Measuring Team Mental Models

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Abstract

In this study we build upon recent methodological contributions on team mental model measurement and propose, describe, illustrate, and empirically validate two such measures, i.e., shared mental models of the task and the team. The proposed measures are based on computationally simple network analysis methods. Teams are effective units of organizational work but members need to coordinate their actions, subtasks and resources. Oftentimes members are not even present at the same time, thus making coordination more difficult. While telecommunication and groupware technologies facilitate coordination, team experiences with these technologies have been mixed, suggesting that we still need to learn more about effective processes and mechanisms that lead to coordinated teamwork. Traditional theories state that teams coordinate explicitly through organization and communication, but more recent research suggests that they also develop team mental models over time about the task, each other, their goals, etc., which helps them develop mutual expectations about task states and member actions, thus helping them coordinate implicitly. While the theoretical grounding in the team mental model literature is strong there is still little empirical evidence to support these theories, partly because of the difficulties involved in measuring these models, which is what motivated this study.

Keywords: team mental models, shared mental models, shared cognition

Measuring Team Mental Models

Groups and teams are important units of organizational work (Hackman, 1987; Sproull & Kiesler, 1991). Teams have become increasingly popular because they bring diverse expertise and skills to the task. However, as more people become involved in a given task, the need to coordinate member activities and subtasks increases too. Furthermore, recent advances in telecommunication and groupware technologies have made geographically distributed (i.e., different-place) and asynchronous (i.e., different-time) collaboration more feasible and popular, but they have also increased team coordination challenges.

Coordination is necessary to manage interdependencies among members, resources and sub-tasks (Malone & Crowston, 1994). The traditional research literature suggests that coordination is accomplished through team/task organization and communication processes and mechanisms (March & Simon, 1958; Thompson, 1967; VanDeVen et al., 1976). Team and task organization mechanisms (e.g., specifications, schedules, plans, workflows, etc.) help coordination primarily when task conditions are relatively certain. When routines change or when task conditions are more uncertain team members generally resort to communication (interpersonal or in groups, formally or informally, and written or verbal). Most collaboration and groupware tool developers have focused their efforts on implementing features aimed at helping team members organize and communicate (Lotus, 1995). However, while organization and communication are the main explicit mechanisms teams use to coordinate, developing organization and communicating divert time and attention from the actual task. More recent literature suggests that as team members develop familiarity with the task and with each other they also develop team mental models, which are shared knowledge structures about things like the task, the team, and its goals and strategies. These shared mental models help team members anticipate each other's moves and project future states of the task, thus helping them coordinate implicitly (Cannon-Bowers et al., 1993). While there are subtle differences in the terminology, we use the terms "shared mental models" and "team mental models" interchangeably in this paper.

While the potential benefits of team mental models for team coordination and performance are encouraging, more empirical work is needed to better understand how these team models develop and to what extent they impact team coordination and performance. This knowledge will also help us define key features for the next generation of collaboration and groupware tools. However, in order to produce meaningful research on team mental models, we need to develop proper measurements for this construct. Measuring team mental models is difficult because these are cognitive structures and, as such, are unobservable and thus cannot be measured directly. The literature on team mental models is beginning to address measurement issues (Carley, 1997; Cooke et al., 2000; Fussell et al., 1999; Mathieu et al., 2000), but as discussed later on in this paper, more work is needed to develop sound measures. This research proposes and tests the validity of two such measures, one for the shared mental model of the task (SMMTask) and one for the shared mental model of the team (SMMTeam).

Team Mental Models

Mental models or schemas are organized knowledge structures individuals posses about the environment they interact with (Johnson-Laird, 1983; Rouse & Morris, 1986). Mental models help us make sense of the environment around us and help us predict its future states. Humans develop mental models for just about everything (e.g., driving, interacting with people, playing an instrument, etc.). Team members also develop individual mental models about the task and about other members, but as they interact with each other in the context of the task, they also develop related shared mental models, which are based on knowledge similarities among them. It has been suggested that teams form and use shared mental models about a number of things such as the task, equipment, resources, strategies, goals, team members, and roles (Cannon-Bowers et al., 1993; Klimoski & Mohamed, 1994). While teams can have a multitude of shared mental models, each affecting different aspects of the joint task, for analytical purposes, it is useful to reduce these models to a few general categories. Different types of team mental models have been described in the literature, but most of the knowledge similarities among team members can be reduced to things related to either the team or the task (Cannon-Bowers et al., 1993; Cooke et al., 2000; Mathieu et al., 2000; Rentsch & Hall, 1994).

The effect of shared mental models on team coordination and performance has received a good amount of attention in the literature in the last few years (Cannon-Bowers et al., 1993; Klimoski et al., 1994; Kraiger & Wenzel, 1997; Mathieu et al., 2000), particularly in the domain of real-time tasks. Shared mental models are perhaps best exemplified in high paced real-time activities like sports competitions, emergency crew operations, and squadron flights in which teams operate in a highly coordinated fashion without much communication because of their shared knowledge about the task and each other, which was previously acquired through experience working and training together. Real-time tasks also make evident the effectiveness of team mental models when it is lacking. Teams that don not share task and team knowledge in this domain tend to be uncoordinated, which can even result in crises and disasters (Helmreich, 1997; Weick, 1990, 1993; Weick & Roberts, 1993).

While most of the prior literature on team mental models deals with real-time tasks, recent studies also suggest that shared mental models have a positive effect on non-real-time team performance (Espinosa et al., 2000; Fussell et al., 1999). In fact, it is likely that the limited opportunity for asynchronous and distributed teams to communicate and interact with each other may affect the team's ability to develop effective mental models, thus making it difficult to coordinate. This is why it is important to identify and test collaborative tool features that promote team mental model formation. But in order to be able to gain a deeper understanding about which factors influence team mental model formation and which types of shared mental models affect which aspects of coordination and performance, we need consistent and methodologically sound measures of team mental models.

Previously Proposed Team Mental Model Measures

A few authors have proposed methods and metrics to measure team mental models. One of these is based on member similarities in words used to communicate (Carley, 1997). This method requires text input, which can come from work documents, written memos, electronic mail, discussion boards, interview transcripts or any other record of team interaction. In a nutshell, this method requires parsing text contributed by all team members and then looking at the common use of single words, or groups of contiguous words to derive a team mental model measure based on similarity of individual cognitive maps. These maps are based on similarity of groups of words used in communication. This method is very useful when doing archival research, particularly when members are not available for observation, interviews or surveys. When team members are available it may be better to also elicit information about team and task knowledge beyond what may be recorded in formal documents and test the reliability of these two methods.

Another study operationalized shared mental models using four separate measures: amount and evenness of task knowledge within the team, and consensus and accuracy within the team about members' task knowledge (Fussell et al., 1999). Amount and evenness of task knowledge can be interpreted as measuring task knowledge similarity, while consensus and accuracy can be interpreted as measuring team knowledge similarity. However, amount and evenness of knowledge are based on individual task knowledge amounts and not on knowledge overlap among members. Also, consensus about team members' task knowledge is computed using inter-rater reliability scores of member knowledge ratings done by all team members. But inter-rater reliability scores are based on correlation scores, which measure the linear relation between variables and not necessarily their proximity or similarity. For example, one member's ratings about a peer's task knowledge could be exactly twice as high as that of another member's yielding a perfect correlation score, but the actual similarity between the two sets of ratings scores is relatively low.

Another method proposed uses QAP (quadratic assignment procedure) correlation (Mathieu et al., 2000). QAP is a network analysis method (Hubert, 1987) used to correlate two square matrices, which is available in network analysis software like UCINET (Borgatti et al., 1999). This study used dyad teams and operationalized individual mental models of the task and team as squared matrices. It then used QAP correlation to evaluate the similarity between individual mental models to compute team mental model values. The QAP correlation value is identical to the Pearson correlation between all the corresponding elements of the two matrices. The difference is in the significance levels reported (p-values). Because dyadic network matrix elements are not always independent, the p-value reported by QAP is not based on whether the correlation is significantly different from 0, but on whether one of the matrices is significantly different from a random matrix. This method is conceptually sound and very useful for network data and has also been extended for multivariate regression analysis (Krackhardt, 1987, 1988). However, the use of QAP correlation to measure shared mental models in this context has some limitations, including: (1) again, high correlation values indicate strong linear association between two variables and not necessarily actual similarity; (2) a significant correlation reported by QAP does not necessarily mean that it is significantly different than zero; (3) the significance level reported by QAP changes slightly every time the procedure is run because it compares one of the matrices against a random matrix, which is generated each time by permuting the rows and columns of the other matrix a large number of times; (4) for teams with three members or more one would have to compute every possible pair-wise correlation using QAP and then average them out to produce some sort of reliability score.

A very comprehensive recent methodological review on team knowledge measurement suggested important characteristics of measurement approaches for shared mental models measures (Cooke et al., 2000). One thing this study and others (Levesque et al., 2000) suggest is the use of similarity metrics to measure common team knowledge using inter-rater reliability scores or percentage of identical responses within the team. Besides the problem discussed about correlation measures, another problem with most inter-rater reliability scores is that, they generally increase as the number of raters increases, thus making it less useful for comparisons of different size teams. In fact, if all pair-wise correlation scores are positive, as the number of raters goes to infinity, many popular reliability scores approach a value of one (Ghiselli et al., 1981), making reliability measures less useful for large teams. Another thing this study suggests is that knowledge structure and distribution within the team, and not just shared knowledge, may be a critical factor in team performance. For example, a team with a strong aggregate shared mental model but with a low knowledge similarity between the team leader and the rest of the team may be dysfunctional. But to the best of our knowledge none of the measures proposed or used in empirical studies to date address the issue of knowledge distribution within the team.

The measures described in this section represent important methodological contributions to the study of team mental models. The next two sections build upon these contributions while attempting to overcome some of the limitations discussed. In these two sections we propose and describe two measures of shared mental models, one about the task and one about the team itself. More specifically, the measures we propose below incorporate the following properties related to shared mental models: (1) they are based on knowledge similarity (Carley & Krackhardt, 1996) and not on correlation or reliability scores; (2) they are constructed from dyadic knowledge similarities and not from team aggregates of individual scores; and (3) they are applicable to any team size and to any number of knowledge areas. The proposed measures also comply with general criteria for aggregate measures (Allison, 1978): (1) if all pair-wise knowledge similarities equal 0, the measure equals 0; (2) if any pair-wise similarity is greater than 0, the measure is also greater than 0; (3) the measure is scale-invariant and bounded, in this case between 0 and 1 (i.e., results can be compared across studies). In addition, the methods described below also have the following properties: (1) they are based on simple network analysis methods that are computationally simple; (2) provide a way to represent team mental models visually using graph theory principles; (3) provide a way to analyze the structure of the team's knowledge and derive useful metrics, such as: a given individual's knowledge similarity with others; members' knowledge centralization; cliques; and clusters, which are particularly useful when studying large teams.

<u>Proposed Measure #1: Shared Mental Model of the Task (SMMTask)</u>

The shared mental model of the task within a team is a function of the task knowledge shared by every dyad in the team. The task knowledge shared between any two members can be measured in a number of ways (Levesque et al., 2000; Mathieu et al., 2000). We propose two other ways to do this, one that can be used when diagnostic information about members knowledge in each task area can be obtained, and another one when it cannot.

a) When members' task knowledge can be assessed.

When members' knowledge in all relevant task areas can be evaluated quantitatively via tests, archival data or peer evaluation questionnaires, the resulting scores can be used to construct a knowledge matrix **K**(nxt) with one row for each of the n team members and one column for each of the t task knowledge areas, with elements k_{ij} representing the knowledge rating of member i in area j. In network analysis terminology, matrices like this that represent people's relations to other things (e.g., knowledge, professions, affiliations, etc.) or to other people are called "sociomatrices". More specifically, a people-by-thing (i.e., task knowledge, etc.) matrix is called an "incidence matrix" (Scott, 1991). We call this incidence matrix **K** the team's "knowledge matrix". While this matrix provides useful information about members' individual knowledge in each task area, we are more interested in task knowledge that is shared between pairs of members. Consequently, we need to transform matrix **K**(nxt) into another incidence matrix **KS**(nxt) with elements ks_{ij} representing the knowledge similarity member i has with all other members about task area j. We call this matrix the team's "knowledge similarity" matrix **KS**. This transformation is illustrated in Figure 1 and described below.

Place Figure 1 about here

To transform **K** into **KS** we first need to compute the knowledge similarity between every pair of members in every task area. Since any two members can only share knowledge that is possessed by both of them, the amount of task knowledge shared between members i and i' about task area j cannot exceed $\min(k_{ij}, k_{i'j})$. If a task is disaggregated into fine grained subtask areas such that if $k_{ij} > k_{i'j}$ we can say that i knows more about task area j than i', then we can safely assume that the shared task knowledge between i and i' in task area j is indeed $\min(k_{ij}, k_{i'j})$. This information can then be used to construct task knowledge similarity matrices $\mathbf{TKS_J}$ (nxn) for each task area j. $\mathbf{TKS_J}$ contains one row and column for each of the n team members, is symmetric, has null diagonal elements, and has off-diagonal elements $tks_{jii'}=\min(k_{ij}, k_{i'j})$, where $tks_{jii'}$ represents the amount of knowledge of the least knowledgeable member between i and i' in task area j, which is how much knowledge i and i' have in common in that area. The example in Figure 1 contains j=3 task knowledge areas: financial management, production and marketing. We keep the diagonal elements null because diagonal values would represent the amount of task knowledge possessed by individual members but we are not interested in individual knowledge, only in task knowledge that is shared between members. A person-by-person sociomatrix like this is called an "incidence matrix" in social network terminology (Scott, 1991).

Once we have computed $\mathbf{TKS_J}$ matrices for all t task areas for which we have task knowledge diagnostic information we can then compute an aggregate task knowledge similarity matrix **TKS** by adding the task knowledge similarity values for each pair of members across all task knowledge areas. In other words, $\mathbf{TKS} = \sum_{j=1}^{t} \mathbf{TKS_j}$. This incidence matrix gives us the aggregate knowledge across all task areas shared by every pair of members, which is equivalent to the shared mental model of the task within the team. A task knowledge incidence matrix like **TKS** is very informative because it not only shows how much task knowledge is shared between any two members but, more importantly, it also provides information about the knowledge structure of the team (i.e., centralized, dispersed, etc.). They also enable us to use powerful network analytic methods to do things, such as: computing key network attributes (e.g., densities, centralities, etc.), identify relationship patterns (e.g., cliques, clusters, sub-groups, etc.); performing network-based statistical analysis; identifying knowledge isolates and gaps; and providing visual representations using graphs (Wasserman & Faust, 1994) called "sociograms".

Figure 1 illustrates visual representations of task knowledge similarity matrices using sociograms. Lines between members can be drawn with different thickness representing the amount of shared task knowledge. However, such graphs become too dense and uninformative, particularly for large networks. One way to simplify the visual representation of a network is to draw lines only for amounts exceeding a given cutoff value x^* deemed to be an important threshold with special meaning (e.g., average knowledge in rating scale, etc.), as we did in Figure 1 using a cutoff value $x^* = 4$ (mid-point of the rating scale) for individual task knowledge similarity matrices and a cutoff value of $x^* = 12$ (mid-point of aggregate scale) for the aggregate matrix. In this example we can see from Figures 1 and 2 that members share very little task knowledge in finance. The $\mathbf{TKS_{FINANCE}}$ matrix is very sparse, with only members 5 and 6 sharing substantial task knowledge in this area, so full group discussions about finance beyond these two members may not be all that effective. The $\mathbf{TKS_{PRODUCTION}}$ matrix shows a fair amount of task knowledge shared by some members but not by others. In contrast the $\mathbf{TKS_{MARKETING}}$ matrix represents a fully connected network, evident of a large amount of shared task knowledge in this area by all members, which should facilitate common grounding in strategic marketing discussions. We can also see that on the aggregate **TKS** matrix that member 1 is an knowledge isolate, while 5 and 6 have the highest amounts of shared task knowledge with other members in all task areas and on the aggregate. This could be valuable information, for example, when analyzing team leadership factors.

These incidence matrices contain all the necessary information to compute the SMMTask variable based on pair-wise knowledge similarity. However, it is computationally convenient to summarize the information provided in these incidence matrices in a single knowledge similarity adjacency matrix **KS** (nxt). Each element k_{ij} in this matrix represents the average knowledge similarity of member i with all other members in task area j. For example, the **KS** adjacency matrix illustrated in Figure 1 has n=6 members and t=3 tasks, and we have added two extra rows and columns to provide shared task knowledge aggregates for each task area and each member. The first row and column contain raw aggregates, while the second row and column contain normalized aggregates. The normalized are bounded between 0 and 1, thus facilitating comparisons across different team sizes, number of task areas and rating scales. The normalized value was computed by dividing the raw aggregates by: (1) scale range (i.e., max value minus min value); (2) team size (for column aggregates and overall aggregate); and (3) number of task areas (for row aggregates and overall aggregate). The SMMTask variable is the resulting overall normalized aggregate, which is also bounded between 0 and 1.

b) When members' task knowledge cannot be assessed.

The second way we propose to evaluate the task knowledge shared between two members is based on similarity of responses to selected task-relevant questions. When it is difficult, impractical or not feasible to obtain diagnostic information about team members' task knowledge in different areas, one can ask other task-relevant questions and compare the similarity of responses between pairs of members. Because team mental models are based on shared knowledge and knowledge similarity about things, the similarity of responses between two members should give an indication of how close their mental model of the task is. For example, if we were to ask questions about the purpose and use of certain software tools to two individuals, we would probably get more similar responses from two software engineers than from one software engineer and one hardware engineer. The main challenge when using this method is identify a sufficient number of task-relevant, non-redundant questions such that members can answer them using continuous or ordinal scales so that response similarities can be computed quantitatively. One way to do this is to identify actual tasks the team has completed, or is currently working on, and ask task questions for which response accuracy can be verified. For example, in one study we are currently conducting with software development teams we first identified software projects carried out by each team. We will now use project information to ask project-specific questions like: "Please give us an estimate of how many software modules this project affected"; "How much of this project work involved software repair?"; and "Please rate the technical complexity of this project."

We can use these responses to build an adjacency matrix **R** with elements r_{ij} each containing the response by member i to task question j. We call this matrix the "response" matrix. The knowledge similarity matrix **KS** can then be constructed from **R** using a similar method to the one used in part a above. The difference here is that responses in **R** are not in themselves diagnostic of task knowledge, but these responses are used to compute similarities among members' task knowledge. We begin by using **R** to construct a task knowledge distance matrix $\mathbf{TKD_J}$ for each for each task question j. $\mathbf{TKD_J}$ is a symmetric matrix with blank diagonal elements and off diagonal elements $tkd_{jii'}=|r_{ij}-r_{i'j}|$, representing the absolute value of the difference or distance between responses to question j by members i and i'. We then use each of these $\mathbf{TKD_J}$ matrices to construct a task knowledge similarity matrix $\mathbf{TKS_J}$. $\mathbf{TKS_J}$ is a symmetric matrix with blank diagonal elements and off diagonal elements $tks_{jii'}=maxR-minR-tkd_{jii'}$, where maxR and minR represent the maximum and minimum values of the rating scale used to elicit responses to task questions. All this does is to reverse the scales such that the highest possible distance between two members (i.e., maxR – minR) gives a similarity score of 0, while a distance of 0 gives the highest possible similarity score (i.e., maxR – minR). The resulting $tks_{jii'}$ values represent the task knowledge similarity in area j between members i and i'. We can then proceed as described in section a) above.

Proposed Measure #2: Shared Mental Model of the Team (SMMTeam)

While SMMTask is about shared knowledge of the task, SMMTeam has to do with shared knowledge about the team. But because both team mental models are about shared knowledge, the SMMTeam variable can be constructed in a similar fashion to the SMMTask variable, except that in this case the resulting measure for SMMTeam needs to be based on members' beliefs about the team. Members' beliefs can be elicited by asking questions about each other. Responses to these questions can then be compared between pairs of member to evaluate their similarity. The method used to calculate SMMTeam is illustrated in Figure 2 and described below.

Place Figure 2 about here

As with the SMMTask variable, we need to start by constructing a "response matrix" **R**(nx(nxq)), which is an incidence matrix with one row for each of the n members of the team and nxq columns, one for each of the q questions asked to each of the n members. Notice that we are asking the same question to each of the n members of the team, which is why we get n columns for each question asked. We can also use **R** to construct member distance matrices $\mathbf{MD_Q}$ (nxn) for each question asked. Similar to $\mathbf{TKD_J}$, $\mathbf{MD_Q}$ are symmetric matrices with blank diagonal elements, but in this case the off-diagonal elements are $md_{qii'} = \sum_{j=1}^{n} |r_{ij} - r_{i'j}|$. In other words, since each person rates every member (including self), the distance for question q between members i and i' is now based on the aggregate value of the distance in responses made about every member. As we did with $\mathbf{TKD_J}$, we can now construct a member similarity matrix $\mathbf{MS_Q}$ (nxn) for each distance matrix $\mathbf{MD_Q}$ by reversing the scale. Thus, $\mathbf{MS_Q}$ is a symmetric matrix with blank diagonal elements and off-diagonal elements $ms_{qii'}$= n (maxR – MinR) – $md_{qii'}$, where maxR and minR represent the maximum and minimum values of the rating scale used to elicit responses to member questions. The $ms_{qii'}$ represent the similarity of responses to question q between members i and i' about all team members. The $\mathbf{MS_Q}$ matrices for all questions are then aggregated into an overall member similarity matrix $\mathbf{MS} = \sum_{i=1}^{Q} \mathbf{MS}_i$. The respective member similarity measures can now be aggregated to compute an overall value for SMMTeam. As with SMMTask too, it is useful to normalize this measure to be able to compare SMMTeam values regardless of team size, number of questions asked and rating scales used. This can be done by calculating averages instead of sums in all computations above and then dividing the resulting global average by the scale range maxR – minR. This normalized value will also be bound between 0 and 1.

The resulting matrix **MS** is an adjacency matrix that represents the shared mental model of the team, which can be used to compute network analytic measures and graph sociograms as explained for SMMTask. The example illustrated in Figure 2 shows similarity matrices and a sociogram constructed from responses to three questions asked about each of the six members provided by each member. Because valued graphs can be very dense and confusing, only lines corresponding to an average response distance of two scale points or less are shown. Average response distances of one scale point or less are represented by a thicker line to visually represent strong member similarities about the team. It is easy to see from this sociogram that members 5 and 6 have a stronger shared mental model about the team with other members and with each other.

One final point about SMMTeam is that while the description above applies to one global SMMTeam variable, different SMMTeam variables could be computed using the same method but grouping questions by whether they pertain to members, work processes, team interaction or anything else about the team (i.e., construct one response matrix R_M, R_{WP}, R_{TI}, etc. for each group of questions). These various SMMTeam variables may be useful in evaluating and explaining different aspects of shared mental models of the team.

Preliminary Empirical Validation of the Proposed Measures

New proposed measures and constructs need to be empirically validated. To the best of our knowledge, none of the previously suggested measures of shared mental models have been empirically validated. In this section we do preliminary statistical testing of the convergent, concurrent and discriminant validity of our measure (Ghiselli et al., 1981). The data used to validate the proposed measures comes from 57 teams who were engaged in a graduate level management simulation course in 1998 for approximately 10 weeks. Teams ranged in size from four to six members with more than 75% of the teams having five members. Each team managed a simulated firm and reported to an external board of directors composed mostly of professionals from the local business community. Teams (i.e., firms) competed against each other by formulating strategies based on multidisciplinary decisions involving production, distribution, finance, marketing and strategy. This course's simulated environment is very real to student teams who compete against other teams for their grades. Course grading is based on firm performance, board evaluations and other relevant factors. Data was systematically collected during the simulation period from: (1) voluntary student surveys conducted at 3 time periods, with an approximate response rate of 70%—we only used data for teams in which at least 3 members responded, which is approximately 74% of the teams; and (2) team performance ratings from external board evaluations. A number of variables (explained below) were computed using this data. Table 1 shows descriptive statistics for these variables, Table 2 shows the correlation matrix for all variables in all time periods and Tables 3, 4 and 5 show the respective correlation matrices for each of the three time periods. Appendix A shows the questionnaire items used for these variables. The two shared mental model measures used (SMMTeam and SMMTask) were constructed using the method described in the previous two sections using responses to peer ratings of each other's knowledge in specific task areas (i.e., finance, production and marketing) regarding their companies.

Place Tables 1-5 about here

Convergent Validity

First of all, proposed items should measure characteristics we wish to measure (Ghiselli et al., 1981). Team mental models develop through training and from experience working together over time (Cannon-Bowers et al., 1993). Consequently, it is natural to expect that shared mental models would get stronger as the task progresses. Some researchers have hypothesized about this time effect but have not found empirical evidence to support it (Cooke et al., 2000; Levesque et al., 2000). This lack of support may be because: (1) the study task is too short to register any significant increases; (2) shared mental models are fairly stable and increase very slowly over time; (3) once the team gets fairly familiar with the task and with each other the strengthening levels off; or (4) shared mental models develop only to the extent that teams interact substantially over time. We explored the change in shared mental model strength over time and found results worth noting. These results are illustrated in the box plots in Figure 3 (shaded regions represent quartiles above and below the median, while the lines represent the 25 and 75 percentiles). Consistent with prior findings, we did not find overall significant increases in SMMTeam. However, SMMTeam did increase moderately from T1 to T2 ($F=4.954$, $p=0.028$) and then leveled off (decreased slightly, but not significantly), supporting the notion that once teammates get to know each other's skills, and once members form opinions about each other, there is not much further change in SMMTeam. The slight decrease from T2 to T3 may even suggest that some teams may weaken their consensus about team members' knowledge, perhaps due to disappointments from low performance ratings or member conflict and disagreements. On the other hand, SMMTask increased steadily and significantly over the task period ($F=50.902$, $p<0.001$), thus providing some evidence of team learning leading to strengthening of their shared knowledge of the task.

Place Figure 3 about here

We also explored the extent to which team interaction and shared mental models correlate. We measured team interaction by asking team members to rate their communication frequency with each other on a 1-6 scale and then taking within-team averages of all responses. Communication frequency had a significant and positive correlation with SMMTask ($r=.58$, $p<0.001$) and SMMTeam ($r=0.27$, $p=0.002$). However, this significant correlation was only observed at time 1 ($r=0.45$, $p=0.001$ and $r=0.44$, $p=0.002$ respectively) and was not significant at time 2 or time 3, suggesting that that shared mental models may be most affected by team interaction during the early stages of the task.

Finally, we expected teams with stronger shared mental models to believe that they had more overlapping knowledge with each other and could, therefore, substitute for each other more easily. So, we constructed a self-reported member substitutability variable as the average response to 3 questionnaire items (Chronbach-$\alpha = 0.75$) that asked about the member's perceptions of task knowledge overlap and member substitutability within the team. This measure was significantly correlated with SMMTask ($r=0.51$, $p<0.001$), but only moderately correlated with SMMTeam (r=0.22, p=0.011).

Concurrent Validity

Thorough testing of the concurrent and predictive validity of these measures is beyond the scope of this study. However, preliminary concurrent validity can be evaluated by exploring the correlation between these variables and some outcome and process variables that shared mental models are supposed to affect (Ghiselli et al., 1981). Two important process variables in linking shared mental models with performance are appropriate team strategy and coordinated use of resources (Klimoski et al., 1994). A good business strategy is generally an important factor in these business simulations in order to achieve good levels of financial performance and to get good reviews from the external board. We constructed a variable for cohesive strategy as average response to six questionnaire items (Chronbach-α = 0.84) that asked about team members' perceptions of cohesiveness in their strategies. We also constructed an overall task coordination variable using responses to nine questionnaire items (Chronbach-α = 0.79) that asked about the teams' state of task coordination, and a team performance variable from external board evaluations. Evaluations, which weight heavily on final grades, were completed individually by board members using a 1-7 Likert scale immediately after each of the three board meetings held for each team (roughly coinciding in time with the surveys). Current operations and firm performance and proposed strategies are generally discussed and approved at these board meetings, which tend to be very long and involved.

Overall, we found very strong positive correlation of SMMTask with both, cohesive strategy (r=0.59, p<0.001) and task coordination (r=0.40, p<0.001) and moderate positive correlation of SMMTeam to these variables (r=0.22, p=0.012 and r=0.21, p=0.020). Interestingly, SMMTeam was significantly correlated at T1 with cohesive strategy (r=0.36, p=0.013) and task coordination

($r=0.38$, $p=0.008$) but was not significant with either variable at T2 or T3. SMMTask on the other hand was significantly correlated in all three time periods with cohesive strategy ($r=0.55$, $p<0.001$; 0.47, $p=0.001$; and $r=0.40$, $p=0.025$ respectively) and task coordination($r=0.36$, $p=0.012$; 0.40, $p=0.006$; and $r=0.42$, $p=0.016$). These results suggest that SMMTeam may be instrumental in developing a cohesive strategy and task coordination during the early stages of the task or the "forming" and "norming" stages of the team (Tuckman, 1965), but that interaction in some teams can lead to disagreements and conflict (Klimoski et al., 1994) during the "storming" stages, thus offsetting the positive effects of SMMTeam. On the other hand, SMMTask is important in the development of cohesive strategies and task coordination all the time.

Finally, cohesive strategy had a strong positive correlation with performance, i.e., board evaluations ($r=0.373$, $p<0.001$), while task coordination only exhibited a moderate correlation with board evaluations ($r=0.228$, $p=0.010$). Interestingly, none of these variables was correlated to board evaluations in T1 or T2, but cohesive strategy was strongly correlated with board evaluations at T3 ($r=0.532$, $p=0.002$). These results are probably due to the nature of the business simulation of this exercise in which task coordination is not visible to board members, thus having only marginal effect on their evaluations. Cohesive strategy on the other hand is quite visible to the external board, but it seems to have its strongest effect towards the end of the simulation when the actual effectiveness of these strategies can be evaluated. While these are not mediation tests, these results point to some indirect association between shared mental models and team performance through their positive association with cohesive strategy and task coordination.

Discriminant Validity

As discussed before, the research literature on shared mental models seems to be in general agreement that teams have multiple mental models, but that these can be grouped into two general categories, those that have to do with the task and those that have to do with the team, for which we have proposed measures in this study. However, this is an empirical issue that needs further investigation. One way to empirically validate this argument is to construct a number of variables to measure the multiple mental models that teams may have and then reduce these to a few orthogonal categories using factor analysis and then assess whether these factors pertain to the task and the team. Such validation is beyond the scope of this paper because we have only measured two shared mental model variables. However, we can use correlation data to get a sense for the orthogonality of these two variables. Overall, SMMTask and SMMTeam are somewhat positively correlated ($r=0.30$, $p=0.001$). The correlation analysis by time periods shows that correlation holds at T1 ($r=0.49$, $p<0.001$), but is almost negligible at T2 and very moderate at T3. These results suggest that SMMTask and SMMTeam are not systematically correlated all the time, but they don't seem to be totally independent either. Also, the strong correlation at T1 may suggest that teams with substantial task knowledge overlap may be better able to evaluate team members' knowledge at the beginning, but as the task progresses and members specialized in their respective roles it may become more difficult to do so.

Conclusions

This study has reviewed the current state of research in shared mental models measurement and found that while substantial methodological contributions have been made recently in this area there are still no widely agreed upon measures of shared mental models that can be used to compare results across studies or to conduct powerful meta-analysis studies. The main contributions of this paper are the two proposed measures for shared mental models, one about the task and one about the team, which, among other things: (1) build upon strengths of current measures; (2) are computationally simple in the sense that no specialized statistical or network analysis software is necessary; (3) are based on sound principles of aggregate measures; (4) are based on knowledge shared at the dyad level and not on individual knowledge or team aggregate knowledge; (5) allow the computation and visual representation of both shared knowledge and distribution of knowledge; and (6) show preliminary convergent and concurrent validity with other measures. Others are encouraged to build upon these proposed measures to be able conduct sound research on this important topic.

This study has many limitations, but its main purpose was to illustrate a computational method to measure shared mental models. Perhaps the most limiting aspect of the study is in the preliminary validity testing section where we focused on analysis of correlation values. Naturally more testing is needed to evaluate the internal and external validity of these measures. Future work planned in this respect will involve more thorough testing of the effect of shared mental models on team process and outcome variables. This will include the formulation of regression models with appropriate control variables, mediation tests (i.e., whether the effect of shared mental models on performance is mediated by cohesive strategy and/or task coordination) and inclusion of some moderator variables. For example, it is believed that accuracy of shared mental models mediates its effect on process variables, which we have not explored here.

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Computation Example: Shared Mental Model of the Task

Knowledge Matrix

Mbr	Fin	Prd	Mkt
1	2.0	2.2	5.5
2	2.7	4.0	6.5
3	2.1	6.2	4.7
4	3.2	2.1	7.0
5	6.0	6.6	6.8
6	5.8	6.0	6.4

Knowledge Similarity: Finance

Mbr	1	2	3	4	5	6
1		2.0	2.0	2.0	2.0	2.0
2	2.0		2.1	2.7	2.7	2.7
3	2.0	2.1		2.1	2.1	2.1
4	2.0	2.7	2.1		3.2	3.2
5	2.0	2.7	2.1	3.2		5.8
6	2.0	2.7	2.1	3.2	5.8	

Knowledge Similarity: All Tasks

Mbr	1	2	3	4	5	6
1		9.7	8.9	9.6	9.7	9.7
2	9.7		10.8	11.3	13.2	13.1
3	8.9	10.8		8.9	13.0	12.8
4	9.6	11.3	8.9		12.1	11.7
5	9.7	13.2	13.0	12.1		18.2
6	9.7	13.1	12.8	11.7	18.2	

Knowledge Similarity: Production

Mbr	1	2	3	4	5	6
1		2.2	2.2	2.1	2.2	2.2
2	2.2		4.0	2.1	4.0	4.0
3	2.2	4.0		2.1	6.2	6.0
4	2.1	2.1	2.1		2.1	2.1
5	2.2	4.0	6.2	2.1		6.0
6	2.2	4.0	6.0	2.1	6.0	

Knowledge Similarity Matrix

Mbr	Fin	Prd	Mkt	All	Norml
1	2.0	2.2	5.3	9.5	0.53
2	2.4	3.3	5.9	11.6	0.65
3	2.1	4.1	4.7	10.9	0.60
4	2.6	2.1	6.0	10.7	0.60
5	3.2	4.1	6.0	13.2	0.74
6	3.2	4.1	5.9	13.1	0.73
All	15.5	19.8	33.8	69.1	0.64
Norml	0.43	0.55	0.94	0.64	

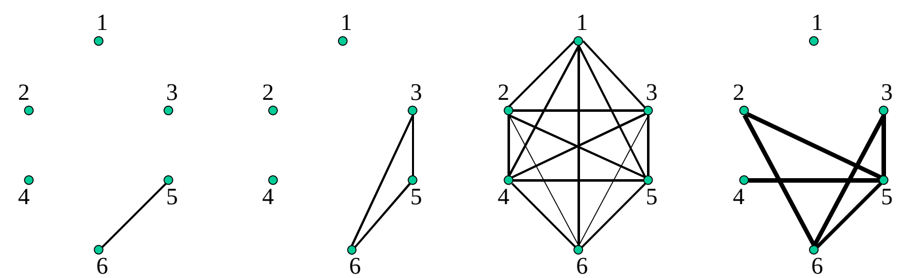
Knowledge Similarity: Marketing

Mbr	1	2	3	4	5	6
1		5.5	4.7	5.5	5.5	5.5
2	5.5		4.7	6.5	6.5	6.4
3	4.7	4.7		4.7	4.7	4.7
4	5.5	6.5	4.7		6.8	6.4
5	5.5	6.5	4.7	6.8		6.4
6	5.5	6.4	4.7	6.4	6.4	

Scale
Min = 1
Max = 7
Tsks= 3

SMMTask = 0.64

Visual Representation: Shared Mental Models of the Task



Finance Production Marketing Aggregate

Figure 1: Shared Mental Model of the Task, Computation and Visual Representation

Computation Example: Shared Mental Model of the Team

Response Matrices RQ

	Q1: Mbr's Financial Task Knowlg						Q2: Mbr's Production Task Knowlg						Q3: Mbr's Marketing Task Knowlg					
Mbr	**1**	**2**	**3**	**4**	**5**	**6**	**1**	**2**	**3**	**4**	**5**	**6**	**1**	**2**	**3**	**4**	**5**	**6**
1	5	4	5	2	1	6	5	4	5	2	5	5	6	4	5	2	1	5
2	1	2	1	1	2	1	1	2	2	1	2	1	2	2	1	1	1	2
3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
4	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
5	2	2	2	3	3	3	3	4	2	5	6	6	3	3	2	2	1	2
6	2	2	2	3	3	3	3	4	2	5	6	6	3	3	2	2	1	2

Member Distance Matrices MDQ

	Q1: Mbr's Financial Task Knowlg						Q2: Mbr's Production Task Knowlg						Q3: Mbr's Marketing Task Knowlg					
Mbr	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
1		2.83	2.83	2.17	2.33	2.33		2.83	3.33	1.67	1.67	1.67		2.33	2.83	2.17	1.67	1.67
2	2.83		0.33	4.67	1.17	1.17	2.83		0.50	4.50	2.83	2.83	2.33		0.50	4.50	0.67	0.67
3	2.83	0.33		5.00	1.50	1.50	3.33	0.50		5.00	3.33	3.33	2.83	0.50		5.00	1.17	1.17
4	2.17	4.67	5.00		3.50	3.50	1.67	4.50	5.00		1.67	1.67	2.17	4.50	5.00		3.83	3.83
5	2.33	1.17	1.50	3.50		0.00	1.67	2.83	3.33	1.67		0.00	1.67	0.67	1.17	3.83		0.00
6	2.33	1.17	1.50	3.50	0.00		1.67	2.83	3.33	1.67	0.00		1.67	0.67	1.17	3.83	0.00	

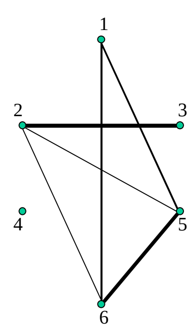
Member Similarity Matrices MSQ

	Q1: Mbr's Financial Task Knowlg						Q2: Mbr's Production Task Knowlg						Q3: Mbr's Marketing Task Knowlg					
Mbr	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
1		2.17	2.17	2.83	2.67	2.67		2.17	1.67	3.33	3.33	3.33		2.67	2.17	2.83	3.33	3.33
2	2.17		4.67	0.33	3.83	3.83	2.17		4.50	0.50	2.17	2.17	2.67		4.50	0.50	4.33	4.33
3	2.17	4.67		0.00	3.50	3.50	1.67	4.50		0.00	1.67	1.67	2.17	4.50		0.00	3.83	3.83
4	2.83	0.33	0.00		1.50	1.50	3.33	0.50	0.00		3.33	3.33	2.83	0.50	0.00		1.17	1.17
5	2.67	3.83	3.50	1.50		5.00	3.33	2.17	1.67	3.33		5.00	3.33	4.33	3.83	1.17		5.00
6	2.67	3.83	3.50	1.50	5.00		3.33	2.17	1.67	3.33	5.00		3.33	4.33	3.83	1.17	5.00	

Overall Member Similarity Matrix MS

	Un-Normalized						Normalized for Scale							
Mbr	1	2	3	4	5	6	1	2	3	4	5	6	Scale:	
1		2.33	2.00	3.00	3.11	3.11		0.47	0.40	0.60	0.62	0.62	Min = 1	
2	2.33		4.56	0.44	3.44	3.44	0.47		0.91	0.09	0.69	0.69	Max= 6	
3	2.00	4.56		0.00	3.00	3.00	0.40	0.91		0.00	0.60	0.60	Questions = 3	
4	3.00	0.44	0.00		2.00	2.00	0.60	0.09	0.00		0.40	0.40		
5	3.11	3.44	3.00	2.00		5.00	0.62	0.69	0.60	0.40		1.00		
6	3.11	3.44	3.00	2.00	5.00		0.62	0.69	0.60	0.40	1.00		SMMTeam =	0.54

Visual Representation:
Shared Mental Model of the Team



Average member rating distance of 2 scale points or less

Average member rating distance of 1scale point or less

Figure 2: Shared Mental Model of the Team, Computation and Visual Representation

Table 1

Descriptive Statistics

Variable	Min	Max	Mean	Std Dev
Board Evaluation	1.97	6.76	4.79	1.060
Task Coordination	3.74	6.63	5.42	0.629
Perceived Subst	2.33	6.92	4.94	0.821
Cohesive Strategy	3.56	6.89	5.44	0.673
SMMTask	0.34	0.80	0.54	0.093
SMMTeam	0.62	0.89	0.79	0.047
Comm Frequency	1.75	5.60	4.18	0.706

Table 2

Correlation Matrix, All Time Periods

Variable	Board Eval	Task Coord	Perceived Subst	Cohesive Strategy	SMM Task	SMM Team	Comm Freq
Board Evaluation		0.23	0.24	0.37	0.42	0.19	0.27
		(0.010)	(0.008)	(0.000)	(0.000)	(0.033)	(0.002)
Task Coordination	0.23		0.44	0.70	0.39	0.21	0.13
	(0.010)		(0.000)	(0.000)	(0.000)	(0.020)	(0.136)
Perceived Subst	0.24	0.44		0.63	0.51	0.22	0.25
	(0.008)	(0.000)		(0.000)	(0.000)	(0.011)	(0.004)
Cohesive Strategy	0.37	0.70	0.63		0.59	0.22	0.26
	(0.000)	(0.000)	(0.000)		(0.000)	(0.012)	(0.003)
SMMTask	0.42	0.39	0.51	0.59		0.30	0.58
	(0.000)	(0.000)	(0.000)	(0.000)		(0.001)	(0.000)
SMMTeam	0.19	0.21	0.22	0.22	0.30		0.27
	(0.033)	(0.020)	(0.011)	(0.012)	(0.001)		(0.002)
Comm Frequency	0.27	0.13	0.25	0.26	0.58	0.27	
	(0.002)	(0.136)	(0.004)	(0.003)	(0.000)	(0.002)	

Note: p-values in parenthesis

Table 3

Correlation Matrix, Time 1

Variable	Board Eval	Task Coord	Perceived Subst	Cohesive Strategy	SMM Task	SMM Team	Comm Freq
Board Evaluation		0.16	-0.06	0.10	0.03	0.03	-0.08
		(0.270)	(0.689)	(0.504)	(0.839)	(0.845)	(0.605)
Task Coordination	0.16		0.40	0.76	0.36	0.38	0.26
	(0.270)		(0.005)	(0.000)	(0.012)	(0.008)	(0.074)
Perceived Subst	-0.06	0.40		0.60	0.46	0.26	0.38
	(0.689)	(0.005)		(0.000)	(0.001)	(0.073)	(0.007)
Cohesive Strategy	0.10	0.76	0.60		0.55	0.35	0.19
	(0.504)	(0.000)	(0.000)		(0.000)	(0.013)	(0.186)
SMMTask	0.03	0.36	0.46	0.55		0.49	0.45
	(0.839)	(0.012)	(0.001)	(0.000)		(0.000)	(0.001)
SMMTeam	0.03	0.38	0.26	0.35	0.49		0.44
	(0.845)	(0.008)	(0.073)	(0.013)	(0.000)		(0.002)
Comm Frequency	-0.08	0.26	0.38	0.19	0.45	0.44	
	(0.605)	(0.074)	(0.007)	(0.186)	(0.001)	(0.002)	

Note: p-values in parenthesis

Table 4

Correlation Matrix, Time 2

Variable	Board Eval	Task Coord	Perceived Subst	Cohesive Strategy	SMM Task	SMM Team	Comm Freq
Board Evaluation		0.10	0.16	0.17	0.01	0.19	-0.03
		(0.483)	(0.270)	(0.245)	(0.960)	(0.211)	(0.822)
Task Coordination	0.10		0.42	0.68	0.40	0.00	0.06
	(0.483)		(0.003)	(0.000)	(0.006)	(0.976)	(0.692)
Perceived Subst	0.16	0.42		0.61	0.60	0.17	0.02
	(0.270)	(0.003)		(0.000)	(0.000)	(0.242)	(0.910)
Cohesive Strategy	0.17	0.68	0.61		0.47	0.05	0.00
	(0.245)	(0.000)	(0.000)		(0.001)	(0.760)	(0.977)
SMMTask	0.01	0.40	0.60	0.47		0.06	0.29
	(0.960)	(0.006)	(0.000)	(0.001)		(0.686)	(0.051)
SMMTeam	0.19	0.00	0.17	0.05	0.06		-0.10
	(0.211)	(0.976)	(0.242)	(0.760)	(0.686)		(0.525)
Comm Frequency	-0.03	0.06	0.02	0.00	0.29	-0.10	
	(0.822)	(0.692)	(0.910)	(0.977)	(0.051)	(0.525)	

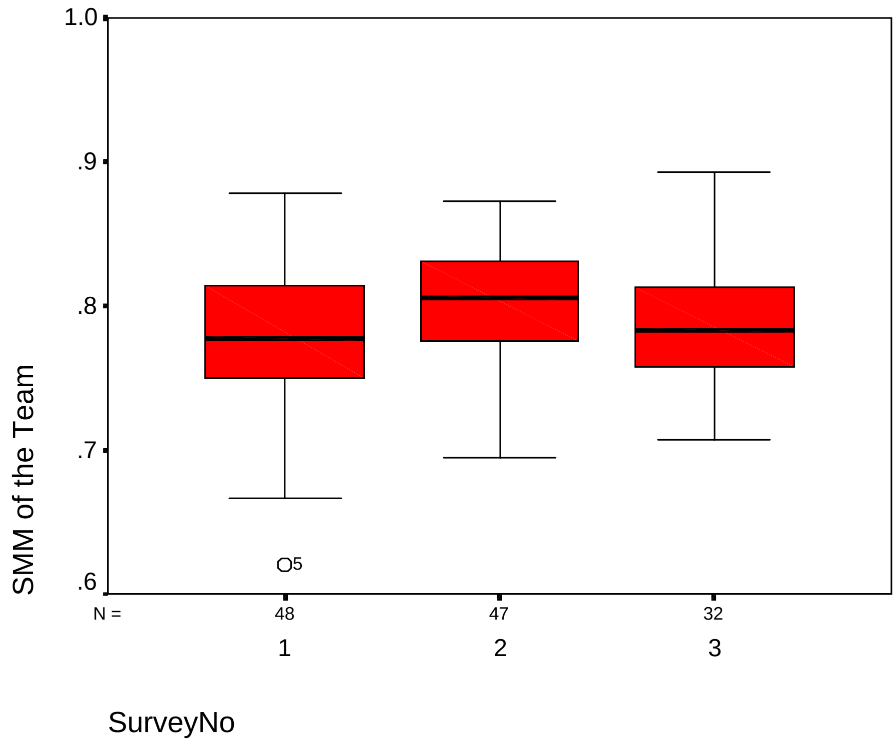
Note: p-values in parenthesis

Table 5

Correlation Matrix, Time 3

Variable	Board Eval	Task Coord	Perceived Subst	Cohesive Strategy	SMM Task	SMM Team	Comm Freq
Board Evaluation		0.25	0.47	0.53	0.39	0.42	0.18
		(0.171)	(0.007)	(0.002)	(0.026)	(0.018)	(0.317)
Task Coordination	0.25		0.44	0.56	0.42	0.26	-0.03
	(0.171)		(0.011)	(0.001)	(0.016)	(0.146)	(0.849)
Perceived Subst	0.47	0.44		0.63	0.48	0.25	0.32
	(0.007)	(0.011)		0.000	(0.006)	(0.172)	(0.073)
Cohesive Strategy	0.53	0.56	0.63		0.40	0.16	0.11
	(0.002)	(0.001)	(0.000)		(0.025)	(0.373)	(0.540)
SMMTask	0.39	0.42	0.48	0.40		0.33	0.32
	(0.026)	(0.016)	(0.006)	(0.025)		(0.061)	(0.076)
SMMTeam	0.42	0.26	0.25	0.16	0.33		0.17
	(0.018)	(0.146)	(0.172)	(0.373)	(0.061)		(0.366)
Comm Frequency	0.18	-0.03	0.32	0.11	0.32	0.17	
	(0.317)	(0.849)	(0.073)	(0.540)	(0.076)	(0.366)	

Note: p-values in parenthesis



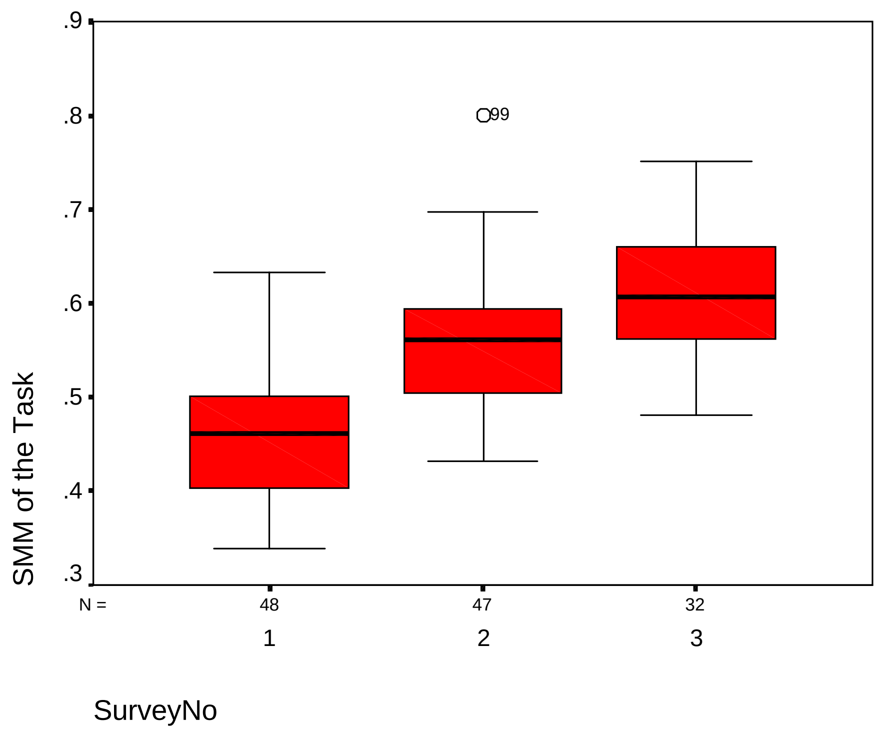


Figure 3: Shared Mental Models Over Time

Appendix A
Questionnaire Items for Study Variables

Perceived Substitutability

1. Members of my team knew a lot about each others' areas of expertise (e.g., marketing, finance, production)
2. Members of my team don't know much about the tasks others are working on
3. If a member of my team couldn't finish his/her task, the rest of us knew enough to take over

Cohesive Strategy

1. My team has a clear idea of what our financial strategy should be
2. My team has a clear idea of what our marketing strategy should be
3. My team has a clear idea of what our production strategy should be
4. Members of my team have a clear idea of what our team's goals are
5. My team knew exactly what it had to get done in order to succeed
6. Members of my team fully understand how competitors' actions will impact our performance

Task Coordination

1. Members of my team often disagreed about who should be doing what task
2. Members of my team did their jobs without getting in each others' way
3. Members of my team often duplicated each others' work
4. Tasks were clearly assigned to specific team members
5. My team wasted a lot of time
6. It was very easy for me to get info from other team members when I needed it
7. I always received the info I needed from other team members on time
8. I usually received just the right amount of info I needed in order to do my tasks effectively
9. It was difficult for me to share my work with others and to get feedback from them