Modeling and Simulation of Human Interaction Based on Mutual Beliefs

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Abstract. This paper presents the modeling and simulation of human-human interaction based on a concept of mutual beliefs, aiming to describe and investigate the cognitive mechanism behind human interactions that is a crucial factor for system design and assessment. The proposed model captures four important aspects of human interactions: beliefs structure, mental states and cognitive components, cognitive and belief inference processes, and metacognitive manipulations. This model was implemented with a Bayesian belief network and some test simulations were carried out. Results showed that some basic qualitative characteristics of human interactions as well as the effectiveness of mutual beliefs could be well simulated. The paper concludes by discussing the possibility of the application of this model and simulation to universal access and HCI design and assessment.

Keywords: Human Modeling, Team Cognition, Interaction, Sharedness, Mutual Beliefs, Agent Simulation, Design and Assessment.

1 Introduction

Although receiving relatively little attention, one of the important issues in the studies of human-computer interaction and universal access is that of cognitive factors specific to the interaction among plural persons through computers and IT systems as well as that of a team as a whole with computers or IT systems. CSCW is one of the research fields studying such interaction through computer systems. The field, however, has heretofore focused mainly on how corroborative activities can be supported or mediated by means of computer systems [1], while paying less attention to the cognitive mechanism behind cooperative activities. One of the reasons for this human-centered, but not "humans-centered", approach in HCI or UA studies seems to be the lack of a sound theory and user modeling that describes the mechanism behind human cooperation in terms of cognitive models. With such a cognitive user model for cooperation, various cognitive simulations similar to those of individual user's cognition by such as ACT-R and SOAR will be possible [2,3], resulting in a further developed understanding of cognitive factors in cooperation. This paper presents the modeling and simulation of human-human interaction based on a concept of mutual belief. In Section 2, the details of the model are introduced, and in Section 3, the model's implementation with a Bayesian belief network is explained. In Section 4, the results of some test simulations as well as the simulation architecture is explained.

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Section 5 concludes the paper by discussing the possible application of this model and simulation to universal access and HCI design and assessment.

2 Model of Team Cognition

In our previous studies [4], we proposed a model of team cognition. The model was intended to describe inter-personal and intra-team factors in cognition in terms of beliefs about a partner's cognition as well as one's own cognition. The model consists of a set of three layers of mental components (both cognitive processes and beliefs) and their interactions. In a dyadic case (A and B), the model is composed of:

a) Ma = A's cognition, Mb = B's cognition (individual cognition except beliefs
b) Ma'= A's belief about Mb, Mb' = B's belief about Ma (belief in another member's cognition)
c) Ma''= A's belief about Mb', Mb'' = B's belief about Ma' (belief in another member's belief)

Fig. 1 shows a schematic of this model, depicting three aspects of team cognition: belief structure, mental components, and the inter- and intra-personal interactions of these mental components. Details of each aspect are explained below.

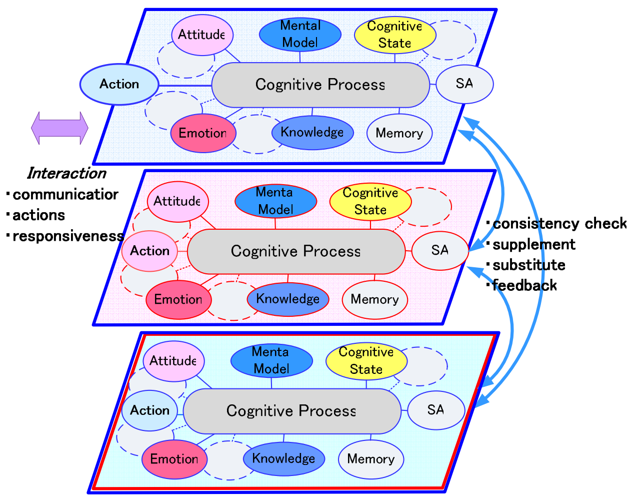

Fig. 1. Team Cognition

2.1 Belief Structure

The ability to infer or simulate the minds of others, that is, to obtain the beliefs of others, is believed to be innate and essential to human-beings [5]. It is necessary therefore to consider this aspect when modeling team cognition. We model team cognition with a structure of mutual belief based on the philosophical study of both team and collective intention [6]. Mutual belief is a set of beliefs hierarchically justifiable, such as in the above condition (b) and (c). Although theoretically mutual beliefs continue infinitely, empirically two or three are sufficient for actual cooperation. Most of the related theories have referred to the importance of the ability to infer and simulate the intentions of others in cooperative activities, while less attention has been paid to the function of beliefs in the third layer (belief in the beliefs of others). There is a high possibility that the third layer has a function in detecting and explaining, as well as recovering from, conflicts among team members.

2.2 Mental Components

People can infer, simulate, feel, and share various aspects of mentality, including cognitive processes, mental states, knowledge, attitudes, and emotions. We refer to these as mental components in this paper. The circles of each layer in Fig. 1 represent mental components. If we can infer that we share some mental components or constructs with others, then they can be mapped onto one's belief structure. For example, when one person gets angry (A's first layer), then another person can easily understand or feel that anger (B's second layer), and at the same time the person who has gotten angry can also infer or expect how the other person perceives their emotion (A's third layer). Recent work has provided a listing of typical mental components identified by qualitative meta-analysis of recent HCI conference papers [7]. The mechanism and relations among the mental components in a single layer correspond to a model of individual cognition. It is therefore possible to incorporate such a model into each layer of the model shown in Fig.2.

2.3 Process and Manipulation

The status of team cognition can be determined by the combination of its process and the status of its mental components. This combination is a key issue in understanding how a team member obtains and updates mental status for establishing and maintaining team cooperation. Communication and the observation of the behavior of partners are the main methods of human interaction. Much research on team cognition has analyzed such observable data to evaluate the efficiency and effectiveness of team cooperation. It is, however, obvious that the analysis of such phenotype interactions cannot directly explain or describe the mechanism behind cooperation because such observable behaviors are the results of the process of team cognition and not that of the reasoning involved in such a process. Indeed, there is another type of interaction involved in team cognition: intra-personal manipulation of mental components such as logical inferences, projections, and prototypes, including beliefs, in a single layer or between different layers,. Based on the status of one's own mental components and the interrelations among the different layers, a person takes action (i.e., observing or communicating with others) to modify their own mental components as well as proactively influence those of their partner. Note that this type of interaction can be the sole reason for proactive interaction in team cooperation, thus providing a genotype of communication and behaviors.

2.4 Interaction Genotype

Fig. 2 illustrates the relations between such observable behaviors and the mechanism and process behind them in communication. The upper two levels correspond to what is talked about and its function, which can be analyzed from verbal protocols. Conventional protocol analysis has dealt with these aspects by analyzing the transcripts of verbal protocols. The lower two levels correspond to the drive or reasoning behind such observable interactions. We call the former type of communication "phenotype" and the latter "genotype" using an analogy of the categorization of human errors [8].

Table 1. Interaction Genotypes

Genotype		Phenotype (Performative)
Category	**Code(Reason/Objective)**	
1. To drive and modify the process of each single layer (cognition and beliefs)	- Lack of necessary/adequate information or knowledge of mental components - Lack of confidence in beliefs	Query Confirm
2. To help partner drive their process (update their cognition and beliefs)	- Belief in the lack of necessary/adequate information about mental components - To avoid conflicts - Look-ahead - Just for sharedness	Inform
3. To modify partner's cognition and beliefs	- To avoid and recover from conflict in the status of mental components - Correct misunderstandings	Inform Query Confirm

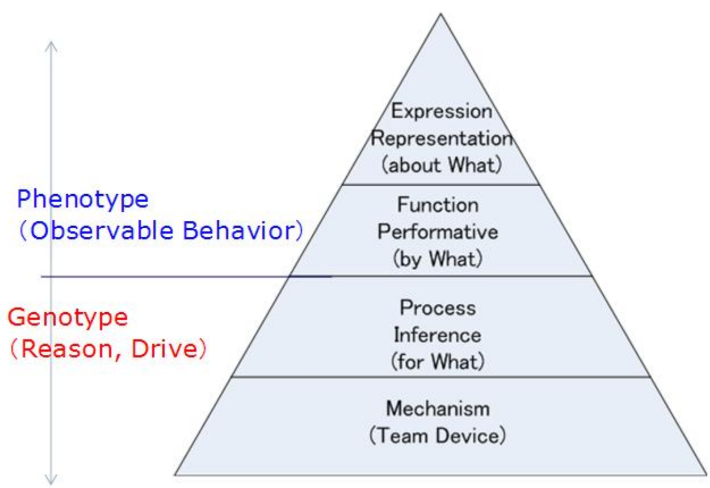

Fig. 2. Phenotype and Genotype of Interaction

To elicit such interaction genotypes in team cognition, we conducted a qualitative analysis of several kinds of data obtained in team tasks: verbal protocols, post experiment interviews, and descriptions of the team behaviors by observers. The results of the inner manipulation of mental components and the genotype of interactions obtained to date are listed in Table 1. The second column shows a code in the data which includes reasons for verbal communication (phenotype) and observable behavior. The left column shows the code categories.

3 Simulation Model

This section describes how the conceptual model was converted into a computational model.

3.1 Cognitive and Inference Process and Cognitive Status

To simulate the non-monotonic human reasoning/inference process based on an uncertain and limited amount of information, a Bayesian Belief Network (BBN) was adopted for the representation of such a process in each layer of the team cognition model. BBNs are probabilistic graphical models consisting of nodes and links. A node for the team cognition model represents a type of cognitive status, such as situation awareness, and the probability of each node represents the degree of belief in the occurrence of the event. A link represents a causal relationship between two different nodes and a conditional probability is assigned to it. The team cognition model can be implemented with six BBNs (three layers * two persons) and the interactions among them.

The cognitive task for the simulation performed in this study was to cooperatively achieve situation awareness. Specifically, a two-person team first obtained information from the environment or a partner and updated the probability of the corresponding nodes, and then all the probabilities of the entire BBN were calculated.

In the simulation, conscious awareness of the occurrence of events was defined by Equation 1. U represents a set of the nodes of which the person is aware. P_i represents the occurrence probability of Node i. T is the threshold of the probability of becoming aware of the occurrence of events.

$$U = \sum_i \{i \mid P_i \geq T\} \tag{1}$$

3.2 Interaction between Different Layers

It is reasonable to suppose that there are unconscious or subconscious interactions between different layers, for example, between own cognitive processes and the processes used in inferring a partner's cognitive status. In a previous study, some evidence for this interaction was observed [9], for example people sometimes tended to believe without evidence that a partner might see the same information as they saw. In a computational model, this is represented as the manipulation of the probabilities of the corresponding two nodes between different layers. Two interaction effects, defined by Equations 2 and 3, were implemented in the present study. α in Equation2 represents the effect of one's own cognition on the belief layers, while βin Equation 3 represents the effect of the partner's belief in their own cognition.

$$P_i = \alpha P_1 \tag{2}$$

$$P_1 = \beta P_2 \tag{3}$$

3.3 Communication Generation

As shown in Table 1, three types of interaction genotype have been obtained to date. In the following simulations, only the third one was implemented in the computational model. The rules derived from this genotype are defined by Equations 4 and 5.

$$\begin{gathered} \textit{If } U_{a1} \neq U_{a2} \textit{ and} \\ \textit{If } U_{a2} \text{ is believed to be false } \textit{then} \text{ Inform } (U_{a1}) \text{ to Modify } (U_{1b}). \\ \textit{If } U_{a1} \text{ is believed to be false } \textit{then} \text{ Correct } (U_{a1}) \text{ based on } U_{a2}. \end{gathered} \tag{4}$$

$$\textit{If } U_{a1} \neq U_{a3} \textit{ then} \text{ Inform}(U_1) \text{ to Modify}(U_{2b}). \tag{5}$$

4 Simulation

The process of obtaining shared situation awareness between agents A and B was simulated. Each agent has its own three layers of BBN. By the combination of these six BBNs, the distribution of knowledge, or heterogeneity of agents, can be represented. An example of the BBNs is shown in Fig. 3. The algorithm of the simulation is illustrated in Fig.4. The left upper nodes are those possessed only by Agent A, while the right-most node is the representative node for the events that Agent A cannot perceive but Agent B can.

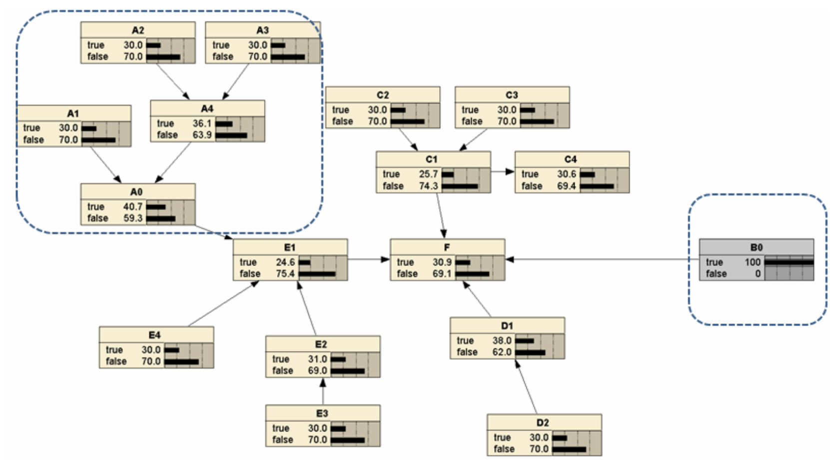

Fig. 3. Agent A's 1st Layer

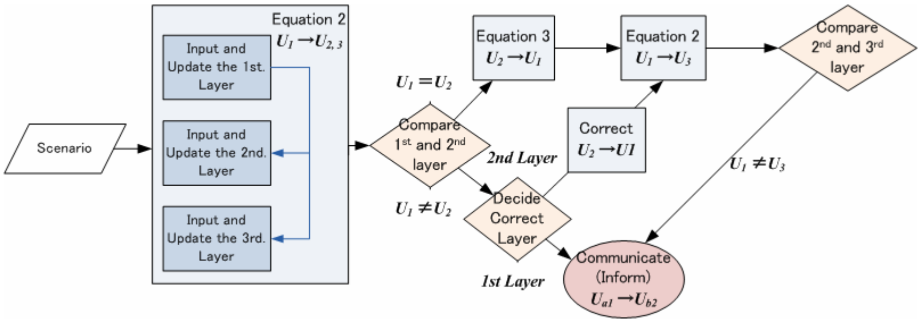

Fig. 4. Overview of the Simulation

This is a scenario-based simulation in which each agent obtains information from the environment sequentially based on the scenario and in which all occurrence probabilities are updated following the process shown in Fig.4.

4.1 Agent Characteristics

The characteristics of an agent can be defined by its tendency in deciding the correct nodes between the 1st and 2nd layer, that is, the extent to which the agent has self confidence on their own cognition. The four characteristics shown in Table 2 were defined and implemented for the following simulation.

Table 2. Agent Characteristics

Type	Character	Description
1	Strong self-confidence	Believe one's own cognition (U_1 is correct)
2	Following blindly	Follow one's partner's cognition (U_2 is correct)
3	Balanced	Decide the one with more detailed knoweldge is correct
4	Balanced (2)	Characteristics 3 without the third layer

4.2 Evaluation Criteria

To assess the performance of the cooperation between the two agents, accuracy and sharedness, defined by Equations 6 and 7, respectively, were introduced. In Equations 6 and 7, U_0 refers to the correct set of nodes that actually occurred in the scenario. Accuracy measures how correctly the team of Agent A and B is aware of the events that actually occur. The first term in sharedness is the completeness of the belief in the partner's cognition (1^{st} layer), while the second term represents the accuracy of the belief in the partner's cognition (1^{st} layer) [10, 11].

$$accuracy = \left\{ \frac{U_{a1} \cap U_0}{U_0} + \frac{U_{b1} \cap U_0}{U_0} \right\} \times 1/2 \tag{6}$$

$$sharedness = \sum_{a,b}\left\{\frac{U_{self2} \cap U_{partner1}}{U_{partner1}} + \frac{U_{partner1} \cap U_{self2}}{U_{self2}}\right\} \times 1/2 \quad (7)$$

5 Results and Discussion

Simulation was conducted with the different agent characteristics combinations. The tested combinations are shown in Table 3, and comparisons of the accuracy and sharedness of each team are shown in Fig.5. 40 trials for each team condition were conducted.

The results show that Team A received the lowest score for both accuracy and sharedness. It was observed from the communication log that each agent insisted on their correctness and did not complement their own cognitions with their partner's. Team B scored the highest for sharedness but not accuracy because the members were strongly mutually dependent on their partners and did not take advantage of the merit of distributed knowledge. Teams C and D exhibited good performance for both accuracy and sharedness. It was also found from the comparison between Teams C and D that activation of the third layer (beliefs about beliefs) was effective on team performance. From the communication log, it was found that feedback (acknowledgement) to the speaker made communication more efficient and effective in Team D. This matches the concept of closed loop communication believed to be one of the important team competencies [12].

Table 3. Combinations of Agent Characteristics

Team	Agent A	Agent B
A	1	1
B	2	2
C	4	4
D	3	3

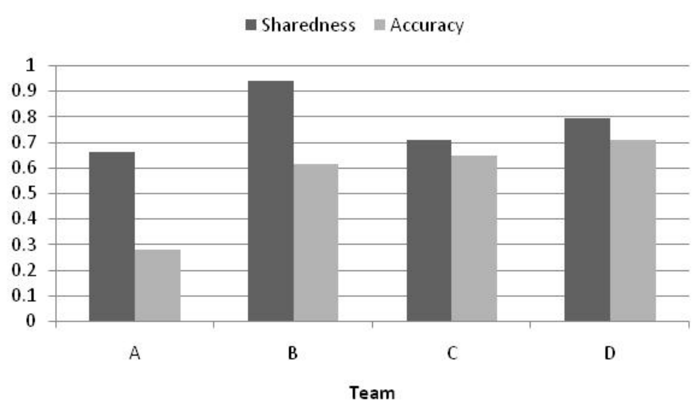

Fig. 5. Accuracy and Sharedness Results

6 Conclusion

This paper introduced a model for the simulation of human cooperative activities based on a concept of mutual belief. One of the characteristics of this model is the capturing of the mechanism behind cooperation not in terms of team function or macrocognition [13,14] but a cognitive user model (process and status). Another important characteristic is that the model separates metacognitive processes for cooperation (vertical) from cognitive/inference processes (horizontal). The model therefore can be used for almost all types of cognitive user models including Card's information processing model [15], Norman's model[16], and Simplex2[7], when applying them to the cognitive aspects of human cooperation.

The simulation results showed that some basic qualitative characteristics of human cooperation were simulated, suggesting in particular that consideration of what one's partner is thinking about oneself (activation of the third layer) is effective for good team performance. Although further testing under various conditions to assess the validity of this model is necessary, the current results show the potential of our simulation to provide a testbed environment for human cooperation that otherwise would be difficult to prepare using laboratory experiments or filed tests.

This type of simulation also could be utilized for the design and assessment of HCI and UA for cooperation and collaboration, such as in the assessment of usability and accessibility through the simulation of the sharing processes of certain mental aspects or components.

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