Simulating the Role of Transactive Memory in Group Performance[1]

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Abstract

Transactive memory systems refers to the idea that people in continuing close relationship develop a shared system for encoding, storing and retrieving information from different substantive domains. Previous studies provide both direct and indirect evidence of the positive impact of transactive memory systems on group performance, such as efficient storage and recall of knowledge, trust development in groups, and the benefits of training people together. This paper is an attempt to unify the experimental research on transactive memory and to extend it to a more dynamic setting for larger groups. In this paper, we develop an empirically grounded simulation model – ORGMEM, a multi-agent information processing system, which can be used to explore the formation of transactive memory and how transactive memory affects group performance. Through a series of virtual experiments, we find that transactive memory improves group performance, decreases group response time, and increases decision quality.

I. INTRODUCTION

The rapid development of computer and information technologies has led experts to claim that a knowledge-based information economy has begun (Eliasson, 1990; Winslow & Bramer, 1994). In a knowledge-based economy, knowledge, as a key resource, has become more and more crucial in determining the competitiveness of both firms and individuals. Therefore, scientists from a variety of fields, such as sociology, psychology, economics, organizational theory and information technology, have found their interests landing in the study of knowledge management (Alvesson, 1998; Cohen, 1998; Burton-Jones, 1999; Cook & Brown, 1999). A key issue in knowledge management is "what knowledge needs to be managed?" Some researchers suggest that it is not only technical knowledge that plays a key part in impacting group performance, but also social knowledge or metaknowledge (Kang, Waisel & Wallace, 1998). In other words, knowledge about social networks and expertise distribution also affect different aspects of group performance (Carley & Dayanand, working paper). This is the idea behind transactive memory systems.

Transactive memory systems[2], as a concept of social cognition, refer to the idea that people in continuing close relationship tend to develop a shared system for encoding, storing and retrieving

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information from different substantive domains (Wegner, 1987). By exploring transactive memory and knowing what other people know, individuals in groups can have access to external memory as well as their own individual memory. As a result, a group information-processing system is formed. Three relevant key processes of transactive memory systems are identified using the metaphor of a directory-shared computer network: directory updating, information allocation, and retrieval coordination (Wegner, 1995).

Previous studies provide both direct and indirect evidence of the positive impact of transactive memory on group performance. First of all, transactive memory helps to efficiently store and recall knowledge through interpersonal relationships (Wegner, Erber & Raymond, 1991; Moreland, Argote, & Krishnan, 1998). When people work together continuously in a group, they tend to develop specializations. As a result, new knowledge is directed to those people who are experts in a particular field so that knowledge can be acquired and stored quickly. In the recalling process, due to the recognition of expertise, the group with transactive memory can retrieve more knowledge than other groups. Secondly, knowing other people's expertise helps people to develop a sense of trust and work together better (Metcalf, 1986; Carley, 1990). In general, individuals are more likely to trust and act on information from the "right" source. Therefore, groups make better decisions when group members accurately recognize the relative distribution of expertise within the group. (Henry, 1995; Littlepage, Robison, & Reddington, 1997; Hollenbeck, Ilgen, Sego, Hedlund, Mafor, & Philips, 1995). Thirdly, groups whose members are trained together recall more and perform better than those whose members are trained separately (Hollingshead, 1998c; Liang, Moreland, & Argote, 1995; Moreland, Argote, & Krishnan, 1996).

Most of the research about transactive memory systems has been conducted using laboratory experiments. Giuliano and Wegner (1985) study the operation of transactive memory in intimate couples and show that in transactive memory systems, individuals are linked to knowledge on the basis of both their personal expertise and circumstantial knowledge responsibility (Wegner, 1987). Hollingshead (1998a) conducts a laboratory experiment on collective recall using dating couples and dyads of strangers as subjects to examine the impact of communication during the learning and recalling processes. Another experiment study conducted by Liang, Moreland, & Argote (1995) using college students as subjects demonstrates the benefits of training people together and the mediating role of transactive memory constructed during the experiment.

In this paper, we try to compliment and extend the lab experiment studies using computational modeling and simulation techniques. First of all, most of the lab experiments conducted so far study small groups containing two to three persons (Hollingshead, 1998a; Moreland, Argote, & Krishnan, 1998). Through virtual experiments, we are able to examine groups as large as twenty or thirty people. Secondly, most of the relationships studied so far are either intimate couples or strangers (Wegner, 1987, Hollingshead, 1998a). Using virtual experiments, a wide range of relationships, such as boss/subordinate, friends, workmates, etc. can be examined. Thirdly, by modeling transactive memory mathematically as three matrixes, we are able to calculate a variety of measurements of transitive memory precisely both on an individual level and a group level.

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[2] In this article, the idea transactive memory systems refer to the system including individuals, resources, tasks, and personal memory as a whole while transcative memory only refers to personal memory about who knows whom, who has what, and who does what.

The rest of this paper is organized as follows. The first two sections describe the design and implementation of the computational model, ORGMEM. Then two measurements of transactive memory are presented and a list of variables of interest is identified. Finally, virtual experiment results and their analysis results are presented to demonstrate the impact of transactive memory in organizations.

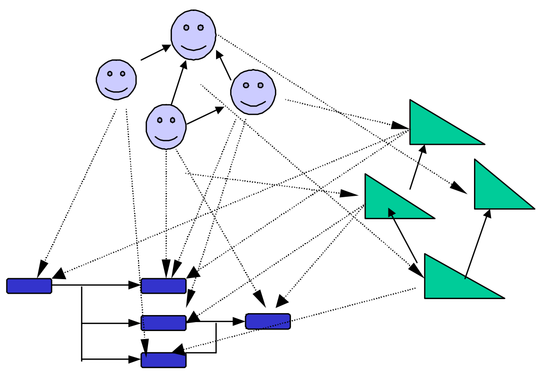
II. MODELING DESCRIPTIONS

ORGMEM is a multi-agent simulation system that imitates the interpersonal communication, information processing, and decision-making processes in organizations. In ORGMEM, agents are intelligent, adaptive, and heterogeneous. In other words, each agent has access to some knowledge (intelligence), is able to conduct a specific number of tasks, and can learn from each other (adaptation). As socially connected agents, each of them also has a transactive memory about who talks to whom, who knows what, and who does what in the group. During the operation process, each agent is able to conduct a variety of activities, such as communicating knowledge, searching for resources, and making decisions. Over time, organizations receive a series of tasks. Agents work on subtasks assigned by the program, make decisions by combining personal knowledge and information from their subordinates, communicate both technical knowledge and social knowledge, and learn from each other. As a result, group communication structure regarding who talks to whom, skill structure regarding who knows what, and transitive memory change over time.

Groups. In ORGMEM, groups are modeled as multi-agent information processing and group decision-making units by applying the PCANNS representation scheme (Krackhardt & Carley, 1998). The PCANNS model assumes that network-based organizations consist of three domain elements: individuals (P), tasks (T), and resources[3] (R). The relationships among these three elements can be summarized into six relational primitives from which the acronym PCANNS is derived: precedence of tasks (P), capabilities linking individuals to resources (C), assignment of individuals to tasks (A), networks of relations among personnel (N), resource needs of tasks (N), and substitutes of resources (S) (Carley, Ren, & Krackhardt, 2000).

According to the PCANNS model, a group can be represented as six relational matrixes in which the values are either 1 or 0, as shown in Figure 2. The value 1 indicates that there exists a connection between two elements; while the value 0 indicates there is no connection between two elements. Take the assignment matrix as an example. The assignment matrix (PxT) tells people who are assigned to what tasks. $A_{ij} = 1$ means that person i is assigned to task j and $A_{ij} = 0$ means that person i is not assigned to task j

[3] In this paper, we use the words "resource" and "knowledge" interchangeably.



	P	R	T
P	0000	0110	00000
	1000	1000	01100
	1100	0001	01001
	1000	0000	10010
R		0000	11000
		0000	00000
		0101	00010
		1000	00101
T			01110
			00000
			00001
			00001
			00000

Figure 1: Illustrative group representation scheme & a group example

Agents. In the ORGMEM program, each agent has a title (analyst, manager, CEO, or president) and a name. Depending on his/her position in the organization, an agent may or may not have a boss or subordinates. Each agent also has certain skills, is assigned to certain tasks, and accumulates experience in their decision-making process. At the same time, each agent has a transactive memory, which contains social knowledge about who talks to whom (IxI), who has access to what resources (IxR), and who is assigned to what tasks (IxT) (as shown in Figure 2). We apply a trinary representation here to better reflect three possible states of transactive memory. A value of 1 in transactive memory indicates that the agent "sees" that there exists a connection between two elements. A value of –1 indicates that the agent "sees" that there doesn't exist a connection between two elements. A value of 0 indicates that the agent doesn't have any knowledge about the connection.

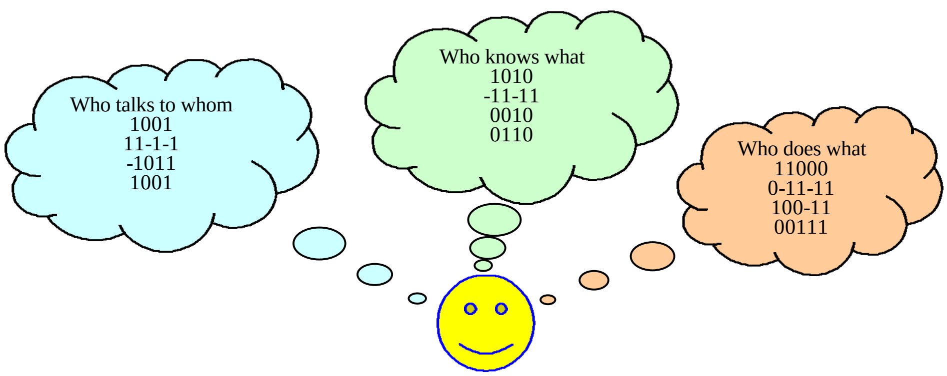


Figure 2: Representation of Transactive Memory

Transactive memory is constructed and modified through interpersonal communication and interaction. At the beginning of the simulation, each individual has only knowledge about his/her own connections to other people, resources, and tasks. When group members communicate with each other, they can exchange their knowledge. For example, person A knows that he himself knows knowledge X, and he can tell person B about this. As a result, person B gains this piece of knowledge and is able to communicate it to other people. As the process continues, individual transactive memory grows. Another way of changing transactive memory is through observation. For instance, two people who have never talked to each other before can both learn that there is a connection between them once they start talking. Person A who lends a resource to person B gets to know that person B has access to that piece of resource. Therefore, both individual transative memory and group transactive memory grow through communication and observation.

Based on their attributes, agents are able to take a series of actions to finish their tasks, such as searching for relevant resources, exchanging information, and making decisions. The following session briefly describes these actions.

Resource searching. In order to perform certain tasks, agents need to have access to relevant resources, such as specific equipment, materials or more frequently technical knowledge[4]. But it is not always true that they already have these resources. As a result, they need to search for the required resources in the group. To be more realistic, in this model, we assume that even if agents have some resources they can still choose to improve their skills by asking for from other agents so that they can perform tasks better. If transactive memory doesn't exist in this group, agents will search for resources by randomly asking other group members until they find the resources or they have been looking for or have asked everybody in the group. On the other hand, if transactive memory does exist, rather than random searching, agents will first look through their transactive memory and pick up the person that they think might have the required resource. Since we assume that the cost from one person to another person is equal across the group, agents don't account for distance when picking somebody to inquire.
According to organizational learning literature, knowledge diffusion is influenced by a variety of factors, such as the recipient's absorptive capacity (Cohen, 1990), the source's motivation, and the relationship between the source and the recipient (Szulanski, 1996). In this model, we assume that interpersonal knowledge transfer is influenced by the difficulty of the knowledge, the recipient's knowledge base, and the source's knowledge base (see Equation 1 in the appendix).

Communication. Previous work has suggested that communication plays an important role in the manner in which knowledge is learned and retrieved in transactive memory systems (Hollingshead, 1998a). In ORGMEM, communication is modeled as the process through which people share and exchange knowledge, and can be based on three mechanisms: random, relative similarity, and information seeking. Relative similarity refers to the phenomenon that people tend to talk to those who are similar to them or have knowledge in common with them (Carley, 1990). Information seeking refers to the phenomenon that people tend to seek for new knowledge by interacting with people from different knowledge domains or from different backgrounds (Carley, 1990). The interpersonal communication probabilities based on both mechanisms are calculated based on both transactive memory and personal skills. Driven by relative similarity (information seeking), agent i is more likely to interact with those agents who are linked to people, resources, and tasks that are similar to (different from) what agent i is linked to. Formula (2) and (3) in the Appendix demonstrate how to calculate relative similarity and information seeking probability.

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[4] Even though resource includes both physical materials and knowledge. In this paper, we focus on only knowledge. Therefore, resource and knowledge are interchangeable and both refers to knowledge in human being's mind.

Forgetting. Human beings forget. Modeling forgetting enables us to simulate the real world better. According to human cognition (Newell & Simon, 1972), a human being's memory consists of two parts: long-term memory and short-term memory. In the process of learning, knowledge is first stored in short-term memory. If this knowledge is repeated or rehearsed enough times, it will be further stored into long-term memory using an index structure. Every time a piece of knowledge is accessed and recalled, the linkage between the index and the knowledge is reinforced. However, if a piece of knowledge is not accessed for a long time, the linkage might become weak and even disappear (Newell & Simon, 1972). That is when forgetting happens. Therefore, in our model, we assume that a piece of knowledge is forgotten if it has not been recalled or accessed for a specific time periods. Similar to the process of knowledge transfer, knowledge forgetting happens continuously. If a piece of knowledge has not been recalled for such a long time period that nobody in the group has access to it anymore, we say this knowledge is out-of-date and organizational forgetting happens. The forgotten knowledge is thrown into a "knowledge trash-can". If that happens, under most conditions, the knowledge doesn't disappear completely. Although the knowledge does not exist in human beings' brains anymore, it still exists in organizations in the form of physical products, documents, and information systems (Argote, 1999). It is retrievable but to a lesser extent compared to knowledge in human beings' brains.

Decision making. Each agent works on subtasks assigned to him/her by the organizational structure and makes decisions independently by applying resources and referring to information from other people. If an agent doesn't have the required resources, s/he needs to find the resources first. In a hierarchical structure, decisions are made from the bottom up along the imposed authority structure. Subordinates make decisions first and then pass their decisions up to the boss. Facing the information from their subordinates, agents refer to their transactive memory and evaluate the value of the information before making their own decisions. Finally, a group decision is made and group performance is determined.

Information evaluation. Agents evaluate information from other agents based on their trust of that agent. The IxR matrix in an agent's transactive memory indicates the skill level of every agent in the group, represented by an integer falling in [0, 9]. Based on that information, every agent is able to count a trust coefficient array that represents his/her trust toward other agents in the group. When an agent receives a piece of information from his subordinate, he weighs this information by referring to his trust coefficient of the source. Equation (5) in the Appendix shows the formula used to calculate trust coefficients.

III. MODE IMPLEMENTATION & MEASUREMENTS

As shown in Figure 3, several processes are simulated simultaneously in ORGMEM. Although decisions are made sequentially along the hierarchy, interpersonal communication and individual forgetting can happen anytime during organizational operations. Figure 3 also demonstrates the interactive and dynamic relationships between organizational processes and agents' skills, transactive memory and experience. For example, agents make decisions based on their past experience, while the feedback regarding the decisions they made supplies information that can be used to update their experience. Similarly, transactive memory indicates the expertise distribution in groups and facilitates the processes of resource searching and information evaluation. At the same time, new knowledge can be introduced into transactive memory through communication and knowledge out-of-date can be removed through forgetting.

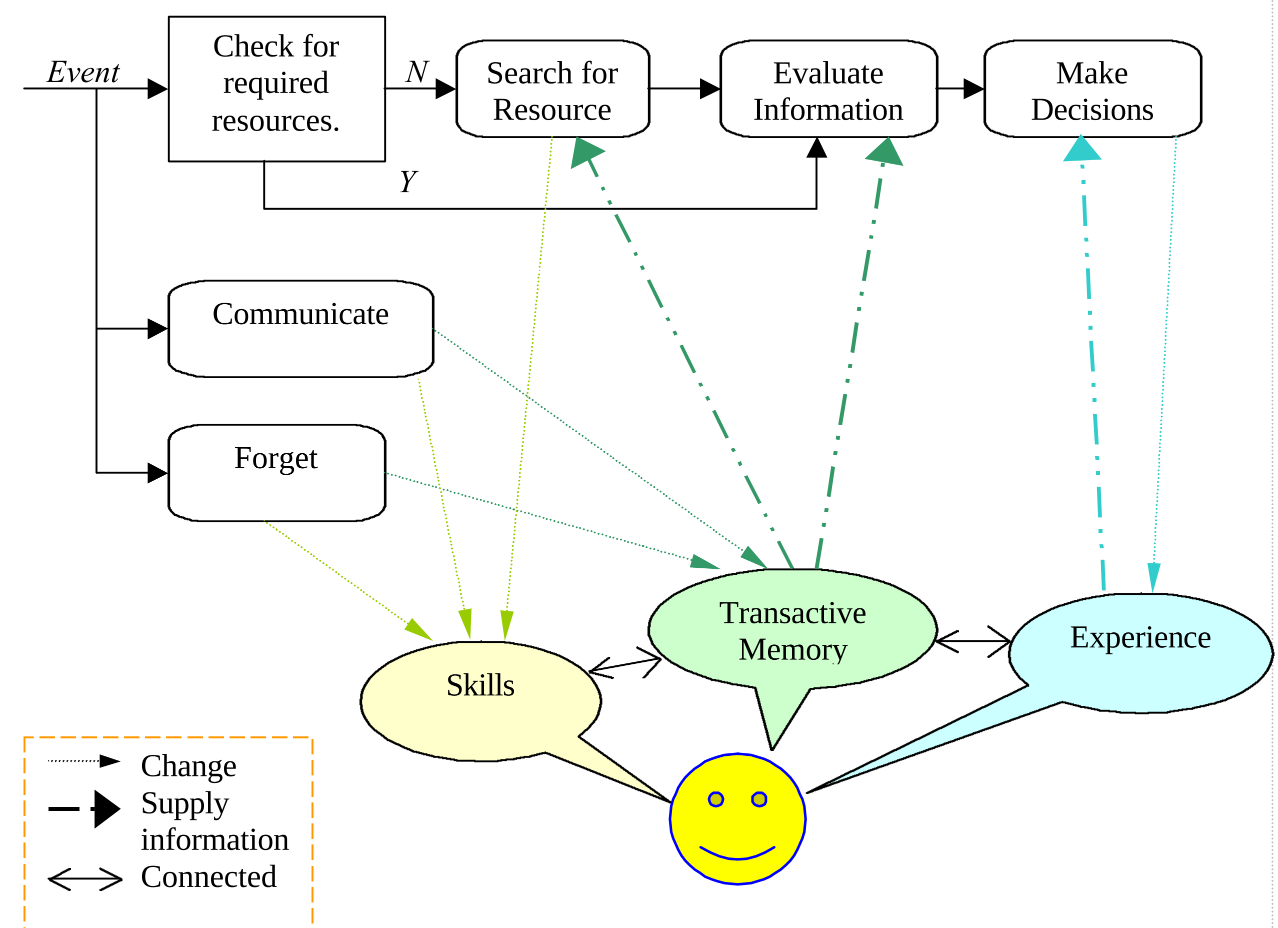

Figure 3: The Dynamic Processes of ORGMEM

Dependent variables. Group performance is measured by two variables: the time taken to finish group tasks and the quality of group operation or decision. Both theoretical and practical reasons can be identified to support these measurements (Moreland, Argote, & Krishnan, 1998). In practice, timing is a crucial factor in organizational operation and decision-making. Usually, the faster groups act or react, the more competitive advantages they could obtain and maintain. On the other hand, organizations need to do the "right" thing and do things "right". Quality becomes another key organizational goal. In ORGMEM, quality captures a variety of aspects of group performance. In the operation task settings, quality can reflect how good the products are or how well the operation processes are planned. In the decision task settings, quality can reflect how good the group decisions are as well as how good the consequences resulted from the decision. Overall, it describes how well the group performs the tasks. In ORGMEM, time is measured by counting the time periods elapsed between the initiation of decision and when it is finished;

quality is jointly decided by the resources available and the organizational settings (Kunz, Levitt, & Jin, 1998). Another potential measure of group performance is accuracy, which measures the number of errors generated in the operation or decision processes. It will be added into the program later.

Independent variables. ORGMEM adopts an innovative memory representation of transactive memory. No matter organizational memory or individual memory, it is usually represented as a binary matrix (Carley, 1991). To better reflect the feature of transactive memory, a trinary format is taken to represent transactive memory instead of a binary one in ORGMEM. Hence there are three values in the memory: 1 means yes; -1 means no; 0 means not sure. Let's take agent i's IxI matrix as an example. An 1 between j and k means that agent i knows agent j communicates with agent k; a –1 means that agent i knows that agent j does not communicate with agent k; a 0 means that agent i doesn't know anything about or not sure about the connection between agent j and agent k. This representation helps us to discriminate "knows not connected" from "don't know if connected", which otherwise will both be denoted as 0. The tradeoff is that it makes the measurement of transactive memory more complicated. Transactive memory is measured from two aspects in ORGMEM: density and accuracy. They can be collected on both individual level and group level. To assure measurement efficiency, self-knowledge is excluded from the calculation of all measures because it is helps neither resource searching nor information evaluation.

Density measures how much useful knowledge exists in transactive memory. It is calculated by dividing the actual number of non-zero information in transactive memory by the maximal possible number of non-zero information. In this context, useful knowledge is equal to non-zero knowledge. Thus, density at the individual level can calculated using the equation 6 in the Appendix. The nominator of the formula consists of three parts corresponding to the three matrixes in transactive memory – people by people (Network/Social matrix), people by resources (Skill/Knowledge matrix), and people by tasks (Assignment matrix). For each matrix, the density is calculated by dividing the number of zeros by the maximal number of zeros that is also the size of the matrix. Afterwards, the densities of three matrixes are averaged to get the overall zero-density of this agent's transactive memory and the density of non-zero knowledge can be obtained by subtracting zero-density from 1. Finally, individual transactive memory densities are average across to get group transactive memory density. Group density is 1 if everybody in the group has a complete knowledge about other groups members' resources or tasks, say the transactive memory systems reach the potential maximum value.

Accuracy measures the percentage of knowledge in the transactive memory that is accurate. In other words, it tells us how much knowledge in the transactive memory reflects the reality. The inaccuracy of knowledge comes from several sources. The main source is out-of-date knowledge. In other words, a piece of information may be true at one moment, but not true any more as time goes on. For instance, Mr. Brown used to work on a C project, learned a lot of C programming, and became an expert of that project. People went to him with questions about that project. Then Mr. Brown switched to work on another project that requires different skills. Six months later, Mr. Brown's mind is filled with the new project and many of the details of the old project are forgotten. But other people don't know this change and keep regarding him as the expert of the old project. Now their knowledge of Mr. Brown as an expert in the old project becomes out of date and thus inaccurate. The inaccurate knowledge won't go away. It stays in people's mind and keep getting diffused through interpersonal communication. That makes another source of inaccurate knowledge. Accuracy can be calculated by dividing the number of accurate non-zero knowledge by the total number of non-zero knowledge. Similarly, individual transactive memory accuracy is obtained by calculating and averaging accuracy across three matrixes in transactive memory and group transactive memory accuracy is obtained by averaging across group members.

Control variables. In the light of previous studies, organizational variables such as size, complexity, and structure also have nontrivial impact on group performance. They are also accounted in the model. Four group measures are included as control variables. Group size refers to the number of personnel in the group. Group density (Gpdns) indicates the density of people by people network, i.e. the number of times divided by the potential maximum number of ties. Skill specialization (Sklspc) indicates how group members specialize in different knowledge domains and is measured by the percentage of people who is the only person that is knowledgeable in one domain. Cognitive load (Cogload) is a comprehensive measure that combines all the six relational matrixes in PCANNS model. The more people one person is connected to, the more knowledgeable one person is, the more tasks one person is assigned to, the higher cognitive load that person has. Moreover, taking responsibility of tasks that require more resources, or require resources that this person doesn't have, or require intense coordination across group members can increase a person's cognitive load. These variables are included, on one hand, because they are measures that intuitively affect group performance; on the other hand, because they tend to be highly correlated with other group measures while uncorrelated with transactive memory measures.

IV. VIRTUAL EXPERIMENTS & RESULTS

All together 54 groups are generated randomly by varying group size, network density, and assignment load to investigate to what extent the lab experiment results with small groups can be extended to larger group settings. Group size goes from 9 to 45. Network density refers to the density of networks connecting people to each other and assignment load refers to the density of networks connecting people to tasks. For each density, three levels – low, medium, and high are simulated. At the same time, different communication modes and complexities are simulated as shown in Table 1.

Virtual Experiments		
Group size	9, 15, 21, 27, 35, 45	6
Network density	10%, 40%, 70%	3
Assignment load	10%, 40%, 70%	3
Communication mode	Random, relative similarity, information seeking, synthesis	4
Communication complexity	1, 5, 10, 20, 30	5
Total		1080

Table 1: Virtual Experiment Descriptions

Each experiment setting is run 100 times and the results are averaged. All together 54*4*5*1 = 1080 data points are collected and included in the analysis. Table 2 shows the descriptive statistics and correlation matrix of the variables included in the analysis.

Variable	N	Mean	Stddev	Size	Gpdns	Sklspc	Cogload	TMdns	Tmacc	Time	Quality
Size	1080	25.33	12.08	1.000	-0.137	-0.408	-0.004	*-0.649*	-0.123	0.081	-0.542
Group Density	1080	0.238	0.117		1.000	0.165	*0.681*	0.096	-0.004	-0.102	-0.686
Skill Specializ.	1080	0.078	0.158			1.000	-0.308	0.248	-0.466	0.401	0.125
Cognitive Load	1080	0.224	0.055				1.000	0.027	0.475	-0.495	-0.474
TM density	1080	0.350	0.361					1.000	0.092	-0.120	0.422
TM accuracy	1080	0.620	0.096						1.000	-0.531	0.103
Time	1080	74.44	25.46							1.000	-0.077
Quality	1080	0.485	0.168								1.000

Table 2: Descriptive Statistics and Correlations Matrix of Variables

Ordinary regression analysis is run to study how transactive memory affects group performance. Different models are explored by accounting a variety of variables and the results are show in Table 3 and Table 4. The coefficient significance and R-square indicate that model 2 in Table 3 and model 2 in Table 4 perform better than other models to reflect the associations between transactive memory and group performance. Therefore, we interpret the regression results based on these two models.

Based on the results from Model 2 in Table 3, higher transactive memory density and accuracy are both negatively associated with time. This suggests that having either more knowledge in transactive memory or more accurate knowledge in transactive memory helps to speed up the resource searching and decision-making processes in groups. The magnitudes of two coefficients also indicate that having accurate transactive memory is more crucial.

Variable	**Model 1**	**Model 2**	**Model 3**
Intercept	74.338(0.655) ***	96.496(3.527) ***	106.20(5.187) ***
TM Density	-5.054(1.825) ***	-6.425(2.195) ***	20.86(10.94) *
TM Accuracy	-138.99(6.856)***	-67.08(8.270) ***	-56.16(9.297) ***
Density*Accuracy			-43.44(17.06) **
Size		0.197(0.073) ***	0.185(0.073) **
Skill specialization		40.94(5.095) ***	35.09(5.579) ***
Cognitive load		-135.71(12.52) ***	-133.07(12.53) ***
R-square	0.2866	0.3998	0.4034
Adj R-square	0.2853	0.3970	0.4001

Table 3: Regression Analysis Results of Group Performance (TIME) vs. TM

Moreover, we can see that group measures such as size, skill specialization, and cognitive load also have significant effect on the time taken to finish group tasks. Smaller and looser groups with lower skill specialization and higher cognitive load tend to react or make decisions more quickly than larger and tighter groups with higher skill specialization and lower cognitive load.

Based on the model 2 in Table 4, both higher transactive memory density and accuracy are positively associated with group performance quality, which implies that holding density constant, increasing transactive memory accuracy helps the groups perform better. The roles of density and accuracy in affecting quality are pretty consistent with their roles in affecting time. Similarly, group measures, such as size and group density also have significant impact on group performance quality. Smaller and looser groups with lower network density seem to outperform other groups.

Variable	Model 1	Model 2	Model 3
Intercept	0.485(0.005) ***	0.949(0.007) ***	0.902(0.013) ***
TM Density	0.194(0.013) ***	0.061(0.006) ***	-0.066(0.030) **
TM Accuracy	0.114(0.049) **	0.035(0.025) *	-0.018(0.025)
Density*Accuracy			0.202(0.048) ***
Size		-0.008(0.001) ***	-0.008(0.001) ***
Group Density		-0.117(0.015) ***	-0.119(0.015) ***
Skill specialization		0.001(0.014)	0.028(0.016) *
R-square	0.1820	0.8918	0.8936
Adj R-square	0.1805	0.8913	0.8930

Table 4: Regression Analysis Results of Group Performance (QUALITY) vs. TM

VI. CONCLUSION

A computer simulation program – ORGMEM is designed and implemented in this project and applied to explore the relationships between transactive memory and group performance. Transactive memory's positive impacts on group decision timing and quality are demonstrated and the results partially correspond to the previous studies. Moreland, Argote and Krishnan (1998) study radio assembly in their lab experiments and conclude that groups whose members are trained together appear to have more complex and accurate transactive memory and thus generate fewer errors in their operations. The quality measure in this article takes decision-making accuracy into account, which is comparable to error rate in Moreland et al.'s study. Our findings regarding performance quality are consistent with the lab experiment results and both suggest that groups with transactive memory tend to outperform other groups. However, in the lab experiments, the time saving due to the existence of transactive memory is not significant, whereas transactive memory is predicted to shorten group response time in our results. There exist two potential causes of this discrepancy. On one hand, the computational model doesn't match the lab experiment setting perfectly. The computational model examines only time related to research searching and decision-making while a large amount of time in the lab experiment is spent on putting components together to build a radio, which is hard to simulate in the computer system. On the other hand, the discrepancy may be also due to a size effect. In a three people group, the time taken to search for a specific knowledge is so trivial that it can be completely ignored. But in large groups with twenty or forty people, the search cost may increment dramatically with the group size. More evidence needs be collected in the future studies to draw further conclusions.

APPENDIX

Knowledge Diffusion. Let agent i's knowledge in domain r at time (t) be denoted by $S_{ir}(t)$ and the maximum knowledge in domain r be M_r. An agent's learning potential in domain r, i.e. how much this agent can learn is denoted by $(\mathrm{M_r} - S_{ir}(t))$. Since the amount of knowledge an agent can learn in each domain is limited, the more knowledge an agent has, the more difficulty the agent experiences to improve his/her knowledge. There is a decreasing return to scale. So what agent i knows at time (t+1) is denoted by:

$$S_{ir}(t+1) = S_{ir}(t) + \alpha_r * S_{jr}(t) * (M_r - S_{ir}(t)) \qquad (1)$$

s.t. $0 \le S_{ir}(t) \le M_r$ and $0 \le \alpha_r \le 1$

Communication Probability. Let $S_{ir}(t)$ be agent i's knowledge in domain r and $S_{jr}(t)$ be agent j's knowledge in domain r, $RS_{ij}(t)$, the probability that agent i will interact with agent j based on relative similarity, can be calculated as:

$$RS_{ij}(t) = \frac{\sum_{r=1}^{R} \min(S_{ir}(t), S_{jr}(t))}{\sum_{k=1}^{I}\sum_{r=1}^{R} \min(S_{ir}(t), S_{kr}(t))} \qquad \text{s.t.} \qquad 0 \le RS_{ij}(t) \le 1 \qquad (2)$$

The probability that agent i will interact with agent j based on information seeking, IS_{ij}, can be calculated by dividing the relative expertise of agent j compared to agent i with the sum of relative expertise of everyone else in the group compared to agent i.

$$IS_{ij}(t) = \frac{\sum_{r=1}^{R} (S_{ir}(t) = 0 \;\&\; S_{jr}(t) \ne 0)}{\sum_{k=1}^{I}\sum_{r=1}^{R} (S_{ir}(t) = 0 \;\&\; S_{jr}(t) \ne 0)} \qquad \text{s.t. } 0 \le IS_{ij}(t) \le 1 \qquad (3)$$

Forgetting. Let β_r be the forgetting coefficient in domain r. By combining knowledge transfer and forgetting, an individual agent's knowledge at time (t+1) can be represented using the following formula.

$$S_{ir}(t+1) = S_{ir}(t) + \alpha_r * S_{jr}(t) * (M_r - S_{ir}(t)) - \beta_r * S_{ir}(t) \tag{4}$$

s.t. $0 \le S_{ir}(t) \le M_r$ and $0 \le \alpha_r \le 1$ and $0 \le \beta_r \le 1$

Trust. Let $trust_{ij}$ be agent i's trust toward agent j at time (t) and IR_{ij} be agent j's knowledge level in agent i's transactive memory. Agent i's trust toward agent j can be calculated as:

$$trust_{ij}(t) = \frac{\sum_{j=1}^{R} IR_{ij}(t)}{M_r * \mathrm{Re}\,sourceComplexity} \tag{5}$$

Transactive Memory Measures. Both transactive memory measures depend on an agent's perception of the underlying social structures, rather than the actual structures. For example, agent i's perception of the underlying social network, i.e. who does agent i thinks interact with whom can be denoted by $PSN_{ijl}(t)$ and it can have one of three types of states: i thinks j interacts with l ($PSN_{ijl}(t) = 1$), i thinks j doesn't interact with l ($PSN_{ijl}(t) = -1$), or i doesn't know ($PSN_{ijl}(t) = 0$). Similarly, agent i's perception of the underlying knowledge network, i.e. who does agent i thinks has access to what knowledge can be denoted by $PKN_{ijk}(t)$ and it can have one of three types of states: i thinks j has k ($PKN_{ijk}(t) = 1$), i thinks j doesn't have k ($PKN_{ijk}(t) = -1$), or i doesn't know ($PKN_{ijk}(t) = 0$). Finally, agent i's perception of the underlying assignment network, i.e. who does agent i thinks is assigned to what tasks can be denoted by $PAN_{ijw}(t)$ and it can have one of three types of states: i thinks j does w ($PAN_{ijw}(t) = 1$), i thinks j doesn't do w ($PAN_{ijw}(t) = -1$), or i doesn't know ($PAN_{ijw}(t) = 0$). On the other hand, the actual social, knowledge and assignment networks can be denoted as $ASN_{jl}(t)$, $AKN_{jk}(t)$, and $AAN_{jw}(t)$.

$$density_i(t) = 1 - \frac{\sum_{j=1}^{I}\sum_{l=1}^{I}(PSN_{ijl}(t)=0)/(I*I) + \sum_{j=1}^{I}\sum_{k=1}^{K}(PKN_{ijk}(t))/(I*K) + \sum_{j=1}^{I}\sum_{w=1}^{W}(PAN_{ijw}(t))/(I*W)}{3} \tag{6}$$

Let $CT(PSN_{ijl})$ be the number of non-zeros in the network matrix of agent i's transactive memory. Accuracy at the individual level can be calculated by the following formula[5].

[5] $\wedge$ here means the value in matrix PSN_{ij} is consistent with the value in matrix ASN_{ij}. We consider only useful information here, say 1s and –1s in matrix PSN_{ij}. $PSN_{ij} \wedge ASN_{ij} = 1$ if $PSN_{ij} = 1$ and $ASN_{ij} = 1$ or $PSN_{ij} = -1$ and $ASN_{ij} = -1$. This formula can be applied at different time points. The item (t) is ignored to save space.

$$accuracy_i = \frac{accuracy_{SN} + accuracy_{KN} + accuracy_{AN}}{3} \quad (7)$$

in which

$$accuracy_{SN} = \sum_{j=1}^{I}\sum_{l=1}^{I}(PSN_{ijl} \wedge ASN_{jl})/CT(PSN_{ijl})$$

$$accuracy_{KN} = \sum_{j=1}^{I}\sum_{k=1}^{K}(PKN_{ijk} \wedge AKN_{jk})/CT(PKN_{ijk})$$

$$accuracy_{AN} = \sum_{j=1}^{I}\sum_{w=1}^{W}(PAN_{ijw} \wedge AAN_{jw})/CT(PAN_{ijw})$$

$$CT(PSN_{ijl}) = I * I - \sum_{j=1}^{I}\sum_{l=1}^{I}(PSN_{ijl} = 0)$$

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