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A FRAMEWORK FOR MEASURING TEAM MENTAL MODELS IN DESIGN

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1. Studying collaboration in design

When designers work together in teams there is some room for problems that might arise. This is especially the case if not all members are located at the same location and no face-to-face communication can take place. It may happen that team members have different conceptions about the goal or who is in charge of what because the duties were not clearly allocated or because of misunderstandings. This may lead to a suboptimal performance because work may have to be redone or is carried out by more members than necessary. One way to prevent such problems is to take a detailed look at what happens in the mind of the designers in a team.
Collaboration and Integrated Product Development are two central aspects of nowadays design and they seem to have become increasingly important in recent years. Many design activities and important decisions in the design process are made in teams. This might be due to organizational factors affecting the designers or due to the demand of dealing with complex design tasks in which several experts from one or more different parties must share their knowledge in collaborative teams. Although there are many benefits from such forms of collaboration they also bear potential problems. For example, members of distributed teams can not share their information directly when they do not meet at the same location, and not all members of multidisciplinary teams possess the same background knowledge. An investigation of distributed teams showed that problems in teamwork can be found which are due to insufficient overlap in background knowledge and different use of terminology [MacGregor *et al.*, 2001]. Similar problems can be expected to arise in multidisciplinary teams as well. The knowledge might not be shared in a resourceful way, some team member might lack important background knowledge, team members might be unfamiliar with the terminology used, tasks might not be efficiently or clearly divided, or there might be problems in the team communication. As a result collaborative design asks for coordination between team members. In order to understand and support design teams the importance of studying designers and their roles and relationships in teams has been pointed out [Cross & Cross, 1995]. Therefore a good understanding of the processes that influence teamwork in design help to identify and overcome problems of cooperation and facilitate task performance.

2. Team mental models

Although there is some body of research on design teams at team level concerning issues like supporting designers in teams with sketching tools or communication aids, requirements and processes at a cognitive level have received much less attention. Nevertheless, the information exchange between team members' representations seems to be an important issue during the design process [Badke-Schaub & Frankenberger, 2003]. What is it that designers do with their knowledge when solving a problem in a team? A framework that seems useful for studying design teams at a more cognitive level is the concept of mental models. The idea of mental models as mental representations

or “small scale models” of the world people use to represent and make sense of events has been proposed by Craik in 1943 and was elaborated in more detail by Johnson-Laird (1983). Mental models are defined as organized knowledge structures humans’ process in order to describe events in their environment, to make sense of them and to predict future events. Mental models are conceived as basic cognitive structures that influence behaviour and decision making. At the time, this concept was primarily used for studying and modelling deductive logics and the interaction between individual human users and physical and computer systems, but it has since been applied to study other fields as well.

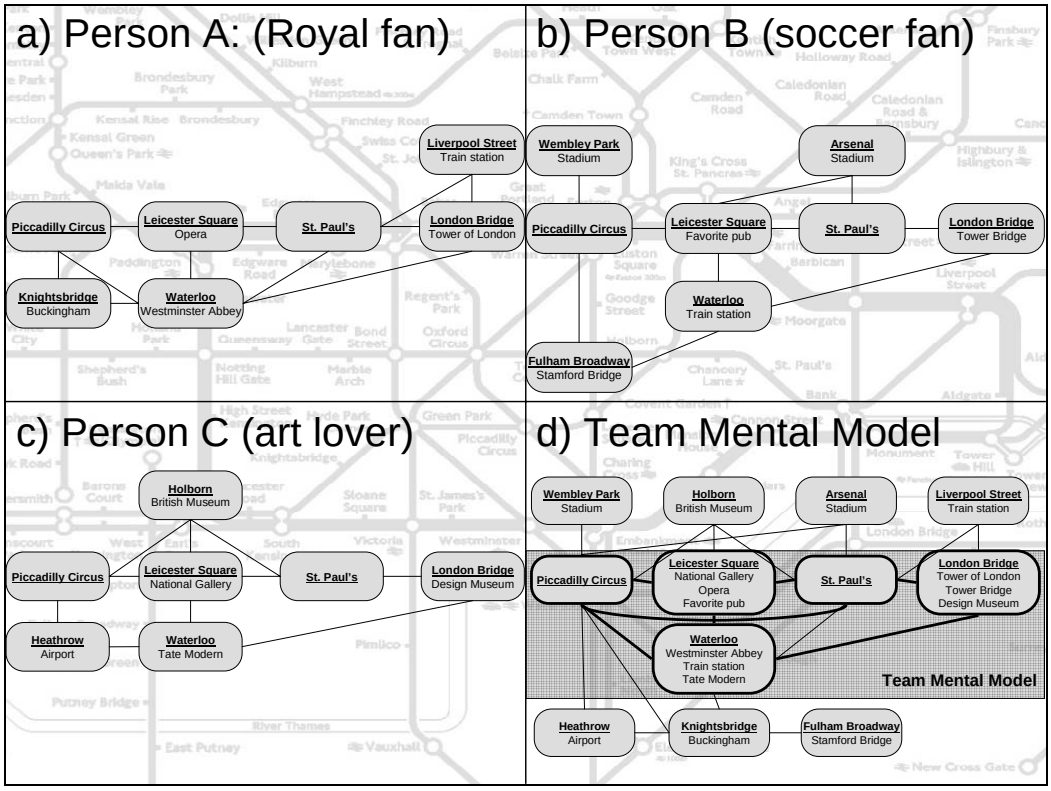

Figure 1. Mental models of London Underground

An example of a mental model is given in Figure 1a. Suppose that this model is learned by experience rather than by reading the plan of the underground. It shows a mental model of a visitor of London who is familiar with transportation possibilities between keypoints that are relevant to him. Notice that the model of the connections between the keypoints is no one-to-one representations of the world in terms of distance or real orientation and location of the connections. It is rather a model that represents how the underground system can be used in order to get from one point to another. The information that is stored can be visual as a map, but it can also be explicit knowledge that is stored linguistically like what is found at a special location. The holder of the model which is shown in Figure 1a is a tourist who is interested in places related to the Royals who arrived by train, so his keypoints includes the most important museums and the train station. The mental models about the London transportation system from two other persons are shown in Figure 1b and 1c.

It is also used to study how knowledge is distributed between several members of a team. The concept of shared mental models or team mental models has been introduced to characterize knowledge or belief structures held by members of a team, which enable them to form accurate explanations and expectations about the task, and to coordinate their actions and adapt their behaviours to the demands of the task and other team members [Cannon-Bowers *et al.*, 1993; Klimoski & Mohammed, 1994]. We

use the term mental model because we want to focus on mental models that are shared by members of a team with common goals.
Figure 1d represents team mental model of all three persons. Note that they have overlapping as well as additional mental models. In this article, the term shared is used to refer to mental models that are overlapping.
It has been shown that team processes, above all communication and decision making, are influenced by team mental models. These are two central aspects in collaborative design. It can therefore be expected that the study of team mental models could reveal insights that help to facilitate the performance of design teams and to improve the communication between design team members.
Numerous studies in other domains have pointed out a positive effect of such team mental models on teamwork in various areas such as in flight deck teams [Cooke *et al.*, 2000; Mathieu *et al.*, 2000], power plant control crews, long-term student groups, software development teams [Carley, 1997], and management teams [Ensley & Pearce, 2001]. It is assumed that the development and existence of team mental models improves team performance. On the other hand the relationship between the existence of team mental models and team performance is not linear and far from clear. There are also studies that predict no or even negative effects [Smith-Jentsch *et al.*, 2005]. Furthermore it is assumed that too much sharedness might lead to effects like groupthink that negatively influence teamwork. Groupthink means that team members desire unanimity at the expense of examining only few alternatives and not being critical about each other ideas. It is known that it can negatively influence the quality of group decisions.

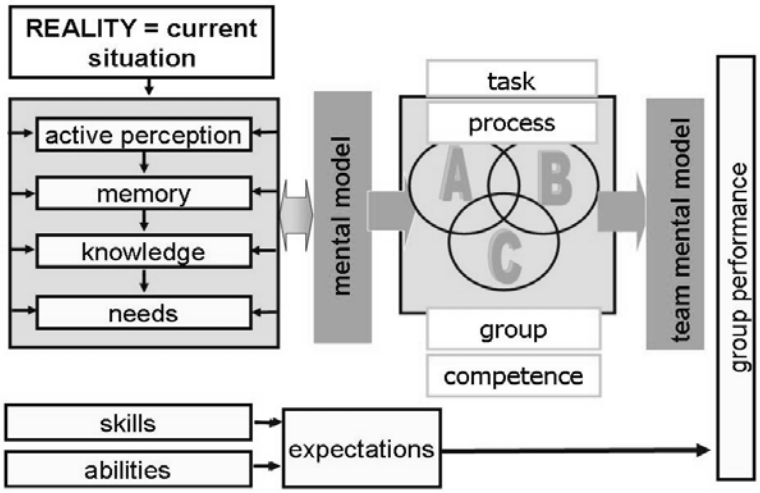

Figure 2. Model of the development of team mental models

When examining design teams much can be learned from an analysis of team communication [Stempfle & Badke-Schaub, 2002]. The processes in the team that influence the outcome of a decision making task can be studied by observing and analyzing team members during a design task. Such an evaluation can not only provide information about task and team knowledge of team members but it can also reveal how this knowledge develops during the task. Studying team mental models in design teams using such a method could reveal insights into the development of team mental models. Furthermore, it was pointed out that in situations in which communication is difficult team mental models might serve a greater function than when communication is easy [Mathieu et al., 2000]. Distributed design teams in which team members might be located at several locations might have communication problems. A detailed investigation of cognitive processes that play a role can be expected to be beneficial. A schema of how team mental models are developed and their influence on

team performance is given in Figure 2. The development of a mental model depends on the current situation. That means a mental model is built based on requirements and constraints which determine the cognitive processes of a given situation. The mental models that are developed can contain knowledge about the task, the process, the group or the competence. These types of models are discussed later in more detail. These models will shape how the team performs a task. The individual models can be shared to some degree, both by dyads and by all members of a team. Individual skills and abilities which should not to be shared on a short time interval, built up expectations in each team members that have an impact on (sub)goals that are aimed. These expectations therefore have some impact on the team performance as well. Team mental models also depend on the task demands. Team mental models should be carefully considered for every domain because they are very different for each task and every team. This might be one major reason why there is no commonly shared typology surrounding team mental models. Nevertheless, two major types of mental models that can be shared between team members have been identified. These are models about the task and models about the team. A more detailed distinction into four models that is commonly used was proposed by [Mathieu et al., 2000]: The task model, the equipment model, the team model, and the team interaction model. These models were identified when the main research focus in studying mental models was on human system interaction. This is illustrated by the equipment/technology model that is included. For many studied areas as flight crews or software development teams, this might be suitable. For designers, it is difficult to imagine how a design task could be described in such models. It seems that there are other demands for developing mental models in design. We propose four adapted types of models that can be identified in design. They can thus be used to learn more about the cognitive processes that underlie members' behaviour in design teams. The adapted model is shown in Figure 3.

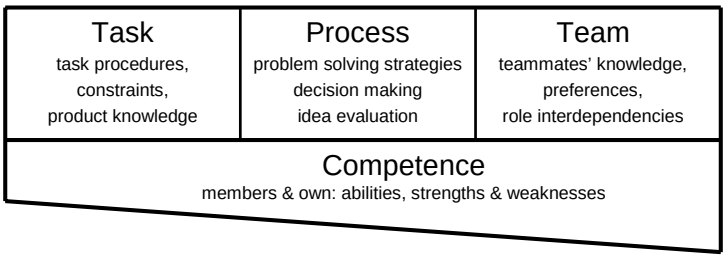

Figure 3. Types of mental models

The related knowledge content is presented in the box inside each type of these models. At the time when the original model was proposed the main research focus on mental models was on human system interaction. We make a distinction into a task model, a process model, a team model, and a competence model. In our task model all knowledge that is relevant to a particular task is included. In fact, that is all knowledge which belongs to the two types of the original model. From a design perspective, the knowledge about the technology is not different in essence from other knowledge related to a task. This is why we include knowledge about the equipment into our task model. It also includes product knowledge which could contain information about relevant information of the object to be designed in such a task. Additionally, we propose a process model that contains knowledge of how to solve a design task. This can be problem solving strategies and methods that are used by designers when performing a task. The model is different from the task model as it focuses on *how* to handle a task and not *what* is needed when performing a task. In other words, it focuses on the process of solution finding rather than the design knowledge that is relevant to the task.

Our model also includes a team model. It includes almost all knowledge that was previously divided into the team model and the team interaction model. We propose that knowledge about the team mates and the manner how to interact with them are closely related and should not be divided. Moreover, a competence model that consists of knowledge and belief about oneself and others is added. It embraces the knowledge about other abilities, the confidence that a member is able to perform a task, and the responding roles and responsibilities. Therefore, this model is related or based on the three

other models. Competence related issues have an impact on the task acceptance and should consequently contribute to the team performance.
In the remainder of this document we outline some empirical studies regarding team mental models from several disciplines. This overview gives an impression how mental models can be assessed, what is the purpose / benefit of measuring them and in what way they influence team performance. A major focus in this comparison lies on similarities and difference between these studies and their domains and design as a research area. Then an outline of the advantages of a classification schema is provided, which can be used as starting points which could be used to study team mental models in design teams during the process of performing a task. These methods have the advantage of providing detailed information about the process how team mental models are developed and adapted. This offers a possibility of studying the influence of team mental models in design teams on the team performance and the resulting output of the team.

3. Task requirements in different domains

The importance of analyzing task and team behaviour when studying design teams has been suggested by Cross [Cross & Cross, 1995]. An investigation of design teams also revealed that some problems in teamwork can be linked to different use of terminology [Kleinsmann & Valkenburg, 2003], which might be due to mental model differences. Team mental models related both to the task and to the team can thus be expected to provide valuable information that can be used to improve the information exchange and the decision making process in design teams. As has been outlined before, team mental models are task dependent. In order to learn from other studies it is therefore useful to compare the requirements of the different disciplines with design. Table 1 shows a comparison of task related requirements in studied domains. Note that the dimensions and classifications are chosen to distinguish between the requirements of the different fields rather than to classify or judge the fields.

Table 1. Comparison of the requirements of TMM in studies fields

Requirements	Flights crews	Software development teams	Management teams	Design teams
Decision time available	-	+	+	+
Reversible operations	-	+	+	+
Undo possible	-	+	+/-	+/-
One best solution	+	+/-	-	-
Risk to person	+	-	-	-
Amount of choices	-	+	+	+

It should be obvious that design tasks have different requirements than the areas which have already received attention. So far, highly structured tasks such as flight decks control are most extensively studied. There are two major reasons for that. First, the tasks are very similar to classical human system interaction studies in which mental models have been used for some time. The second reason is that such tasks are rather limited in the sense that there are only a limited number of decisions one has to make and action which can be performed. Furthermore, the time interval in which decision must been made are in the range of seconds. That means that there is no time to clarify misunderstandings that might be due to unshared mental models. In such kinds of areas, methods which are used to measure the content of mental models are used. In the next section, it is argued that these methods might not be well suitable for the field of design. For other domains such as software development and management teams, tasks are more dynamic and the number of choices that can be made is higher. The concepts which are used might therefore be more numerous and thus more difficult to identify and less methods that focus on the content of mental models are applied.
Design can be viewed as a discipline with different requirements as those other domains which are described. Most obviously, a design task is a wicked problem in which the desired outcome is not known at the start. Furthermore, there might be less pressure due to low time restrictions, the

possibility of reconsideration or the amount of risk, and this also contributed to the large amount of choices that exist. This makes it difficult to identify the concepts that are used by the team members which are needed to compare and analyse them. The studies which focus on management teams which have similar task requirements face the same difficulty. It can be seen that methods were used that do not go into much detail into the content of the mental models. This is even more the case for design tasks as it is very difficult to identify typical operations or used concepts. Other measuring techniques are consequently needed in order to investigate them in this domain. One method that can be applied to the study of mental models in design is proposed in the next section.

4. Measuring team mental models in design teams

As mental models are hypothetical constructs they cannot be directly observed. Interviews or questionnaires are used most of the time to determine whether information was shared among team members or not. These methods focus on the perceived sharedness of knowledge between members of a team. However, such means, although easy to use, lack some important issues regarding mental models: they have a small degree of emphasis on the content and structure of the mental models that are used, there are no well established procedures to use the methods, and they lack reliability.
This is why the exclusive usage of such methods is not sufficient to assess how mental models are developed and what mechanisms play a role when they are exchanged. Although other methods such as content analysis or concept mapping, which tend to measure the detailed content of mental models and the similarity between concepts, are used as well, the conclusions about the amount of sharedness of the mental models are mostly done afterwards. An excellent overview of such used methods to measure and elicit team mental models is given by Langan-Fox *et* al. [Langan-Fox et al., 2000]. Using these methods individually measured mental models are compared to determine how and to what degree the mental models are shared by the team members. The relationship between the existence of team mental models and team performance is then done after the task is performed. Therefore, as Mohammed, Klimoski, and Rentsch [Mohammed *et al.*, 2000] pointed out, the conclusions for performance differences across teams are often post hoc explanations. It is also suggested that methods assessing the content of mental models like cognitive mapping lack the potential of measuring the process of how team mental models are formed. Another problem in measuring mental models is that they are not fixed structures in the mind but they develop over time. This is also a point that methods lack, which focus on measuring the content of mental models. They might provide an accurate description of a mental model at a point in time during a task, but as these models develop over time a comparison of then afterwards might not be an accurate means to determine the sharedness.
The two issues that received most attention when studying team mental models are the content of the model and how they are distributed in a team. Although the first point might not be assessed in detail with methods like interviews or questionnaires, what knowledge is used and exchanged is always the central issue. Then it is of concern how the model is distributed. It could be that a model is shared by all team members or only by dyads. Models that are shared can be identical or only similar to some extent. This is also a key point that should receive attention. Besides the accuracy of the models and the importance of the models there are other points as well that should be considered. A model can be shared in a team but at the same time it can be wrong or inaccurate. Of course, misconceptions have a negative effect on the outcome, probably even more as they are shared by several members. It should therefore be verified to what extent the models that are shared are accurate. The second point, the importance of the model that is shared, should also be considered. Just because a model is shared does not make it relevant to the task and it should. Therefore the importance of the model to a task can be expected to weight the impact on team performance.
We argue that a useful way to study mental models is through behavioural analysis. Observing teams in real task settings give an opportunity to investigate the development, exchange and adaptation of mental models without using artificial methods that disturb the task. In order to so, a category system must be developed that can be used to analyze the observation data. To formulate such a category system, the four proposed categories, which are used to make a distinction between different types of team mental models in design, can be used. A schematic overview the categorization system that is

used to assess mental models is provided is Figure 4. In Figure 4a, a scoring table is presented that is used to obtain the relevant categories that are based on a prior analysis. Every utterance 1 to i by person A is for every model, in the example the task model, associated into one or more categories. After every utterance is scored, a ranking list is developed that orders the categories by their importance based on the times that they are scored. This is repeated for every model and for every person. Due to this ranking list, the team mental models can be calculated as in Figure 4b.
The main advantage of such a category system would be that the development of mental models as a process could be investigated. Other methods have the advantage of investigating in detail the content of mental models, they cannot measure how they are developed and changed over time.

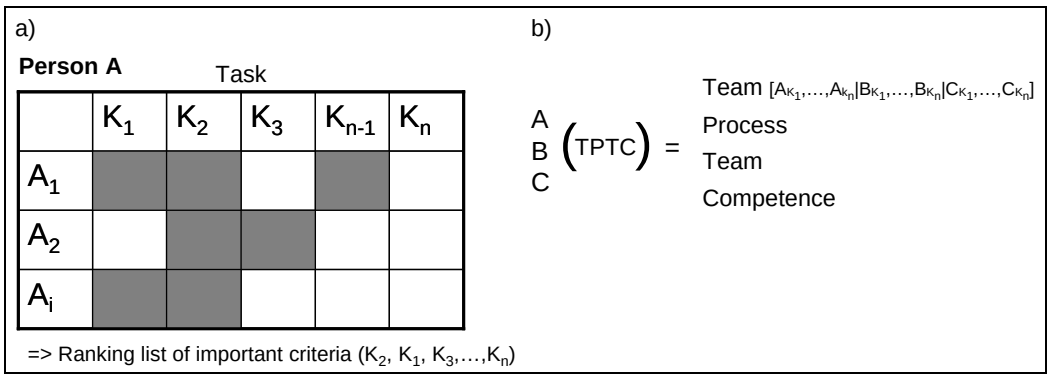

Figure 4. Categorization scheme

The advantages of the category system can be elaborated based on two examples that are essential in the design process: idea generation and evaluation. Within idea generation in groups contributions from other team members are of major importance. It is vital to understand what is meant by other team members in order to let this process produce fruitful results. A categorization scheme could provide an excellent measure to determine whether underlying knowledge is shared when ideas are uttered in a group. The same is true for the second example, evaluation, in which it is of importance to understand what others are talking about. In order to appraise an outcome of a task or a solution to a problem the criteria and essential aspects should be similar to all team members. Otherwise it is possible that different standards are set. In order to agree on an optimal evaluation, the mental models of a task that is appraised should be similar to all team members.
Another aspect which is related to distributed teams that could contribute from such a categorization system would be the transfer of information between team members. This in an essential issue in distributed teams. It should be clear what others understand of the task, who can do a special task, and how the roles are divided.
One major benefit from such a categorization schema that cannot be done with other methods is the potential to analyse visual information. Sketching is a central tool in the design process and the existing methods do not pay attention to that fact. There are no direct indications in the mental model literature that describe how to analyse visual information. Applying a category system could be a fruitful technique to get some information out of sketches about the underlying mental models.

5. Discussion

Studies in a wide range of disciplines have shown the positive effect of team mental models on team performance. However, these domains were much more limited in the number of decisions a team member has to make when performing such a task. As was shown, the discipline of design is quite different from such studied areas and other means of measurement might be needed in order to study team mental models. Besides, it was argued that especially design teams could benefit from such an investigation as many design teams are characterized by locally distribution or multidisciplinary. This is why the study of designers at a cognitive level can help anticipating many problems that might arise during such teamwork. A distinction of four types of mental models was proposed: task, process,

team, competence. Based on these types, we described a framework to develop a categorization scheme to analyze observational data from design teams that can be used to research mental models in teams from behavioural analysis. The benefits of such a method in comparison to existing methods were also outlined.

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