mystery. Heterogeneous teams had some knowledge in common and some uniquely held knowledge.

Dependent variables. Four dependent variables were used in the experiment: (1) accuracy of decision, (2) time for task completion, (3) time spent in each collaboration stage and cognitive process state, and (4) frequency of utterances.

Procedure. The experimental task required participants to work in teams of three to solve a murder mystery (Stasser, 1995) and reach consensus on who committed the murder.

Data Analyses. Parametric statistics were used to analyze outcome measures while verbal protocol analysis was used to analyze the collaboration stage and cognitive process state data.

Results

There was no significant effect of decision accuracy across collaboration mode and knowledge distribution conditions, Yates corrected Chi Square (1) = .27, p = .6056. There was a significant interaction effect, $F(1, 24) = 6.026$, $p = 0.02$, between collaboration mode and knowledge distribution on the mean percent time spent in Knowledge Construction with the face-to-face heterogeneous teams spending longer in this stage than the asynchronous, distributed heterogeneous teams. During Collaborative Team Problem Solving there was a significant collaboration mode effect, $F(1, 24) = 6.944$, $p = 0.014$, with asynchronous, distributed teams spending more time problem solving than the face-to-face teams. With respect to frequency of utterances, the face-to-face heterogeneous teams had a significantly higher frequency, $F(1, 24) = 5.64772$, $p = 0.025802$, during Knowledge

Construction than the other three team types. There were no significant effects in Team Consensus, collaboration mode: $F(1, 24) = 0.518$, $p = 0.478$; knowledge distribution: $F(1, 24) = 0.117$, $p = 0.734$; collaboration mode/knowledge distribution interaction: $F(1, 24) = 0.829$, $p = 0.371$. Because none of the teams entered the Outcome, Evaluation and Revision, no data was available for analysis. Two cognitive process states were significantly different during Knowledge Construction between the face-to-face and asynchronous, distributed teams, Wilks lambda = 0.402, $F(1, 24) = 3.158$, $p = 0.022$. Asynchronous, distributed teams spent significantly more time understanding the problem than face-to-face teams, while the face-to-face teams spent more time building team knowledge. During Team Problem Solving, face-to-face teams spent significantly more time using conventions to transfer meaning than asynchronous, distributed teams, while the asynchronous, distributed teams spent more time developing solution alternatives than face-to-face teams, Wilks lambda = 0.0003, $F(1, 24) = 9605.498$, $p = 0.000$. There was no significant difference between the four-team types in the cognitive processes used during Team Consensus, Wilks lambda = 0.815855, $F(1, 24) = 1.65519$, $p = 0.205648$. Again, because the teams never entered the Outcome, Evaluation and Revision stage, no data was available for analysis.

EXPERIMENT II

Method

Participants. Ninety-six undergraduate students from a local community college served as participants in this study.

Design. The experimental design used in this experiment was a two by two randomized factorial with two levels of collaboration mode (face-to-face and asynchronous, distributed) and two levels of knowledge uncertainty (static and dynamic). There were a total of 32 teams. During collaborative problem solving the face-to-face teams solved the Non-Combatant Evacuation Operation (NEO) scenario (Warner, Wroblewski and Shuck, 2003) through direct speech discussions around a conference table while the asynchronous, distributed teams used the Electronic Card Wall (EWall) collaboration environment to communicate with other team members. Team members assigned to the static teams received the NEO scenario information and it remained the same throughout the experiment. Team members assigned to the dynamic teams had updated intelligence and weather information presented to them 30 minutes into the session. All asynchronous, distributed team members were in separate office modules within the laboratory. All teams were given 60 minutes to solve the problem.

Dependent variables. Same as in experiment I

Procedure. Participants were required to work in teams of three to develop a course of action for a collaborative problem-solving task. Using a Noncombatant Evacuation Operation (NEO) scenario students were instructed to develop a plan to rescue three Red Cross workers. Required elements of the final plan included U.S. forces to be used, means of transportation, weapons, a specific timeline of events and a detailed plan. Each team member was given the General Information section of the NEO scenario, which included a situation report, topographical maps and other descriptors of the island, an explanation of U.S. military assets available and information on hostile forces in the area. In addition, each team member was assigned as an expert in either local intelligence, available weapons or local environmental issues, and provided with information pertinent to their area of expertise. Combining the general information with the expertise information could develop an appropriate plan. The effectiveness of the final plan submitted was rated using a scoring matrix developed by operational military personnel.

Data analyses. Same as in experiment I.

Results

A 2 x 2 randomized factorial analysis of variance was used to analyze time to task completion across collaboration mode and knowledge uncertainty along with quality of decision and frequency of utterances. There were no significant differences in time to task completion between the face-to-face and asynchronous, distributed teams, $F(1, 28) = 0.26$, $p = 0.616$; or knowledge uncertainty, $F(1, 28) = 1.88$, $p = 0.180$; or the interaction, $F(1,28) = 0.13$, $p = 0.720$. There was no significant difference in the quality of decision between collaboration mode, $F(1, 28) = 2.366$, $p = 0.135$, knowledge uncertainty, $F(1, 28) = 0.072$, $p = 0.790$, or the interaction, $F(1, 28) = 0.372$, $p = 0.546$. Both face-to-face and asynchronous, distributed teams achieved scores of over 80% accuracy on their final plans. With respect to the frequencies of utterances, there was a significant main effect between the face-to-face and the asynchronous, distributed teams, $F(1, 28) = 96.4956$, $p = 0.00$, with the mean number of utterances for the face-to-face teams being 847.31compared to a mean of 91.13 for asynchronous, distributed teams. There were no significant differences in knowledge uncertainty, $F(1, 28) = 2.0628$, $p = 0.162$, or the interaction between collaboration mode and knowledge uncertainty, $F(1, 28) = 2.7352$, $p = 0.109$. A 2 x 2 randomized factorial analysis of variance was used to analyze total utterance frequencies by collaboration stages across collaboration mode and knowledge uncertainty, as well as with the mean percentage of time spent in each stage and cognitive processes. There was a significant difference in the total number of utterances between collaboration modes, with face-to-face teams having significantly more utterances across all four collaboration stages than asynchronous, distributed teams (Knowledge Construction: $F(1, 28) = 60.813$, $p = 0.00$; Team Problem Solving: $F(1, 28) = 55.272$, $p = 0.0$; Team Consensus:

$F(1, 28) = 26.875$, $p = 0.00$; Outcome, Evaluation & Revision: $F(1, 28) = 8.127$, $p = 0.00$). There was a significant difference between collaboration modes in the mean percentage of time spent in each collaboration stage with face-to-face teams spending more time in Knowledge Construction than asynchronous, distributed teams, $F(1, 28) = 6.505$, $p = 0.01$. Asynchronous, distributed teams spent significantly more time in Team Problem Solving than face-to-face teams, $F(1, 28) = 5.601$, $p = 0.02$. There were no other significant main and interaction effects for collaboration stages. There was a significant difference between collaboration modes in three cognitive process states: individual task knowledge development, $F(1, 28) = 4.979$, $p = 0.03$; individual visualization & representation of meaning, $F(1, 28) = 13.372$, $p = 0.00$; and convergence of individual mental models to team mental model, $F(1, 28) = 12.053$, $p = 0.00$. Face-to-face teams spent significantly more time in each of these states than asynchronous, distributed teams. There were no other main or interaction effects in the Knowledge Construction stage. In Team Problem Solving, there was a significant difference between collaboration modes in two states: individual visualization and representation of meaning, $F(1, 28) = 6.838$, $p = 0.01$; and knowledge interoperability, $F(1, 28) = 14.131$, $p = 0.00$. Face-to-face teams spent more time in visualization and representation of meaning while the asynchronous, distributed teams spent more time in knowledge interoperability. There was also a significant difference in knowledge uncertainty, $F(1, 28) = 4.522$, $p = 0.04$, with dynamic teams spending significantly more time in convergence of individual mental models to team mental model than static teams. In Team Consensus, there was a significant difference between collaboration modes, $F(1, 28) = 4.979$, $p = 0.04$, with face-to-face teams spending more time in convergence of individual mental models to team mental model than asynchronous, distributed teams. In Outcome, Evaluation and Revision, there were no significant main or interaction effects with respect to the cognitive process states.

DISCUSSION

In terms of outcome measures (i.e. percent correct decisions), collaboration mode, knowledge distribution and knowledge uncertainty made no significant difference on collaborative team performance, even when compared across two different problem solving domains. Face-to-face and asynchronous, distributed teams achieved the same high quality solution in the same amount of time *but the asynchronous, distributed teams required less communication*. These results suggest that the structure of the EWall environment (used in the NEO scenario problem) and the web-based text forum (used to solve the murder mystery problem) permit more effective communication and collaboration when compared to the face-to-face team environment. With respect to the collaboration stages, both face-to-face and asynchronous, distributed teams demonstrated behavior that supports the existence of Knowledge Construction, Team Collaborative Problem Solving and Team Consensus stages during collaborative problem solving. The empirical data showed that the stages are task dependent because the Outcome Evaluation & Revision stage was not used by any of the teams during the murder mystery task but was employed when solving the NEO scenario. For the *cognitive processes*, asynchronous, distributed teams seem to focus on individual convergence of data to knowledge in order to build knowledge compared to face-to-face teams, which employ many more processes to build knowledge. In Team Problem Solving, the asynchronous, distributed teams focused on sharing knowledge and developing solution alternatives whereas face-to-face teams spent most of their time visualizing and representing meaning in order to derive possible solutions. In Team Consensus, face-to-face teams spent more time than asynchronous, distributed teams converging individual mental models to a team mental model in order to reach consensus. This could be the result of the structure of the EWall and the web-based text forum, which provides clear knowledge of how close the team is to reaching consensus. The data suggest that there is no significant difference in the cognitive process states used during Outcome, Evaluation & Revision between face-to-face and asynchronous, distributed teams.

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