Communication and performance in teams
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2 THEORETICAL BACKGROUND

The factors that influence team performance have received a great deal of attention in recent literature. To position our research in the context of other research, we provide an overview of these factors. Subsequently, we turn to the theory and research concerning knowledge and mental models in teams that forms the basis of the research described in this thesis. The chapter finishes with conclusions and several issues with respect to team performance research and, more specifically, the shared mental model construct.

2.1 Introduction

In an extensive state of the art review concerning small-group and team research covering the period 1955-1980, Dyer (1984) asserted that there was a lack of adequate theory that could be applied to teams as defined in the previous chapter. Questions that had to be answered included: what are the unique features of teams, what are the characteristics of good teams, and what factors influence team performance? Since the publication of Dyer's review, many researchers have embraced the team as a research object and determined a large number of factors that influence team performance. In the first part of this chapter, we will provide an overview of these factors. The purpose is to provide a context in which the research described in this thesis can be positioned. In the second part of this chapter, we focus on several of these factors. More specifically, we focus on knowledge and mental models in teams and their (hypothesized) effect on team processes and, in turn, performance. The purpose is to provide a detailed insight in the theory and research that forms the basis of the research described in this thesis.

2.2 Team performance factors

In order to provide an overview of the factors that influence team performance, we reviewed several models: the general model of group effectiveness (Gladstein, 1987), normative model of group effectiveness (Hackman, 1987), team effectiveness model (Salas et al., 1992; Tannenbaum, Beard, & Salas, 1992), flight crew performance model (Helmreich & Foushee, 1993), team process model (Annett, 1996), task oriented model (Dickinson & McIntyre, 1997), adaptive team model (Serfaty, Entin, & Johnston, 1998), model of team effectiveness factors (West et al., 1998), and the comprehensive model of team performance (Millitello, Kyne, Klein, Getchell, & Thordsen, 1999). The models provide a starting point to develop an understanding of the various factors that may play a role in team performance. A drawback of these models is that although the factors may have high face validity, there is often little empirical evidence about their effects on team performance (Cannon-Bowers, Tannenbaum, Salas, & Volpe, 1995).

When reviewing the team performance models, it becomes clear that the complexity of team research is in particular determined by the large number of factors that must be considered in the study of teams (Salas et al., 1992). Furthermore, different labels are used to describe similar factors. Consequently, the
list of factors is rather confusing and it appears that with each new model, a new set is identified. In an attempt to organize and integrate the factors and processes that are described by the various models, a framework is presented in Figure 2.1. Note that it is not our purpose to propose yet another model with new labels for factors already known, but rather to organize the list of factors in a clear and simple framework.

Figure 2.1: A framework for team performance factors

The framework is organized from the perspective that team performance is a result of taskwork and teamwork, which is influenced by various input factors including situational, organizational, team, and task factors. Several researchers distinguish between two tracks of task execution when performing in a team (Baker et al., 1998; Dyer, 1984; Fleishman & Zaccaro, 1993; McIntyre & Salas, 1995). The taskwork track refers to the activities and behaviors related to the tasks performed by individual team members. Team members can perform these activities independently of other members. The teamwork track refers to the activities and behaviors that serve to strengthen the quality of functional cooperation of team members. Because tasks have to be performed in a team, members perform teamwork for which team members need specific knowledge, skills, and attitudes. In the following sections, the input factors, teamwork factors, and performance outcome are described in more detail.

2.2.1 Input factors

Situational factors

Input factors from the world outside the team are situational factors. Although three models include situational factors, these are not further specified (Helmeich & Foushee, 1993; Salas et al., 1992; Serfaty et al., 1998). Orausen and Connolly (1993) mention two important situational factors: a dynamically changing situation and high time pressure. A dynamically changing situation is concerned with an entire series of events in which several actions need to be taken. The situation changes within the period in which a decision or action is required and prior information can be outdated on the moment decisions or actions are needed. Consequently, teams have to consider the dimension of time explicitly. Teams must consider not only what actions should be performed, but also when actions should be performed (Brehmer, 1992). Another consequence is that continuous situation assessment is
necessary. This is especially important for teams such as military or fire-fighting teams in which the course of action depends largely on developments in the situation.

Teams often need more time to execute tasks or make decisions than there is available, which causes time pressure. According to Orasanu and Connolly (1993), time pressure has two implications. First, when team members experience high levels of time stress, this may result in exhaustion and loss of vigilance. Second, time constraints may lead to the use of simplified, though rapid, decision-making strategies. Because a comprehensive review of all alternatives cannot be performed, potential alternatives may be overlooked. Serfaty et al. (1998) emphasize that, in order to adapt to time-pressured situations, a team must adjust their communications and engage in implicit coordination.

Organizational factors

Teams usually work within a larger organization that partially determines the team’s effectiveness. Although the majority of the models include organizational factors (Gladstein, 1987; Hackman, 1987; Helmreich & Foushee, 1993; Salas et al., 1992; Tannenbaum et al., 1992; West et al., 1998), West et al. (1998) assert that there is little empirical research in this area. Tannenbaum et al. (1992) specify six organizational factors: reward systems, resource scarcity, management control, organizational climate, competition, and inter-group relations. However, a description of how these factors influence team performance is not provided. Hackman (1987) emphasizes the effect of reward systems on team performance, besides information and education systems. Reward systems refer to the way task performance is appraised by the organization. Shea and Guzzo (1987) investigated organizational rewards such as recognition, career advancement, and financial rewards in relation to team performance. The authors found that team performance is enhanced when organizational rewards are geared to the extent of interdependency among team members. In case of low interdependency, the individual contributions of the team members should be rewarded, whereas in case of high interdependency, the contribution of the team as a whole should be rewarded. Another organizational factor is the goal teams are aiming at. Goals are often set by the organization and tell team members what should be done and how much effort is needed to achieve the goals. Conflicts may occur when one goal is opposed to another or when goals are unclear or ambiguous (Orasanu & Connolly, 1993). The effects of goals on performance is well investigated and formulated in the theory of goalsetting (Locke & Latham, 1990). One of the main findings of the goalsetting theory is that performance increases in case of challenging, specific, and clear goals.

Team factors

Team factors refer to characteristics that can be applied to the team as a whole rather than to specific individuals and include size, structure, composition, and cohesiveness (Annett, 1996; Gladstein, 1987; Hackman, 1987; Helmreich & Foushee, 1993; Salas et al., 1992; Tannenbaum et al., 1992; West et al., 1998). The number of team members determines team size (Gladstein, 1987). Several studies showed that team performance first increases and then decreases with size (Nieva, Fleishman, & Reich, 1978). Performance decreases with an increasing size because coordination requires more effort in large than in small teams (Hackman, 1987). According to Dyer (1984), there is limited work on team size with respect to teams that work in command centers. The equipment in the command center often has a fixed number of workstations that determines team size. Nevertheless, this may not be valid anymore, because the design process of future command centers starts with team size rather than equipment as a fixed constraint.
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Team structure is an input factor that involves the way in which tasks, decision authority, and expertise is organized within a team. Lanzetta and Roby (1960) investigated the effects of function specialization and concluded that under low workload conditions teams with generic functions perform better than teams with specialized functions. Under high workload, however, there were no effects of team structure on performance. According to Hollenbeck et al. (1995), team structure can be viewed in terms of decision authority and the distribution of knowledge. In hierarchical teams (in contrast to consensus teams) team members have status differences because one member (e.g., the team leader) is held responsible for the final decision. The distribution of knowledge determines how the expertise of the members is organized within a team. Other authors use the term team structure to refer to the division of the team task into component pieces of information and capabilities, and the assignment of these elements to individuals in the team (Urban, Bowers, Monday, & Morgan, 1995). In the non-hierarchical structure, team members have identical information and capabilities for performing a team task. In the product structure, each team member (except the leader) performs similar functions but in different domains.

Team composition refers to the configuration of the individual characteristics of the team members (Jackson, May, & Whitney, 1995). The research in this area concentrates on the question to what extent heterogeneity is advantageous and if a right mix of members is valuable (West et al., 1998). A large number of characteristics is considered including age, gender, rank, ethnic background, knowledge, skills, attitudes, and personality (Klimoski & Jones, 1995). Whether team composition influences team performance depends largely on the type of diversity being studied, the task being performed and the way in which effectiveness is defined (West et al., 1998). Researchers classify diversity often into two types: characteristics related to the roles or tasks of the team members and personal characteristics that are related to the members themselves. With respect to task-related diversity, many studies show that heterogeneity of skills in teams performing complex tasks is good for effectiveness. The evidence concerning the effect of diversity in personal characteristics on team performance is mixed. For example, the results of the effect of compatibility in personality on performance are conflicting. For other personal characteristics, such as ethnic diversity, there is more evidence of their effects on performance. For example, some studies show that ethnic diversity has initially a negative effect on team performance, but when a team gains experience over time this effect disappears (see, for a more detailed review, West et al., 1998).

Cohesiveness has been defined as the mutual attraction among members of a group and the resulting desire to remain in the group (Morgan & Bowers, 1995). Other researchers use similar definitions in which interpersonal attraction and team members’ liking for the team as a whole is a central point (West et al., 1998). According to West et al. (1998), cohesiveness affects team performance because it influences team members’ helping behavior and generosity, cooperation and problem-solving orientation during negotiations, and their membership of the team. Oliver, Harman, Hoover, Hayes, and Phandii (1999) performed a meta-analysis and concluded that cohesiveness is positively related to performance, whereby the team performance is more influenced than individual performance.

Task factors

Task factors are the characteristics of the tasks that team members have to perform and include complexity, structure, and load (Hackman, 1987; Salas et al., 1992; Tannenbaum et al., 1992; West et al., 1998). Complexity refers to the demand characteristics of tasks. Simple tasks have low complexity, whereas difficult tasks have high complexity (Dickinson & McIntyre, 1997). The organization of the tasks determines the task structure (Dickinson & McIntyre, 1997). Several studies investigated the relation between task structure and performance (Briggs & Johnston, 1967; Johnston & Briggs, 1968).
Johnston and Briggs (1968) demonstrated that performance of team members in a simulated air-interception task was better when they worked independently of one another. Performance decreased when tasks were structured such that interaction among team members was needed. According to Johnston and Briggs, this task structure led to additional coordination activities that imposed workload beyond task demands. This decreased performance. Several researchers view load (or workload) as a task factor (Briggs & Naylor, 1965; Dyer, 1984; Urban et al., 1995). In an experiment, Urban et al. (1995) found differences in performance dependent on the type of workload. Team performance decreased when teams were confronted with a sequence of stimuli presented at a high rate, whereas there was no performance decrease when teams were confronted with a high volume of stimuli at a steady average rate. According to Urban et al., team members were able to adapt to this type of workload by using more efficient communication strategies.

2.2.2 Teamwork factors

Teamwork factors involve the knowledge, skills, and attitudes that members need to perform effectively as a team (Cannon-Bowers et al., 1995; McIntyre & Salas, 1995). Several researchers include teamwork factors such as communication, coordination, leadership, and backup behavior in their models (Annett, 1996; Hackman, 1987; Helmreich & Foushee, 1993; Millitello et al., 1999; Salas et al., 1992; Serfaty et al., 1998; Tannenbaum et al., 1992; West et al., 1998). In order to identify those teamwork factors, different methods are applied. McIntyre and Salas (1995) collected data from three types of military teams (in total 55 teams) using questionnaires and instructors performance ratings. Based on these data, the authors identified four critical teamwork behaviors: performance monitoring, intra-team feedback, communication, and backup behavior. Cannon-Bowers et al. (1995) worked inductively from the literature and gathered a list of over 130 teamwork labels. This list was sorted which resulted in the following eight major teamwork competencies: adaptability, shared situational awareness, performance monitoring and feedback, leadership and team management, interpersonal skills, communication skills, and decision-making skills. Klein (2000) asserts that a team can be considered as an intelligent entity that processes information, makes decisions, solves problems, and makes plans. Based on a number of research projects, Klein identified the following set of teamwork factors: control of attention, shared situation awareness, shared mental models, applications of strategies and heuristics to make decisions, solve problems and develop plans, and meta-cognition.

Other researchers have identified teamwork factors for the purpose of measuring and evaluating team performance (Brannick, Salas, & Prince, 1997; Smith-Jentsch, Johnston, & Payne, 1998a). Based on a literature review, Dickinson and McIntyre (1997) identified and defined seven so-called core components of teamwork that comprise communication, situation awareness, team initiative/leadership, monitoring, feedback, backup behavior, and coordination. Smith-Jentsch et al. (1998a) developed the Anti-Air Teamwork Observation Measure (ATOM). Initially, the ATOM consisted of the seven components that Dickinson and McIntyre had defined. In a later stage, the ATOM was cut back to four critical teamwork components: information exchange, communication, supporting behavior, and team initiative and leadership. The reasons for reducing the number of teamwork components were that the large number of components was too difficult to rate by observers, there was redundancy in the definitions of the components, and several components correlated highly with each other. It is interesting to note, first, that in validation studies, three of the four ATOM components together accounted for 16% of the variance in team performance. Second, only the information exchange dimension uniquely and significantly distinguished between experienced and less experienced teams. The other dimensions possibly tap teamwork skills that do not arise naturally from experience, but require systematic feedback. Third, the ATOM was specifically developed for anti-air warfare teams.
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The components will have to be adapted for other kinds of teams (e.g., less hierarchically structured teams such as air-traffic control teams).

In the next sections, the teamwork factors concerning skills and attitudes are further outlined. Because the theory concerning team knowledge and mental models play an important role in the remainder of this thesis, this is described extensively in section 2.3.

Skills

Teamwork skills refer to the individual abilities of members to perform activities that improve the cooperation in a team and include communication, coordination, adaptability, performance monitoring, team self-correction, team decision making, shared situational awareness, and team leadership.

Communication is the exchange of information between a sender and a receiver. Several studies investigated whether effective teams communicate in a different manner than ineffective teams (Kanki, Greaud, & Irwin, 1991; McIntyre & Salas, 1995; Orasanu, 1990, 1993). In these studies, communication in teams is observed and scored during task execution and then related to team performance. These studies show that effective teams have similar communication patterns using the same proportions of commands, questions, and acknowledgements (Kanki et al., 1991), confirm messages (McIntyre & Salas, 1995), and use proper phraseology, avoid excess chatter, and ensure themselves that communication is audible and ungarbled (Smith-Jentsch, Zeisig, Acton, & McPerson, 1998b). Other studies investigated the purpose of communication. Based on observations of navigation teams on board of naval vessels, Seifert and Hutchins (1992) point at three important purposes of communication: information exchange, error detection, and the acquisition and maintenance of a shared awareness of the situation. The importance of communication to develop and maintain shared situation awareness is also emphasized by other researchers (Helmreich & Foushee, 1993; Orasanu, 1990, 1993; Smith-Jentsch et al., 1998b). In the aviation domain, effective cockpit crews tend to communicate more overall and, in particular, crews who exchanged more information about flight status committed fewer flight errors (Helmreich & Foushee, 1993). Orasanu (1990, 1993) also observed that effective cockpit crews engaged in highly task directed communications involving plans, strategies, intentions, possibilities, explanations, warnings, and predictions.

Coordination is a process by which team resources, activities, and responses are organized to ensure that tasks are integrated, synchronized, and completed within established temporal constraints (Cannon-Bowers et al., 1995). As described earlier, a distinction can be made between explicit and implicit coordination (Kleinman & Serfaty, 1989).

Several researchers assert that an important teamwork skill is adaptability (Blickensderfer et al., 1998b; Entin & Serfaty, 1999; Kozlowski, 1998; Marks et al., 2000). Team members in effective teams are able to use information from the situation in order to adjust team strategies such as implicit coordination, reallocating team resources, and backing each other up (Cannon-Bowers et al., 1995). Implicit coordination is a type of adaptation in which team members adapt to situations where communication channels are limited due to high time pressure, excessive workload, or other environmental features. Another type of adaptation is the dynamic reallocation of functions whereby team members take over tasks of teammates experiencing high workload. This way, a team is able to balance the workload during high-workload, time-pressured, or emergency situations (Briggs & Johnston, 1967). A related concept is backup behavior. Backup or supportive behavior is the mechanism by which team members assist the performance of teammates and compensate for one another’s weaknesses by correcting errors and shifting workload (Smith-Jentsch et al., 1998b). Johnston and Briggs (1968) evidenced that backup
behavior is positively related to team performance. Under high workload conditions, fewer flight errors occurred when team members were allowed to compensate for teammates' behavior than when such compensation was not possible.

The ability of team members to give, seek, and receive task-clarifying feedback during task performance is called performance monitoring (McIntyre & Salas, 1995). This includes the ability to accurately monitor the performance of fellow team members, provide constructive feedback regarding errors, and offer advice for improving performance. A similar concept is team self-management, which is the ability of a team to observe its processes, recognize its level on team characteristics, and make adjustments to reach a higher level of performance (Millitello et al., 1999). McIntyre and Salas (1995) collected data from three types of military teams (13 naval gunfire support teams, 11 anti-submarine warfare teams, and 31 guided missile teams). During task performance, instructors observed the teams using forms to rate critical team behavior, individual performance, and team performance. In addition, team leaders were also asked to rate team members with the individual performance form. Finally, team members had to fill in a questionnaire regarding individual and team abilities, motivation and expertise. Based on the data obtained from the ratings and the questionnaires, McIntyre and Salas concluded that effective teamwork requires that team members keep track of each other's performance, while carrying out their own tasks. The authors also concluded that the follow-up activity of monitoring is important for effective teamwork. Team members of effective teams provide each other with feedback and accept it from each other.

Team self-correction discussions often take place after task performance, where events and actions are reviewed, and plans are formulated to improve performance for the next time (Blickensderfer et al., 1997b, 1997c). In an experiment, Blickensderfer et al. (1997c) found support for the hypothesis that team self-correction discussions improved the coordination behaviors of the team members. Helmreich and Foushee (1993) also assert that reflective behaviors such as team self-correction are important for effective team behavior. The authors use the term team self-critique that includes considerations about the performance outcome, process, and team members involved. A conceptually similar teamwork skill is group task reflexivity defined as the extent to which members overtly reflect upon the objectives of the group, strategies and processes, and adapt them to current or anticipated endogenous or environmental circumstances (West et al., 1998). In an experiment, Hackman, Brousseau, and Weiss (1976) studied the effect of strategy discussions by 36 four-person teams that had to perform an assembling task. The results show that team members did not engage spontaneously in strategy discussions. A simple verbal instruction, however, supported team members to discuss their strategies. When team members engaged in strategy discussions, the performance increased only when the task required explicit coordination and the sharing of information among members. When the task was straightforward in the sense that the most salient strategy was fully task appropriate, strategy discussions did not result in an improved performance.

Decision making is defined as "a bundle of interconnected activities that include gathering, interpreting, and exchanging information; creating and identifying alternative courses of action; choosing among alternatives by integrating the often differing perspectives and opinions of team members; and implementing a choice and monitoring its consequences" (Guzzo, 1995 p. 4). Decision making in teams is distinct from individual decision making in that information is often unequally distributed among team members and must be integrated. The integration process may be complicated by uncertainty, the effects of status differences among team members, and the failure of one team member to appreciate the significance of the information he or she holds. Cannon-Bowers et al. (1995) add that for effective
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decision making, because team members have specific expertise or different information sources, team members must exchange information and resources.

The development of **shared situational awareness** in a team refers to the degree to which team members develop the same interpretation of ongoing events in the situation (Endsley, 1995; Salas, Prince, Baker, & Shrestha, 1995). Especially in dynamic environments, it is easy for the different team members to form divergent impressions without realizing it and for discrepant assumptions to create difficulties. Situation awareness is defined as “the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future” (Endsley, 1995 p. 36). Salas et al. (1995) concluded that team situation awareness involves two critical processes. The development of individual situation awareness and teamwork to develop shared situation awareness. Team members each develop their own set of situation awareness elements. Overlap, however, must exist among team members’ situation awareness elements. Team situation awareness is dependent on both the individual and the shared part of situation awareness.

**Leadership** skills include the ability to facilitate teamwork (McIntyre & Salas, 1995; Tannenbaum, Smith-Jentsch, & Behson, 1998). Several researchers point at three important functions that team leaders must perform in order to facilitate teamwork (Brannick, Prince, Prince, & Salas, 1995; Smith-Jentsch et al., 1998b; Tannenbaum et al., 1998). First, leaders must provide guidance to the team members. The coordination of activities must be directed and structured by team leaders and they must state clear team and individual priorities. Second, team leaders must monitor the performance and provide feedback when necessary. Team leaders must know their stuff and be willing to listen to other team members who have special expertise (McIntyre & Salas, 1995). Third, leaders should also provide team members with knowledge structures that will help the team adapt to changing task demands. Leader briefings that include knowledge about the importance of various elements in the task environment constitute a vehicle through which leader communication takes place (Marks et al., 2000).

**Attitudes**

Several researchers assert that for effective functioning, team members must possess a certain attitude towards the team (Burke, 1997; Driskell & Salas, 1992b; McIntyre & Salas, 1995). Different concepts such as **team orientation** (Burke, 1997; Driskell & Salas, 1992b; McIntyre & Salas, 1995), **team identity** (Burke, 1997; Millitello et al., 1999), and **collective behavior** (Driskell & Salas, 1992b) describe that it is important for team members to recognize that their success is dependent on their interaction, and the team’s goal goes beyond that of the individual team members. When team members have a positive attitude towards the team, members view themselves as team players. Based on the previously described observations of military teams, McIntyre and Salas (1995) concluded that effective teamwork implies an attitude of team members to show the willingness to provide backup to fellow members during operations. In effective teams, members show a willingness to jump in and help when needed, and accept help without fear of being perceived as weak. Besides backing each other up, team members may coach each other (Millitello et al., 1999). Coaching occurs when more experienced team members offer direction to less experienced members, supporting individual team members to perform better on their individual tasks (see also Helmreich & Foushee, 1993).

The extent to which team members coordinate, evaluate, and employ task inputs of fellow team members in an interdependent manner is called **collective behavior** (Driskell & Salas, 1992b). In an experiment, 60 two-person teams participated in a task that was developed to operationalize relevant aspects of team decision making. In the first phase of the experiment, team members were classified as either egocentric or collectively oriented. In the second phase of the experiment, egocentric teams,
collectively oriented teams, and a control group of team members that did not participate in the first phase, performed a task that was similar of that of phase one. The results indicated that the egocentric teams performed no better than their team members did as individuals. The collectively oriented teams, however, performed better than the individual members did that formed the team. According to Driskell and Salas (1992b), these findings show that in collectively oriented teams, members benefit from the advantages of teamwork. That is, collectively oriented team members benefit from the opportunity to pool information, share resources, and check errors that are afforded by the team environment.

2.2.3 Performance outcome

What performance criteria can be defined to determine whether a team is effective? For researchers using experimental tasks, this question is relatively easy to answer. Researchers often define team performance in terms of achieving the task goals. For example, in a low-fidelity simulation of the Tactical Naval Decision Making (TANDEM) task, the goal is to identify correctly objects on a radar screen and to take adequate countermeasures. Because the objects are pre-defined, the accuracy of the identifications and countermeasures can be normatively determined. In this type of task, performance is often measured by the accuracy and timeliness of team members’ activities that contributes to goal accomplishment. In real-world situations, performance criteria can also be defined in terms of the extent to which the outcome satisfies the goal (Annett, 1996). However, goals of many real-world situations are often ill defined. Moreover, there may be multiple (possibly conflicting) goals from which the relative priority is not clear (Orasanu & Connolly, 1993). Because goals may be diffuse and performance is rarely clear-cut good or wrong, several researchers advocate a more subjective approach. That is, team effectiveness should meet or exceed the performance standards of interested stakeholders (Hackman, 1987; West et al., 1998).

Another way to determine team performance is to use multiple criteria such as the quantity and quality of products or services as well as time, errors, and costs (Tannenbaum et al., 1992). Helmreich and Foushee (1993) provide an example of using multiple criteria in the aviation domain. In flight operations, safety is the most important goal (followed by efficient completion of missions and compliance with organizational rules). The best measure of effectiveness in aviation is the frequency of accidents. However, accidents happen so infrequently that reliable statistical evidence is hard to obtain (only when one aggregates over long periods). In such cases, team performance criteria need to be drawn from measures such as records of operational errors, observer ratings of team effectiveness, and measures of attitude and job satisfaction.

Several researchers assert that it is important not only to concentrate on the extent of goal accomplishment, but also on the state of the team and its members (Hackman, 1987; Tannenbaum et al., 1992). Teams usually have to perform subsequent tasks and it is important to maintain the motivation and ability to perform those tasks. According to Tannenbaum et al. (1992), possible performance criteria are changes in the team (e.g., new roles and processes, or greater versus lesser cohesiveness) and changes in individuals (e.g., improved versus decreased skills, attitudes, or motivation). Hackman (1987) provide two other criteria of this type. First, social processes in carrying out the work should maintain or enhance the capability of members to work together in subsequent team tasks. Second, group experience should, on balance, satisfy rather than frustrate the personal needs of group members.
2.3 Knowledge and mental models in teams

In the following section, we will first describe the shared mental model theory, followed by an overview of the research.

2.3.1 Shared mental model theory

Mental models

To explain how people interact with the world, researchers have introduced the mental model construct (Wilson & Rutherford, 1989). The basic assumption is that people not only have knowledge, but that knowledge is organized into structures or meaningful patterns that are stored in memory (Cannon-Bowers et al., 1993; Johnson-Laird, 1987; Rouse & Morris, 1986). These organized knowledge structures, or mental models, are viewed as cognitive mechanisms that enable people to describe, explain, and predict system functioning (Rouse & Morris, 1986). The description function enables the development of an understanding of the purpose of a system (why a system exists) and the form of that system (what a system looks like). The explanation function enables statements about system functioning (how a system operates) and the state (what a system is doing) at particular times. The prediction function enables the formation of expectations of the future states of the system (what a system will be doing) (Rouse & Morris, 1986). Other researchers describe similar functions as important features of mental models. For example, Johnson-Laird (1987) asserts that mental models enable team members to draw inferences and make predictions, to understand and interpret phenomena, to decide what actions to take, and to control system execution.

Two features of mental models are particularly interesting in situations in which rapid comprehension and response is required. First, because knowledge is organized into structured patterns, it enables people to process information in a rapid and flexible manner. When people retrieve information from memory, related information becomes more easily accessible. According to Cannon-Bowers et al. (1993), mental models provide a "heuristic function by allowing information about situations, objects, and environments to be classified and retrieved in terms of their most salient and important features" (p. 226). Second, mental models are not fixed structures in the mind. Based on interaction with the world and prior experiences, models develop over time. Incomplete models will be elaborated and inaccurate models will be modified or even rejected as new perceptions contradict with the currently held model (Norman, 1981).

Shared mental models

A shared mental model refers to organized knowledge structures that allow team members to describe, explain, and predict teamwork demands (Cannon-Bowers et al., 1993; Rouse et al., 1992). The ability to form appropriate expectations and explanations provide team members with a flexible mechanism to adapt quickly and efficiently to the changes in the teamwork demands during task performance. Based on their common explanations, team members are able to select actions consistent and coordinated with those of their teammates (Mathieu et al., 2000) and interpret each other's behaviors accurately (Rouse et al., 1992). Furthermore, based on their common expectations, team members are able to anticipate on each other's task-related needs by providing information, resources, or other support to teammates in a timely manner (Rouse et al., 1992). Consequently, shared mental models influence communication in teams. Explicit and extensive communications to ask for information or to make arrangements concerning "who does what when" and "who provides which information when" are not needed if team members hold shared mental models. Instead, team members are able to provide each other with a) the
information needed to complete the tasks successfully, b) without explicit communications, and c) on the time in the task sequence of a teammate when this information is needed (Stout et al., 1996). When team members perform this, they engage in implicit coordination (Kleinman & Serfaty, 1989). Table 2.1 delineates how implicit coordination, resulting from shared mental models, is expressed in the way team members communicate.

Table 2.1: Communication features when team members engage in implicit coordination because of having shared mental models

<table>
<thead>
<tr>
<th>Implicit coordination</th>
<th>Communication features</th>
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| Team members provide each other only with the information needed to accomplish the tasks | • Less communication (because there is no communication for explicit coordination or strategizing)  
• The exchange of relevant information only |
| Team members provide each other information in advance of requests | • The exchange of information before being requested  
• Less requests  
• In case of requests, answers will be given |
| Team members provide each other information on the time in the task sequence of a team member when this information is needed | • The exchange of relevant information in time  
• In case of requests, answers will be given as soon as possible |

Shared mental models are also important for effective team performance in changing situations (Orasanu, 1990, 1993; Stout et al., 1996). Team members that have shared mental models of the situation are able to interpret the situation in a compatible manner and to take actions both accurate and expected by their teammates. If, for instance, team members adapt to changes in the situation by adjusting their tasks and employing new strategies, the informational needs of team members may change. Team members that keep track of these changes in an up-to-date shared mental model are still able to provide each other with relevant information in advance of requests and engage in implicit coordination.

Keeping up-to-date shared mental models is especially important in non-routine or novel situations (Marks et al., 2000; Orasanu, 1990, 1993). Orasanu (1990, 1993) uses the term shared problem model to refer to mental models of the problem or the situation. Such shared problem models include a common understanding of the problem, goals, information cues, strategies, and team members’ roles. Orasanu asserts that team members develop a shared problem model specific for a unique problem based on shared background knowledge to interpret that problem. Shared problem models create a context in which decisions can be made. They are needed to ensure that all team members are developing strategies for the same problem. Shared mental models in changing and novel situations serve as an organizing framework that enables team members to make suggestions, provide alternative explanations, employ their expertise, generate and test hypotheses, and offer information useful to determine strategies or solve problems in that particular situation. In order to keep up the performance in novel situations, team members must have a compatible understanding of that situation, which supports team members to determine strategies cooperatively. Based on a shared mental model of the situation, team members are able to effectively exchange “information and thought processes to overcome the challenges brought on by novel elements in the environment” (Marks et al., 2000 p. 982). The better the mental models concerning the situational circumstances, the more team members are able to determine effective strategies cooperatively.

An important issue concerning shared mental models is whether shared must be interpreted as having in common or distributed (Mohammed & Dumville, 2001). Most of the research has emphasized that team members must have overlapping or commonly held mental models. The basic assumption is that the greater the similarity between the mental models of the team members, the greater the likelihood that
team members are able to explain and predict the teamwork demands accurately (Cannon-Bowers et al., 1993; Converse, Cannon-Bowers, & Salas, 1991; Kleinman & Serfaty, 1989). Inspired by the research concerning information sharing (Stasser & Titus, 1985) and transactive memory (Wegner, 1987), Mohammed and Dumville (2001) recently contended that shared mental models comprise both the overlapping and complementary perspective. Whether team members need common or distributed mental models, depends on the domain. Although several researchers have defined what should be shared in mental models (Blickensderfer, Cannon-Bowers, Salas, & Baker, 2000; Cannon-Bowers et al., 1993; Converse et al., 1991; Mathieu et al., 2000), the question whether this is overlapping or distributed has received little empirical research to date.

Related to the question whether shared means overlapping or distributed, is the question what should be shared in mental models. Orasanu (1990, 1993) asserts that team members share organized knowledge in their mental models. In addition to shared knowledge, Rouse et al. (1992) assert that shared explanations and expectations of the task and team performance are also important for team performance. Cannon-Bowers et al. (1993) are even more explicit in stating that it is the expectations rather than the mental models that are held in common. This concerns especially the expectations that describe when and how team members should interact with each other to accomplish the task. The discussion what should be shared is not yet resolved. Researchers have put most effort in defining the knowledge content of shared mental models (Blickensderfer et al., 2000; Cannon-Bowers et al., 1993; Converse et al., 1991; Mathieu et al., 2000).

**Knowledge content**

Several researchers have described what knowledge team members need in their mental models (Blickensderfer et al., 2000; Cannon-Bowers et al., 1993; Converse et al., 1991; Mathieu et al., 2000). We divided the list of knowledge elements into two domains: team and situation knowledge. **Team knowledge** comprises all elements related to the team such as the tasks, members, interdependencies, and interactions. **Situation knowledge** comprises all aspects of the (dynamic) environment outside the team. The division into the two knowledge domains is motivated by the effect of shared mental models on team processes and performance. Team knowledge is important to develop accurate explanations and expectations of the teamwork. Situation knowledge is important to develop accurate explanations and expectations of the environment outside the team. Furthermore, whereas team knowledge is important for communication and coordinated team performance, situation knowledge is important to determine strategies cooperatively.

**Team knowledge.** Cannon-Bowers et al. (1993) describe the following four team knowledge elements:

1. **Equipment knowledge.** Knowledge about the dynamics and control of the equipment and how it interacts with the input of other team members helps team members to understand each other's (informational) needs on a detailed level. Rouse et al. (1992) argue that this knowledge is important only as much as it helps team members to form expectations about the task and the team, and that those expectations enable teams to perform more effectively. Examples of equipment knowledge are operating procedures, equipment limitations, and likely failures.

2. **Task knowledge.** Knowledge of the task is needed to understand how tasks can be accomplished, what important information is, how information must be combined, and which procedures are required. It is also important that team members know how situational circumstances influence the way tasks are performed. Examples of task knowledge are task procedures, likely contingencies and scenarios, strategies, and physical constraints.
3. **Team interaction knowledge.** Knowledge of the interdependencies among team members and how each individual contributes to the team performance ensures that team members understand how to interact and help each other, which information should be exchanged among team members, and when and how this information exchange should take place. Examples of team interaction knowledge are the roles and responsibilities of team members, interaction patterns, information flow and communication channels, and information sources.

4. **Team members’ characteristics.** Team members may also need to be familiar with teammates’ characteristics including their knowledge, skills, attitudes, and personal preferences. This helps team members to tailor their behavior in accordance with what they expect from their teammates. Note that this knowledge is specific to particular teammates and, therefore, not applicable across teams.

Blickensderfer et al. (2000) add that team members need common knowledge about the team goals to ensure that team members are working towards the same goal. Another team knowledge element described by Blickensderfer et al. is task plans, procedures, and strategies. Compared to the task knowledge element described by Cannon-Bowers et al., Blickensderfer et al. emphasize the procedural and temporal characteristics of tasks. Common knowledge about how the task is accomplished in terms of plans, procedures, and strategies ensures that team members perform the same plans, procedures, and strategies. Several researchers emphasize that team members should have knowledge of the sequences and timing related to task actions and behaviors (Blickensderfer et al., 2000; Cannon-Bowers et al., 1995; Rentsch & Hall, 1994; Rouse et al., 1992; Stout et al., 1996). Knowledge of task procedures, sequences, and timing enables team members to form expectations of what will happen next, based on which team members can select actions appropriately.

Finally, inter positional knowledge (IPK) comprises knowledge about team members’ roles, responsibilities and informational needs, which is important to understand the interdependencies between team members (Cannon-Bowers et al., 1993; Volpe et al., 1995). Based on this understanding, team members are able to predict each other’s informational needs and anticipate on those needs, which is important for implicit coordination (Blickensderfer et al., 2000; Cannon-Bowers et al., 1998; Cannon-Bowers et al., 1993; Rouse et al., 1992; Stout et al., 1996; Volpe et al., 1995). Knowledge about each other’s tasks also gives team members an understanding when teammates need information and for what purposes. Compared with the four knowledge elements described above, IPK can be viewed as a composite of task and team interaction knowledge. Both knowledge elements comprise knowledge of the tasks, team members’ roles and contributions, and the interdependencies among team members’ tasks.

**Situation knowledge.** The following four situation knowledge elements are described in the literature:

1. **Environmental features and properties.** Knowledge of the features and properties of the environment and elements in that environment enable team members to develop common expectations and explanations about the situation (Endsley, 1995; Stout et al., 1996).

2. **Cues and patterns.** Certain cues or patterns in the situation may trigger a course of action. Knowledge of cues and patterns ensures that team members have a common understanding what the implications are for the team and the task, how the team should proceed, and what particular actions team members have to take (Blickensderfer et al., 2000).

3. **Ongoing developments.** Based on knowledge of the ongoing developments in the situation, team members are able to develop common expectations about how events are likely to unfold. This enables teams to develop strategies for those events and, therefore, adapt to changes in the situation (Cannon-Bowers et al., 1993).
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4. Problems. Shared knowledge of problems that may occur in the situation ensures that all team members are solving the same problem and have the same understanding of priorities, urgency, cue significance, what to watch out for, who does what, and when to perform certain activities (Orasanu, 1990, 1993).

Note that although team and situation knowledge are defined as two different knowledge domains, they are related to each other. Situation knowledge enables teams not only to develop strategies cooperatively, it also determines the way tasks are performed in teams. In order to adapt to situational demands, a modification in how tasks are organized or executed in a team may be required (Entin & Serfaty, 1999). Because this has implications for the teamwork, team members must update their team knowledge. For example, when a team adapts to a high workload situation by adjusting the team organization and re-assigning tasks, team members must update their knowledge of each other's roles, responsibilities, and informational needs. When team members fail to perform this, performance will degrade because under these circumstances, anticipating on each other's informational needs and engaging in implicit coordination will be hindered as a result of changes in team members' tasks and, therefore, informational needs. The bottom line is that knowledge in shared mental models is not static. Both team as well as situation knowledge need to be updated.

Knowledge types

One of the important features of mental models is that they are not fixed structures in the mind (Norman, 1981). Accordingly, researchers have theorized that mental models comprise different knowledge types that differ in the extent to which knowledge is static or dynamic (Blickensderfer et al., 2000; Stout et al., 1996). Blickensderfer et al. (2000) distinguish explicitly between pre-task knowledge and knowledge that develops dynamically during task execution. According to these authors, pre-task knowledge resides in long-term memory and team members carry it with them into task performance. During a task execution session, pre-task knowledge is combined with information coming from observations and interpretations of specific characteristics of the ongoing developments in the team and situation. This results in a dynamic understanding “on the fly,” that embodies knowledge of the developments and the changes in both the team and the situation. Other researchers acknowledge the idea that pre-task knowledge is related to dynamic knowledge. For example, Orasanu (1990, 1993) asserts that team members use shared background knowledge to interpret specific problems that originate during task execution and develop a shared understanding of that problem.

A more refined division in knowledge types is made by Converse and Kahler (1992) and further described by Stout et al. (1996). These researchers distinguish between declarative, procedural, and strategic knowledge (see also Cannon-Bowers et al., 1995; Rouse et al., 1992). Declarative knowledge is knowledge about what dimensions and concepts there are in the world and what the relationships between them are. Procedural knowledge is knowledge about how and in which order activities have to be executed. Strategic knowledge is knowledge of the specific context in which activities have to be performed. It is contingent on the conditions in which tasks are performed and needs to be updated when these conditions change. Whereas procedural and declarative knowledge is static knowledge that provides team members with a general and global understanding of how and when interaction in a team is required, strategic knowledge is dynamic knowledge that is specific for a task situation and is updated dependent on developments during task execution and interactions with the team. Cannon-Bowers et al. (1995) theorize further that declarative and procedural knowledge is applied to the dynamic and changing task that results in strategic knowledge. This includes an understanding of which cues or patterns are associated with particular task strategies, what resources and expertise are available in the team in order to solve a problem, and what task strategies are appropriate.
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Given the division into the three knowledge types, one can begin to think how this is related to the previously described knowledge elements of shared mental models. Although researchers have put effort in describing the knowledge elements and types, a clear division between knowledge types and, in turn, the relation to the content has yet to be made. In Table 2.2, we present an overview of the knowledge elements and types that are important for shared mental models.

Table 2.2: Overview of the knowledge elements and types in shared mental models

<table>
<thead>
<tr>
<th>Team</th>
<th>Declarative</th>
<th>Procedural</th>
<th>Strategic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Goals</td>
<td>Plans and procedures</td>
<td>Strategies, action plans, and solutions</td>
</tr>
<tr>
<td></td>
<td>Members’ tasks, roles and responsibilities</td>
<td>Members’ task sequence</td>
<td>Members’ task execution</td>
</tr>
<tr>
<td></td>
<td>Members’ interdependencies and informational needs</td>
<td>When members are interdependent, need information, and interaction is needed</td>
<td>Priorities</td>
</tr>
<tr>
<td></td>
<td>Members’ characteristics</td>
<td></td>
<td>Adjusted task execution</td>
</tr>
<tr>
<td></td>
<td>Equipment and system functioning</td>
<td></td>
<td>Adjusted informational needs</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Situation</th>
<th>Feature of elements</th>
<th>Timing and sequences of environmental elements</th>
<th>Ongoing developments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Environmental features</td>
<td></td>
<td>Cues and patterns</td>
</tr>
<tr>
<td></td>
<td>Features of elements</td>
<td></td>
<td>Problems</td>
</tr>
</tbody>
</table>

2.3.2 Research on shared mental models

In this section, studies that investigated the relationships among shared mental models, team processes, and performance are reviewed. We start with a review of the studies in which conceptualizations about shared mental models that we have not yet covered will be described. This is followed by a description of various measurement methods. Subsequently, the studies that employed shared mental models as an explanatory construct are described, followed by a review of the empirical studies. At the end of this section we will determine which (parts of) the shared mental model received empirical support and present a model in which all possible relationships are illustrated.

Conceptual studies

Klimoski and Mohammed (1994) carried out an extensive review of the literature concerning the concepts and theories that are related to shared mental models. Two domains are distinguished including collective strategic decision making and team dynamics and performance in which the authors collected a large number of concepts that have in common the idea that information in teams can be processed in a way that exceeds the cognitive capacities of individuals. Various concepts such as group cognition (Bonham, Shapiro, & Heradstveit, 1988), collective cause map (Bougon, Weick, & Binkhorst, 1977), shared problem models (Orasanu, 1990, 1993), teamwork schemas (Rentsch et al., 1994), and collective mind (Weick & Bougon, 1993) were critically reviewed on their proposed definitions, form, and application. In addition, their functions, antecedents, and consequences were described. Klimoski and Mohammed conclude that team mental model-like concepts are very popular, but rather casually used. That is, concepts are rarely clearly defined by researchers. The authors prefer the term team mental model because it restricts the problem domain to teams and it allows for the notion that teams can have common as well as distributed mental models. Although we subscribe this notion, we still prefer the term shared mental model because team mental models do not seem to include important situation knowledge.

Stout et al. (1996) have conceptually examined the relationship between shared mental models, communication, and the development (and maintenance) of team situational awareness. According to
Stout et al., team situational awareness depends on the shared mental models of the team members including declarative, procedural, and strategic knowledge and communication patterns that are referred to as strategizing. When team members enter a task execution session, they have common declarative knowledge that enables them to form a compatible understanding of the mission, task, members' roles, and necessary activities to achieve the task goals. Team members also have shared procedural knowledge that allows them to understand the sequence of task activities that is required to perform efficiently. In changing situations, team members must develop and maintain strategic knowledge that provides them with a common understanding of the operational context, actions that must be taken when unexpected events occur, and the information that should be obtained or exchanged to respond appropriately to the situation. Shared mental models are transformed into team situational awareness, either with or without the process of explicit strategizing, which refers to a communication process in which team members clarify, confirm and disseminate information, plans, expectations, roles, procedures, strategies, and future states. Stout et al. hypothesize that explicit strategizing helps to develop and refine shared mental models and is especially important to develop strategic knowledge. The opportunity for a team to strategize depends on the situation. There are situations when it is possible, when it is not possible, and when it is limited possible. Stout et al. assert that in situations where teams have no opportunities for strategizing, team members must rely on their shared mental models, such that team members coordinate “seamlessly” or implicitly.

The relation between team self-correction, shared mental models, and team processes and performance is theorized by Blickensderfer et al. (1997b). Team self-correction is a process that takes place mostly after a performance session in which team members think about and discuss teammate roles and responsibilities, review events, correct errors, discuss strategies, and make plans for the next time. An example of this self-correction behavior is that of a typical sports team. After finishing the game, team members often discuss the game play-by-play in the bar. This “replay at the bar” allows a team to clarify misunderstandings that occurred, and plan for the next game. Self-correction discussions help to clarify the expectations of the team and the task, which increases task understanding and foster shared knowledge. Because an understanding of each other’s roles is developed, team members have more insight in how to work with each other effectively and coordinate their actions efficiently. In turn, team members adjust their behavior in such way that it meets the needs of their teammates, which improves performance.

Recently, Mohammed and Dumville (2001) have reviewed the research of four different research domains that employ mental model-like concepts in teams. This concerns the research in the domain of information sharing (Stasser & Titus, 1985), transactive memory (Wegner, 1987), collective learning (Brooks, 1994), and shared frames (Mohammed, 1997). According to Mohammed and Dumville, these domains are in the formative stages of research development and have progressed in parallel with little cross fertilization. Therefore, the authors reason that there is much to be gained from integration across disciplinary boundaries. The authors conclude that the various research domains feature different knowledge content domains, such as taskwork, teamwork, and belief systems. Moreover, the concepts reflect varying degrees of emphasis about the definition of shared as overlapping versus distributed or complementary knowledge. Whether team members need common or distributed mental models depends on the domain. Therefore, Mohammed and Dumville emphasize that when researchers employ mental model-like concepts in teams, it must be specified whether the focus is on teamwork, taskwork, or belief structures, and whether an overlapping or distributed notion of sharing is being considered.
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Measurement methods

One problem that complicates the research on shared mental models is the confusion over how to measure cognitive constructs on a team level (Mohammed, Klimoski, & Rentsch, 2000). Recently, several researchers reviewed various techniques and have discussed their applicability in the team domain (Blickensderfer et al., 2000; Cooke, Salas, Cannon-Bowers, & Stout, 2000b; Langan-Fox, Code, & Langfield-Smith, 2000; Mohammed et al., 2000). Because of its multidimensional nature, shared mental model measurement methods include the determination of the knowledge content, the way knowledge is structured or organized, the extent of overlap or distribution of knowledge among team members, and whether knowledge is static versus dynamic.

Knowledge elicitation techniques are used to determine and analyze the knowledge content of mental models (Mohammed et al., 2000). The following eight knowledge elicitation techniques are described in the literature (see, for a detailed description, Langan-Fox et al., 2000):

1. **Observations.** Direct observations can be used to infer team members' mental models during the completion of a task. For example, as an indication of having shared mental models, Entin and Serfaty (1999) used in their experiment the amount of information provided in advance of requests that was observed by subject matter experts.

2. **Interviews and questionnaires.** Several interviewing techniques can be used to elicit knowledge or mental models. Interviews can be transcribed for further analysis and represented in graphs that illustrates the relations between domain concepts. Disadvantages of interview techniques are that they rely heavily on the researcher's interpretation and interviewing abilities, and that it captures only information that can be expressed verbally. Highly structured interviews can take the form of written questionnaires with open questions or multiple choice (Cooke et al., 2000b). Group discussions can be used to elicit team mental models, although a disadvantage is that dominant team members can influence the discussion disproportionately.

3. **Process tracing.** Methods that attempt to collect data during task execution are called process tracing techniques (Cooke et al., 2000b). An example of a process tracing technique is to ask participants to think aloud while performing a task or making a decision. These verbalizations are recorded on audio- or videotape and then transcribed. Another process tracing technique is to collect non-verbal data including keystrokes, actions, facial expressions, gestures, and behavioral events.

4. **Protocol and content analysis.** Protocol analysis involves transcribing verbal data (e.g., obtained from interviews or process tracing), developing a coding schema, and applying this schema to the transcription. Subsequently, frequencies, patterns, and sequential dependencies can be explored (Cooke et al., 2000b). Content analysis is also a method to analyze transcriptions systematically. For this technique, a set of coding rules is used to analyze sentences phrase by phrase and determine important concepts and the relations between them.

5. **Card sorting.** In card sorting, concepts (generated by the researcher or the participants themselves) are written on cards, and participants are asked to sort the cards and position them as to what is closest to what. The assumptions of this technique are that members within a category are closer to a central tendency than others, different situations can lead to different categorizations, and categorization takes place based on participants' naive theories about phenomena in the world.

6. **Repertory grid technique.** The repertory grid technique refers to a procedure in which, first, elements or concepts related to the domain are elicited by interviews. second, these elements are used to elicit dimensions, and, finally, the elements and dimensions are represented in a matrix
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in which the cells are rated. This matrix can be used to determine participants’ pattern of dimensions and knowledge structure by qualitative and statistical methods.

7. Pairwise rating. Pairwise rating involves a technique in which participants are presented with a pair of concepts from a set of concepts. The participants are asked to rate the similarity or relatedness of each pair of concepts. These ratings are transformed into a proximity matrix. In turn, analytical methods such as multidimensional scaling and general weighted networks such as Pathfinder (see below) can use this matrix as input to analyze proximity data.

8. Ordered tree technique. In the ordered tree technique, participants are asked to recall a large, well-learned set of elements many times from a different starting point in the tree. The basic assumption is that participants organize elements into chunks and that the chunks are recalled as units before proceeding with the next one.

Knowledge representation techniques are conceptual methods used to reveal the structure of data or determine the relations between elements that are obtained from participants (Mohammed et al., 2000).

An important difference with knowledge elicitation methods is that these techniques are indirect. Instead of introspection or explicit verbal reports, judgements about conceptual relatedness are required. The following knowledge representation techniques are described in the literature (Mohammed et al., 2000):

1. Multidimensional scaling. Multidimensional scaling generates a spatial representation of the proximity in data such as pairwise estimates of the relatedness for a set of concepts. The basic assumption is that spatial distance can represent psychological distance. Concepts that possess common features or characteristics are located closer in the same space, whereas, within the same space, dissimilar concepts are distant from one another (Langan-Fox et al., 2000). The technique can be used to identify the dimensions that participants use to judge the relatedness between clusters of concepts and the dominance of a particular concept of an individual’s mental model. The ratio between concepts in the same cluster to the mean distance between concepts in different clusters (structural ratio) is used to calculate the strength of dimensions in a mental model.

2. Pathfinder. Pathfinder is a computerized networking technique that transforms paired comparison ratings into a network in which the concepts are represented as nodes and the relatedness of concepts are represented as connections between nodes (Schvaneveldt, 1990). The basic assumption is that the Pathfinder network represents a participant’s mental model of concepts and their relatedness. The relatedness between concepts is represented by the distance between concepts and the number of connections (i.e., the higher the relatedness, the fewer the connections, and the closer the concepts are in the network). The strength is represented by the weights attributed to the connections. An algorithm that finds the shortest path between any two nodes in the network while eliminating paths that violate triangle inequality creates the Pathfinder network (Langan-Fox et al., 2000; Mohammed et al., 2000).

3. UCINET. UCINET is a computerized network analysis program that provides an index of convergence between two matrices (Mathieu et al., 2000). In an experiment, Mathieu et al. (2000) used UCINET. Two matrices were developed that each had nine attributes along the top and side of the grid. One matrix concerned team members’ task mental model and contained task-related attributes. The other matrix concerned members’ team mental model and contained team-related attributes such as coordination and roles. For each cell in the grid team members were requested to rate the relationship between two attributes on a nine-point scale (ranging from negatively related to positively related). With the help of UCINET, Mathieu et al. calculated a correlation between team members’ mental models that served as an index of convergence.
4. **Cognitive mapping.** Cognitive maps are graphic representations that include the content and the structure of participants’ mental models (Mohammed et al., 2000). Various maps can be created depending on the various types of relations (e.g., proximity, contiguity, continuity, resemblance, and so forth). Cognitive maps are often used as follows. Participants are asked to choose from a variety of pre-labeled concepts and place them in a pre-specified hierarchical structure representing knowledge (Marks et al., 2000). Another example is *causal mapping* in which participants determine whether one concept influences the other. If there is a causal relationship, participants are asked to determine for each possible pair of a set of concepts the direction (positive or negative) and the strength (weak, moderate, or strong). A matrix can be obtained in which the existence, direction, and, strength of a relationship are represented (Langan-Fox et al., 2000).

5. **Interaction concept maps.** According to Marks et al. (2000), disadvantages of commonly used mapping techniques are that participants are provided a priori with a fixed map and a limited set of nodes or concepts. Consequently, the only parameter left to vary is the order in which nodes are placed on the map. Furthermore, because the maps of the participants are usually compared to expert maps, the possibility that there may be different yet equally accurate maps is precluded. To overcome such disadvantages, Marks et al. used a technique which they called *team interaction concepts maps*. During an experiment, team members were presented with a map of the performance environment and a large number of concepts that represent different aspects of the task domain. Each member completed a map by selecting 24 pre-labeled concepts they believed best represented the actions necessary to complete the team mission and placed them on the map. A measure of the degree of team mental model similarity was calculated by assessing the overlap in concepts and links. Subject matter experts judged the accuracy of the concept maps.

Measurements on a team level are needed to identify and compare shared mental models. In accordance with the recent ideas that shared mental models contain overlapping as well as distributed knowledge, Cooke et al. (2000b) distinguish between similarity metrics and heterogeneous accuracy metrics.

Similarity metrics measure the extent of similarity, consensus, convergence, agreement, compatibility, or overlap among team members’ mental models. When a questionnaire is used to elicit knowledge, similarity can be measured simply by the number or percentage of responses that are identical for the members of a team. Accuracy, however, is disregarded in this measure (it is conceivable that team members share inaccurate knowledge). Therefore, using the number or percentage of responses that are identical and correct for the members of a team refines this measure by taking accuracy into account. In addition, simple correlation between pairwise ratings for each pair of team members can be used (Blickensderfer et al., 1997c). Output of conceptual methods can also be used to measure similarity. For example, Pathfinder uses a specific network similarity function (NETSIM) to reveal differences in the way knowledge is structured in two different networks. To determine similarity, a ratio is calculated between the number of common connections in two networks and the total number of connections in both networks. Another function of Pathfinder can be used to combine the proximity ratings for all team members to construct an average of a network. Other conceptual methods use parallel means to determine similarity, such as comparisons of concept centrality in UCINET (Mathieu et al., 2000).

Heterogeneous accuracy metrics measure the accuracy of team members' mental models that are associated with their specific roles on a team level (Cooke et al., 2000b). In order to measure heterogeneous accuracy, responses that are associated with the specific roles of team members are added
to calculate a team score. For example, the total number of correct role-relevant responses of each team member are added and used to determine the percentage of the total role-relevant responses.

The difference in measuring static versus dynamic knowledge depends on the rate of change that refers to the speed with which knowledge changes (Cooke et al., 2000b). Especially in rapidly changing situations, the mental models of the team members may change rapidly and the question arises how to measure this. One method to investigate dynamic knowledge is to measure this at discrete points in experimental sessions (Mathieu et al., 2000). The disadvantage of this approach is that teams are repeatedly interrupted in their task performance. Another problem is that during the process of eliciting knowledge, team members’ thought processes may also be stimulated. This may refresh their knowledge that, in turn, affects their task performance, which would not have been affected without knowledge elicitation.

Shared mental models as an explanatory construct

In the earlier work on shared mental models, the construct was employed post-hoc to explain performance in teams. Kleinman and Serfaty (1989) reviewed a study of Kohn, Kleinman, and Serfaty (1987) that employed a low-fidelity command and control simulation task in which two-member teams were required to destroy enemy threats with limited resources. The results of this study show that although the communication was greatly reduced, team members were able to keep up the performance in a high workload situation, compared to a low workload situation. Based on a communication analysis, the authors concluded that there was little explicit coordination, and team members provided each other the necessary information and resources in advance of requests of teammates. According to Kleinman and Serfaty, these team members had shared mental models that allowed them to coordinate implicitly.

Based on studies in a full-mission simulated flight, Orasanu (1990, 1993) employed the shared mental model concept to explain post-hoc communication differences between high and low performing teams. Effective teams (in terms of fewer flight errors) engaged in more task-oriented communication including the formulation of plans and strategies. The author reasons that this type of communication is especially beneficial when teams are confronted with problems that cannot be solved easily. Team members must communicate to develop a shared mental model of the problem that ensures that all members are solving the same problem. This provides a context in which communication can be interpreted, and a basis for developing accurate explanations and expectations of the behavior and needs of other team members.

Empirical investigations

Volpe et al. (1995) employed a simulated air combat task for two team members. In total, 40 teams participated in the experiment. Team members were cross-trained by a brief verbal instruction. The purpose of cross training was to provide team members with knowledge of each other’s tasks, roles, responsibilities, and team members’ informational needs (referred to as IPK by Blickensderfer et al., 1998b; Cannon-Bowers et al., 1998; Volpe et al., 1995). The results show that teams that received a cross training performed better than teams that received no cross training. The prediction that this performance increase would have been most pronounced during high workload periods, however, did not receive support. According to Volpe et al., this was probably due to the relatively high workload in so-called low workload periods, which resulted in a small difference between high and low workload periods. A rating scale was used to measure teamwork such as coordination and performance monitoring. The expectation that cross-trained teams would exhibit higher ratings than teams that are not cross-trained received support. Volpe et al. expected also that cross-trained teams would
communicate more appropriately (i.e., more volunteering of information and acknowledging comments of teammates, and less requesting of information and providing task irrelevant remarks). The communication results, however, were mixed. Although cross-trained team members provided more information in advance of requests, they also made more irrelevant remarks than teams that were not cross-trained. In addition, there were no differences between the training conditions in the number of acknowledgements or requests.

To extend and replicate the Volpe et al. (1995) study, Cannon-Bowers et al. (1998) also employed cross training to manipulate shared mental models. The task was replaced by the TANDEM task that incorporated higher levels of interdependency and need for interaction among team members. In addition, team members received actual “hands-on” training in each other’s task, from which Cannon-Bowers et al. contended that this is more appropriate for tasks with high levels of team member interdependence. Finally, questionnaires were used to measure team members’ IPK as a part of their shared mental models. IPK was measured objectively, to ensure that team members in the cross training condition gained knowledge of their teammates’ tasks, and subjectively to tap team members’ impression of how well they understood the roles and tasks of their teammates and what was expected of them in performing the task. The task was performed by 40 three-person teams. Team members that received cross training reported higher IPK levels on both questionnaires, provided more information in advance of requests, and performed better than team members that received no cross training. In addition, these results were more pronounced during high workload periods. Cannon-Bowers et al. concluded that cross training fosters implicit coordination. However, the mediating role of IPK was not demonstrated given the lack of correlation between IPK and the provision of information in advance of requests. Even more surprising was the lack of a significant correlation between the subjective IPK measure and all other measures. Only objective IPK explained 10% and 16% of the variance in team performance and team process scores, respectively, but was not correlated at all with the provision of information in advance of requests.

Schaaftal and Bots (1997) employed three cross training methods to investigate their effect on team performance (i.e., a written instruction about the tasks of the teammates, practice in each others tasks added to the written instruction, and a written instruction with explicit information about the interdependency among team members). The TANDEM task was used in which 24 three-person teams participated. Only a performance increase (measured by several indicators such as the number of accurate course of actions or decisions made) was found for the teams that received explicit information about the interdependency among team members. These teams also communicated more efficiently by providing each other more often relevant information without being asked first. Moreover, this explained 80% of the variance in team performance. According to Schaaftal and Bots, having knowledge of the interdependencies of team members’ tasks and each other’s informational needs improves team performance. Nevertheless, merely practicing in each other’s tasks is insufficient to achieve this knowledge.

McCann et al. (2000), also using the TANDEM task, hypothesized that teams whose members explicitly experience all team positions will perform better under time pressure. The experiment involved three team training sessions, followed by three time-stressed exercise sessions. In total, 30 three-person teams participated in the experiment. During training, one group of teams was cross-trained by asking each member to perform an entire session at each of the three team positions. The results show that, during training, the performance of the noncross-trained teams improved more quickly than that of the cross-trained teams. During the exercise, the cross-trained group did not achieve the level of performance of the control teams. In addition, the cross-trained group did not outperform the control group on any of
the process measures. The authors speculate that the cross-trained team may indeed have acquired improved team interaction skills, but these may have come at the expense of poorer taskwork skills. In our opinion, other explanations are also possible. Consistent with the results reported by Schaaftal and Bots (1997), merely training each member at each of the three team positions, even while performing the task as a team, is not sufficient for getting to know the teammates’ informational needs.

Minionis et al. (1995) investigated the relationships between mental model similarity, coordination and communication behaviors, and performance. The authors used a low-fidelity tank battle simulation called the Team Wargame Interaction Simulation Training (TWIST) in which 96 three-person teams participated. The goal of this task was to defeat enemy assets while preserving the own assets. In order to develop shared mental models, two training strategies were employed. First, the presentation of specific information about the roles and responsibilities of team members, and, second, team training instead of training in an isolated setting. The similarity between team members’ mental models concerning team interactions was measured using a cognitive mapping technique. Frequency ratings in seven categories (i.e., operational planning, contingency planning, execution, group regulation, feedback, information exchange, and task irrelevant communications) were used to score the communication. The results show that teams that received specific team interaction information had greater mental model similarity than teams that did not receive such information. However, teams that received team training had no greater mental model similarity than the teams in which team members were trained individually. The results show further that the degree of similarity in mental models was positively correlated to team coordination (measured by the average distance between tanks) and performance (measured by the extent of achieving the task goals). Contrary to the expectations of Minionis et al., communication was not influenced by the degree of mental model similarity. Minionis et al. hypothesize that although the frequency of communication types may not be influenced by shared mental models, the pattern of occurrence might vary across different phases of team performance. However, the lack of relationship might also be due to the communication categories chosen. It is not clear how shared mental models are related to those categories.

The relationship between team self-correction, implicit coordination, and team performance was investigated by Blickensderfer et al. (1997c). The authors hypothesized that team members that engage in team self-correction would exhibit higher overlap in their expectations concerning team roles, strategy, and communication. The TANDEM task was used in which 40 teams of three members participated. In one condition, teams received a team self-correction training that consisted of a lecture about what team self-correction is and how it works in the context of a basketball team. In the control condition, team members received general information and exercises that were not related to the TANDEM task, but gave team members the chance to interact with each other in the same amount as the teams that received self-correction training. Observers scored whether teams engaged in team self-correction behaviors such as step-by-step task reviews or bringing up issues and observations. This manipulation check showed that teams that received team self-correction training exhibited more self-correction behaviors than teams that received no such a training. The degree of overlap in expectations was measured by a 45-item questionnaire concerning team roles, team strategy and communication patterns. Agreement coefficients were calculated for each pair of team members and the average of the three coefficients was the degree of overlap in expectations. The results show that teams who were trained to self-correct, developed higher degrees of agreement on expectations and demonstrated more implicit coordination (measured by the amount of information provided in advance of requests) than the control teams. However, there were no performance differences between the conditions. Team expectation scores were positively correlated to implicit coordination and performance, and implicit coordination was moderately correlated to team performance. Whether the relationship between team
self-correction training and team performance was mediated by team expectations could not be tested because performance did not improve as a result of team self-correction training.

In two other studies, Blickensderfer and her colleagues investigated the relationship between overlap in team members’ expectations and knowledge structures and performance (Blickensderfer, Cannon-Bowers, & Salas, 1997a; Blickensderfer et al., 1998b). In the first study, TANDEM was used in which 20 three-person teams participated. The overlap of expectations was measured using the same expectation questionnaire as used in the Blickensderfer et al. (1997c) study. To measure knowledge structures, Pathfinder was used. In total, 22 concepts concerning team members’ roles, informational needs, and communication patterns were selected. Pairwise similarity ratings were obtained from each participant. Contrary to what Blickensderfer et al. expected, the results showed no (positive) relationship between the overlap in expectations as well as knowledge structures and performance. According to Blickensderfer et al., one explanation for the lack of relationship is that the concepts chosen for the expectations questionnaire and Pathfinder assessment were more related to general task knowledge (and thus less important to share) than to team interaction knowledge. Another explanation provided by Blickensderfer et al. is that the relationship between the overlap in knowledge structures and performance is mediated by team members’ skills to perform teamwork accurately. Although team members may have overlapping knowledge structures, they also must take advantage of this knowledge by using efficient and effective team strategies such as implicit coordination. However, team processes were not measured in this experiment.

In the second study, Blickensderfer, Cannon-Bowers, and Salas (1998a) investigated 12 teams that played the game tennis doubles during an intramural tennis tournament. The authors hypothesized that the greater the degree of overlap in team members’ expectations, the better the performance. Overlap in expectations was measured by a 45-item questionnaire that was modeled after the one described in the former paragraph (Blickensderfer et al., 1997c). Teammate similarity on the questionnaire was correlated between the two partners that determined the shared expectation score. To test the hypothesis, a correlation was calculated between the team expectation score and the teams tournament ranking. The results show a moderate negative relation between team shared expectations and team tournament rank, which indicates that the greater the degree of shared expectations, the lower (and thus the better) the numeric rank. Shared expectations accounted for 48% of the variance in team performance in the tournament.

In another study, Blickensderfer (2000) also investigated teams that played the game tennis doubles. Blickensderfer hypothesized that previous experience fosters shared knowledge and that shared knowledge has an indirect influence on team performance via its influence on team processes. Participants were 80 two-person teams that had experience with the game double tennis. Team experience was divided into two aspects: task skill, that is experience with the task in general, and team familiarity, that is experience with a particular team. Task skill was measured by asking participants to provide their skill level according to a national standard for tennis ratings. Team familiarity was measured using a questionnaire in which team members had to indicate how long they played together as a team. Shared knowledge of each other’s roles, responsibilities, and interactions was measured by a 45-item questionnaire that was modeled after the shared expectations questionnaire used by Blickensderfer et al. (1997c). Another 48-item questionnaire was used to measure the knowledge of each other’s characteristics. Team processes were measured by two trained raters that used a rating system. One of the team processes measured was the relative position of team members, which is the degree to which teammates adjust and adapt their positioning with respect to each other during team performance. According to Blickensderfer (2000), this behavior is an example of implicit coordination.
The results show that the degree of team familiarity was positively related to team members' knowledge of roles and responsibilities. In turn, this was positively related to team processes. However, no support was found for the relationships between knowledge of teammate characteristics and team processes, and team processes and performance.

Stout et al. (1999) investigated shared mental models in relation to team planning behavior and implicit coordination among team members. Based on a literature review, Stout et al. identified nine important planning dimensions including setting goals, clarifying each team member's roles and responsibilities, sharing information, and anticipating on how to deal with high workload and unexpected events (e.g., by making agreements about backing each other up). The authors hypothesized that these types of planning behaviors foster shared mental model development. In an experiment, 40 students performed a laboratory task that consisted of a low-fidelity flight simulation (teams consisted of four members: two participants and two experimenters). The results show that team-planning behavior allowed teams to use more efficient communication strategies under conditions of high workload. Teams that were rated as higher in quality of their planning had also better shared mental models of each other's informational requirements and improved their performance. Teams high in planning, provided more information in advance during high workload periods, and teams that provided information in advance of requests during high workload periods also performed better. However, teams with better-shared mental models did not provide more information in advance of requests during high workload periods, contrary to what was predicted. Therefore, better planning directly influenced communication and performance, independent of shared mental models.

Entin and Serfaty (1999) investigated the way teams adapt to stressful situations by using effective coordination strategies. The authors theorized that teams draw on their shared mental models of the team and situation to shift to modes of implicit coordination and thereby reduce coordination overhead. A specific team training procedure was designed to train teams to adapt to high workload by shifting from explicit to implicit modes of coordination. In teams of five, 59 naval officers and one civilian completed a relatively realistic simulation of anti-air warfare tasks in a battleship command center. The results showed that the adaptation training improved performance when compared to teams that did not receive such a training (a specific index for anti-air warfare was used to measure performance). In addition, the adaptive training improved various team processes including coordination. Teams that received the adaptive training provided more information in advance of requests than teams that did not receive the adaptive training. According to Entin and Serfaty, teams that received the adaptation training reduced their coordination and communication overhead, and thereby had more time and cognitive resources to devote to the task. This resulted in a better performance.

Mathieu et al. (2000) investigated the influence of team members' shared mental models on team processes and performance using a low-fidelity simulation of a flight combat for two members. The objective of the study was to investigate whether mental model convergence develops over time, and whether this influences team processes (including coordination and information sharing behaviors) and performance (in terms of completing the mission). In three subsequent experimental sessions, 56 two-person teams participated. Observers rated team processes using a 21-item list to measure three dimensions: strategy formation and coordination, cooperation, and communication. Mathieu et al. made a conceptual distinction between mental models of the team (e.g., roles, responsibilities, interaction patterns, interdependencies, and team members' characteristics) and the task (e.g., equipment, task procedures, task strategies, and environmental constraints). The results show that team processes as well as performance increase over time. However, team members' mental models show no greater convergence after some time. The results further show that team-mental model convergence was
positively related to team processes and performance. These relations were not found for task-mental model convergence. A detailed analysis further shows that the relationship between team mental model convergence and team performance was fully mediated by team processes. Mathieu et al. conclude that the results of this study support the construct validity of shared mental models. The similarity of knowledge structures between two team members can predict the quality of team processes and performance.

The effect of mental model similarity and accuracy on team processes and performance is investigated by Marks et al. (2000). TWIST was used in which 79 three-person teams participated. During the experiment, team members were presented with three performance sessions (i.e., one routine, and two novel sessions). To develop shared mental models, two methods were employed. First, enriched leader briefings that consisted of information about the identification of significant risks and how to deal with those risks, identification of opportunities on the battlefield, and prioritization of actions. Teams in the control condition received briefings that consisted of information about the mission goals only. Second, team interaction training that consisted of an instruction of how to interact effectively as a team. Teams in the control condition received the same task information, but team interaction methods were not included. Mental model similarity and accuracy was measured using team interaction concept maps. The quality of the team processes was judged by subject matter experts that analyzed the communications by rating the following dimensions: assertiveness, decision making and mission analysis, adaptability and flexibility, situational awareness, leadership, and communications.

The results show that teams that received enriched leader briefings or the team interaction training had greater similar and more accurate mental models than the control teams. These effects, however, were not more pronounced in novel situations. Furthermore, the combination of the two mental model development methods (i.e., leader briefings and team interaction training) had no additional effects. The expected positive relation between mental model similarity and the quality of the team process was also supported by the results. However, the expected positive relationship between mental model accuracy and the quality of team processes was not supported by the results. The results show further that for teams with less accurate mental models, the relation between mental model similarity and team processes is stronger than for teams with accurate mental models. There was no support for the hypothesis that these effects would be more pronounced in novel situations. Marks et al. (2000) speculated that in familiar situations team performance might improve when members have both similar and accurate mental models. However, in novel situations, as long as team members are in sync with their teammates, they do not have to depend on a priori developed mental models concerning strategies. Marks et al. speculate that in the end team members adjusted their mental models or formed new ones that were geared to the novel elements in the situation (and, thus, were more accurate). Finally, the results show that mental model similarity and accuracy, as well as team processes were positively related to team performance. The results show further that when teams had less accurate mental models there was a stronger positive relation between mental model similarity and performance than when teams had accurate mental models. Marks et al. also performed an analysis to test whether team processes fully mediated the influence of mental models similarity and accuracy on performance. The result of this analysis was that that the influence of team mental model similarity and accuracy on team performance was partially mediated by team processes.

Instead of using an experimental team task, a different approach was employed by Rentsch et al. (1994). Those authors hypothesized that team members with different levels of team experience have different understandings of the teamwork process. Therefore, they made a comparison between high and low scoring individuals on a team experience test. Using multidimensional scaling techniques and free hand
concept maps, Rentsch et al. found that experienced individuals showed greater consistency across the two different schemas representations than less experienced individuals. Rentsch et al. conclude that this consistency suggests that more experienced individuals generalize their teamwork knowledge to new team situations.

2.3.3 Summary and conclusions shared mental model theory

So far, we described the theory concerning knowledge and shared mental models in teams and the research that is conducted. Given this description, what can we conclude with respect to the shared mental model theory? When reviewing the studies, this question is not easy to answer. The problem is that researchers have not been consistent in the way shared mental models are defined, developed, and measured. Different methods are used to measure team processes and different researchers highlighted different relationships. In order to put some order in this state of affairs, we developed a model in which the relationships between shared mental models, antecedents of shared mental models, team processes, and performance are illustrated.

![Figure 2.2: Shared mental model dimensions and relationships](image)

The model depicted in Figure 2.2 represents the theoretically important relationships (i.e., Relationship 1, 2, 4, and 6) as well as statistical relationships (i.e., Relationship 3 and 5). With the help of this model, we have tried to determine systematically which dimensions are hypothesized and which relationships received empirical support. Toward this end, we made an overview of the type of antecedents, shared mental models, and team processes investigated. Subsequently, for each relationship we indicated whether it received empirical support. The overview can be found in Table 2.3.

Antecedents, shared mental models, team processes, and performance (Relationship 1 to 3)

Several antecedents are investigated in relation to shared mental models, team processes, and performance (Relationship 1 to 3). Most researchers employed particular team training methods to develop shared mental models and investigate their effect on team processes and performance (Blickensderfer et al., 1997c; Cannon-Bowers et al., 1998; Entin & Serfaty, 1999; Marks et al., 2000; McCann et al., 2000; Minionis et al., 1995; Schaafstal & Bots, 1997; Volpe et al., 1995). The main purpose of these training methods is to provide team members with team knowledge such as knowledge of each other’s tasks, roles, responsibilities, and informational needs.
Cross training is the most used team training method. There are different types of cross training, varying from simply providing team members with information about the tasks of the teammates, to positional rotation in which team members actually perform each other's tasks. None of the studies that investigated cross training have measured shared mental models directly. Thus, the hypothesized relationship between cross training and shared mental models is not established. One study measured IPK as a part of shared mental models and related this to cross training (Cannon-Bowers et al., 1998). Team members that were cross-trained not only had higher levels of objective IPK, but also had the impression that they understood the roles and tasks of teammates more clearly (subjective IPK). Therefore, cross training results in higher levels of team knowledge. Whether cross training influences mental models or the sharedness of mental models has not been investigated.

What relationships are established between cross training and team processes? The studies of Cannon-Bowers et al. (1998) and Volpe et al. (1995) showed that cross training is positively related to teamwork. Implicit coordination is usually measured by the provision of information in advance of requests. All studies that measured this, showed that team members that received cross training provided more information in advance of requests than team members that did not receive such a training (Cannon-Bowers et al., 1998; Schaufel & Bots, 1997; Volpe et al., 1995). Implicit coordination also implies that team members communicate more efficiently. Therefore, McCann et al. (2000) expected that the number of utterances would decrease as a result of cross training. However, this hypothesis was not supported. Whether teams received cross training or not, the number of utterances remained the same. Other researchers rated communication in several categories (such as the number of requests or irrelevant remarks) from which it was expected that cross training would result in less communication in those categories (Cannon-Bowers et al., 1998; Schaufel & Bots, 1997; Volpe et al., 1995). However, this was also not supported by the results. The number of irrelevant remarks in the study of Volpe et al. (1995) was even unexpectedly higher.

The results show an equivocal picture with respect to the relationship between cross training and performance. The Cannon-Bowers et al. (1998) and Volpe et al. (1995) studies showed that performance increased when team members were cross-trained. However, Schaufel and Bots (1997) found that merely training in each other’s tasks (i.e., positional rotation) did not result in an improved performance unless team members were explicitly instructed about the informational interdependencies between each other’s tasks. In the study of McCann et al. (2000), cross-trained teams even performed worse than teams that were not cross-trained. It is possible that the different methods that were used resulted in different performance outcomes. However, in three studies (Cannon-Bowers et al., 1998; McCann et al., 2000; Schaufel & Bots, 1997), positional rotation was used and the expected performance increase was only found in one study (Cannon-Bowers et al., 1998). One explanation for this mixed result is that positional rotation may not provide team members with the knowledge needed to improve team performance. According to Schaufel and Bots, positional rotation may support the development of team members’ knowledge concerning each other’s tasks, however, this is not enough to coordinate implicitly. Team interaction knowledge is also important. Schaufel and Bots found that teams that received explicit instructions about the informational interdependencies, performed better than team members who were trained in each other’s tasks. The authors speculated that explicit instructions provided team members with more specific team interaction knowledge than positional rotation does.
<table>
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<tr>
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<th>4</th>
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| Blickensderfer et al., 1997a | • Overlap in expectations  
• Knowledge structures |                                                                 |                                                   |   |   |   |   |   | 0 | No correlation between expectations and knowledge structures |
| Blickensderfer et al., 1998a | Overlap in expectations (team roles, strategy, communication patterns) |                                                                 |                                                   |   |   |   |   |   | + | Relationship 3: performance double tennis |
| Blickensderfer, 2000   | • Task skill experience  
• Team familiarity  
• Team knowledge  
• Members' characteristics |                                                                 | Team behavior indicating implicit coordination | 0/+ | + | + | 0 | + | 0 | Task skill experience/ team familiarity |
| Stout et al., 1999     | Quality of team planning                            | Mental model overlap (team interaction model)                 | Providing information in advance of requests       | + | + | + | 0 | + |   |                                              |
| Entin and Serfaty, 1999 | Adaptive team training                             | • Teamwork  
• Providing information in advance of requests            |                                                   | + | + |   |   |   |   |                                              |
| Mathieu et al., 2000   | Team experience                                    | • Task mental model  
• Team mental model (mental model convergence)                 | Teamwork                                          | 0 | 0 | + | + | 0 | 0 |                                              |
| Marks et al., 2000     | • Enriched leader briefings  
• Team interaction training  
• Mental model similarity  
• Mental model accuracy (team interaction model) |                                                                 | Teamwork (by rating communication)                | +/+ | +/+ | + | 0 | + | + | Enriched leader briefings/ team interaction training |
| Rentsch et al., 1994   | Team experience                                    | Mental model consistency (general teamwork behaviors)         |                                                   | + |   |   |   |   |   |                                              |

*Note:* The antecedents are listed in the first column. The second column describes what types of shared mental models are measured. Team processes are described in column three. Empty cells mean that there are no antecedents, shared mental models, or team processes present or measured. Performance was measured in all experiments. Hence, no column for performance is provided. For each relationship it is indicated whether a positive (+), negative (-), or no (0) relationship (although predicted) was found.
In contrast to the other cross training studies, in the study of Cannon-Bowers et al. (1998) positional rotation had a positive effect on performance. Cannon-Bowers et al. performed a manipulation check which showed that team members that received positional rotation had higher levels of IPK (including team interaction knowledge) than team members that received no positional rotation. Differences among the cross training studies may be explained by the training procedure used. In the Cannon-Bowers et al. study, team members had to perform each other's tasks as long as it took to reach a certain performance level, whereas in the Schaalstal and Bots (1997) study, team members' training time was fixed. It is therefore possible that the teams of the Cannon-Bowers et al. study were better trained in each other's tasks and had more team interaction knowledge, resulting in a better performance. Another explanation is that although cross training may lead to higher levels of team knowledge, this is at the expense of individual taskwork skills. McCann et al. (2000) speculated that this accounted for their finding that cross-trained teams performed even worse than teams that received no cross training. Taken together, merely training in each other's tasks does not guarantee improved performance. The cross training studies indicate that team members need to be fully trained in their individual taskwork, and cross training must, besides knowledge of each other's tasks, also improve members' team interaction knowledge.

Besides cross training, other types of team training are employed to develop shared mental models. In two studies, team members received information about how to interact effectively as a team. The expectation that team interaction information would result in more similar team interaction models received support (Marks et al., 2000; Minionis et al., 1995). Moreover, Marks et al. (2000) found that team members had not only more similar models, but also had more accurate models. Note that the team interaction training methods used by Marks et al. and Minionis et al. (1995) are practically identical to the explicit instruction method used by Schaalstal and Bots (1997). Minionis et al. also compared teams in which the members were trained individually with members that were trained in a team setting. However, this had no effect on the similarity in members' team interaction models. Blickensderfer et al. (1997c) showed that team members that received self-correction training had more overlap in their expectations concerning team roles, strategy, and communication. In sum, these studies support the hypothesis that particular team training methods positively influence mental model similarity and accuracy among team members.

What relationships are established between the above-described team training methods and team processes? Minionis et al. (1995) did not directly test whether team interaction training resulted in differences in team processes. Entin and Serfaty (1999) and Marks et al. (2000) showed that team training resulted in better teamwork behaviors (measured by a general teamwork scale). In two studies, implicit coordination was measured by the provision of information in advance of requests. Entin and Serfaty found that team members that received the adaptive team training provided more information in advance of requests than team members that did not receive such a training. Blickensderfer et al. (1997c) obtained the same results using a team self-correction training. These findings show that particular team training methods have a positive effect on teamwork including implicit coordination. The relationships between these team training methods and team performance, however, are not straightforward. Marks et al. and Minionis et al. did not directly test the relationship between team interaction training and performance. Team self-correction training did not result in improved performance (Blickensderfer et al., 1997c), whereas the adaptive team training did (Entin & Serfaty, 1999). Thus, although particular team training methods improve team members' teamwork and implicit coordination, it is not said that this improves performance as well.
Besides the training methods mentioned, few studies have investigated other antecedents and their relationships with team processes and performance. Stout et al. (1999) investigated planning behaviors and found that team members that were higher in team planning had greater overlap in their team interaction models, performed better, and provided more information in advance of requests. In two other studies, the effect of team experience was investigated. In the first study, team members gained their experience during three experimental sessions (Mathieu et al., 2000). In the second study, a team experience measure was used to differentiate between individuals with high and less experience in teamwork (Rentsch et al., 1994). In both studies it was expected that the higher the experience, the more team members’ mental models would be similar. The difference is that in the first study, team members could develop specific task-related mental models, whereas in the second study, mental models could only be related to general teamwork behaviors. Mathieu et al. (2000) found no differences in mental model convergence in both the team and task model as a result of executing tasks during the experimental sessions. Nevertheless, performance increased over time. Rentsch et al. (1994) found that experienced individuals showed greater consistency in their teamwork conceptualizations than less experienced individuals. Finally, Marks et al. (2000) used leader briefings to provide team members with information concerning the situation (e.g., significant risks, solutions, and opportunities). Note that this is the only study in which it is attempted to provide team members, besides team interaction knowledge, with situation knowledge. Marks et al. found that team members that received the enriched leader briefing had more similar and accurate team interaction mental models.

Shared mental models, team processes, and performance (Relationship 4 to 6)

What is the empirical support for the relationships between shared mental models, team processes, and performance (Relationship 4 to 6)? There are several problems in answering this question. First, the shared mental model construct is employed differently across the various studies. Second, researchers have not always been very precise in defining shared mental models and how they affect team processes. Third, the content and type of knowledge or mental model is measured with various methods, which makes it difficult to determine whether the same construct is measured among the different studies. Finally, the relationship of knowledge or mental models with team processes and performance is investigated in different ways. Whereas in some studies relationships are investigated with knowledge team members individually hold (Cannon-Bowers et al., 1998), in other studies these relationships are investigated with the similarity or accuracy of mental models among team members (Marks et al., 2000; Mathieu et al., 2000; Minionis et al., 1995; Stout et al., 1999). Taken together, it is difficult to compare the studies and obtain a coherent picture of the empirical support.

With respect to the knowledge content, researchers have investigated mainly team knowledge. In the studies in which shared mental models were measured, researchers investigated IPK (Cannon-Bowers et al., 1998), team interaction models (Marks et al., 2000; Minionis et al., 1995; Stout et al., 1999), team roles, strategy, and communication patterns (Blickensderfer et al., 1997a, 1997c, 1998a), and team mental models (Mathieu et al., 2000). In the studies in which shared mental models were not measured, the amount of information provided in advance of requests is often regarded as an indicator of having team knowledge (Entin & Serfaty, 1999; McCann et al., 2000; Schaalstal & Bots, 1997; Volpe et al., 1995). Whereas in most studies team knowledge is investigated, situation knowledge is practically neglected. Although situation knowledge or, in terms of Orasanu (1990, 1993), shared problem models are assumed to be important especially in changing or novel situations, there are no empirical studies that addressed this type of knowledge.

Another problem with respect to the knowledge content is that team knowledge is rather broadly defined. In none of the studies a distinction is made between the team knowledge elements such as we
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described in section 2.3.1 (see Table 2.2). Thus, the effect and the contribution of each element to team processes and performance is not clear. Consequently, effects can only be related to more general descriptions of team knowledge. An exception is the study of Mathieu et al. (2000), in which a distinction is made between task and team knowledge. This study shows that such a distinction in knowledge content is important because task and team knowledge had different effects on team processes and performance. Whereas convergence in team knowledge was positively related to team processes and performance, convergence in task knowledge was not related at all. This shows that it is important to investigate in more detail the effect of specific knowledge elements on team processes and performance.

None of the studies made an explicit distinction between knowledge types (i.e., declarative, procedural, and strategic knowledge). In general, when shared mental models were measured, this is described in terms of the knowledge content as described above. Consequently, no conclusions can be drawn concerning the relative contribution of each type. Based on the methods to develop shared mental models we can derive which type of knowledge is investigated. The training methods provide team members with declarative as well as procedural knowledge. It is possible that the performance differences among the cross training studies can be explained by type of knowledge that is learned. That is, cross training must provide team members not only with declarative knowledge, but also with procedural knowledge. In other words, team members must be trained long enough to translate declarative knowledge into procedural rules. This may explain why, in contrast to the other cross training studies, in the study of Cannon-Bowers et al. (1998) positional rotation resulted in a performance increase. It may also explain why explicit instructions concerning team interactions or interaction training are relatively successful. Those methods may be more geared to team members' procedural knowledge.

Almost all studies have focused on team knowledge that could be trained or learned before task execution. An exception is the study of Mathieu et al. (2000) in which team members had to perform three task execution sessions in succession. In this study, mental model convergence was measured after each session. Presumably, team members developed during task execution, besides declarative and procedural knowledge, strategic knowledge. Nevertheless, there were no explicit measures of strategic knowledge. A problem with strategic knowledge is the measurement methods. In most studies, shared mental models are measured by similarity ratings and questionnaires as elicitation techniques (Cannon-Bowers et al., 1998), and Pathfinder (Stout et al., 1999) and UCINET (Mathieu et al., 2000) to represent the knowledge. The disadvantage of these methods is that they are mostly geared towards declarative knowledge, and less toward procedural and strategic knowledge. These measures do not tap knowledge in the dynamic task environment. Instead, they focus on pre-task performance knowledge.

Apart from the knowledge content and type, the question is whether researchers attempted to measure knowledge or mental models. Most studies claim that they have measured mental models. Exception is the study of Cannon-Bowers et al. (1998) that investigated IPK that can be viewed as a part of the shared mental model that refers to the individual knowledge team members have about each other tasks, roles, responsibilities, and informational needs. The advantage to limit oneself to individual knowledge is that questions whether knowledge is organized in a mental model and whether this is shared among members do not have to be answered. Nevertheless, only small parts of the shared mental model construct are investigated. The studies that claim that they investigated mental models used knowledge representation techniques such as cognitive mapping techniques (Marks et al., 2000; Minionis et al., 1995), Pathfinder (Stout et al., 1999), and UCINET (Mathieu et al., 2000). The basic assumption that
underlies these methods is that the representations (e.g., concept maps, links between concepts) represent team members’ mental models.

The discussion whether the sharedness of mental models must be interpreted as having in common, distributed, or both, cannot be resolved based on the empirical research so far. None of the studies made an explicit comparison between teams in which the same knowledge content is distributed differently among members. Most studies investigated the effect of mental model similarity on team processes and performance. An indication that the similarity of mental models might be more important for team processes is provided by the study of Marks et al. (2000). Whereas in this study mental model similarity was positively related to effective teamwork, mental model accuracy was not related to effective teamwork. Moreover, the less accurate the mental models, the stronger was the relationship between similarity in mental models and effective teamwork. Marks et al. concluded that mental model similarity is more important for team performance than accuracy. Nevertheless, they hypothesized also that, especially in novel situations, team members with similar mental models are, eventually, more able to form more accurate mental models.

Although the Marks et al. (2000) study might indicate that mental model similarity is important, the Cannon-Bowers et al. (1998) study showed that when team members individually have better IPK this also results in better performances. This might indicate that it is not necessarily needed to have commonly held knowledge as long as each team member has enough knowledge of each other’s tasks, roles, responsibilities, and informational needs. However, the correlations between IPK and teamwork and performance were weak and were even missing with respect to the provision of information in advance of requests. It is possible that although teams had better IPK, they also need a certain overlap to improve their teamwork and to coordinate implicitly. Taken together, although most researchers advocate the importance of similarity in mental models, more work is needed to determine which knowledge must to be overlapping and which must be distributed among team members.

What relationships between shared mental models and team processes received empirical support? In most studies, it is hypothesized that similarity in mental models improve team processes and performance (Blickensderfer et al., 1997a, 1997c; Marks et al., 2000; Mathieu et al., 2000; Minionis et al., 1995; Stout et al., 1999). When team processes are measured by using general teamwork scales, this hypothesis received support (Marks et al., 2000; Mathieu et al., 2000). A disadvantage of using general teamwork measurements is, however, that it is not clear which type of teamwork is affected by shared mental models. Moreover, it is not clear how shared mental models affect this teamwork. Although the effect of shared mental models on implicit coordination (and therefore communication) is theorized at length, the effects on other teamwork elements are less clearly theorized.

In several studies, team processes are measured by analyzing the communication (Blickensderfer et al., 1997c; Cannon-Bowers et al., 1998; Marks et al., 2000; Mathieu et al., 2000; Minionis et al., 1995; Stout et al., 1999). The communication is often analyzed by rating the provision of information in advance of requests to find out whether teams engage in implicit coordination. Stout et al. (1999) found no relationship between shared mental model similarity and the provision of information in advance of requests. Blickensderfer et al. (1997c), however, found a moderate relationship between shared expectations and the provision of information in advance of requests. These mixed results can be explained by the differences in mental models measurement. Blickensderfer et al. used a questionnaire in which team members were asked what their expectations are concerning the activities of the teammates. Stout et al. used a knowledge representation technique in which team members were asked to rate how a pair of concepts is related to each other. Pathfinder was used to transform the ratings into a network representation and calculate an index to test the similarity between two networks. In other
words, whereas Blickensderfer et al. measured the hypothesized result of a shared mental model, namely expectations. Stout et al. measured the mental model itself. It is possible that team members in the Stout et al. study were not able to benefit from their shared mental models and develop shared expectations.

Another possibility is that the provision of information in advance of requests may be one indicator of implicit coordination, but not the only one. Other indicators are also no communication to coordinate or strategize and the provision of relevant information on the moment in a team member's task sequence when this is needed. Based on this we expect that team members will communicate less, have fewer requests, and provide each other necessary information in time. To be better able to measure implicit coordination, other measurements of the communication are needed including the total amount, timeliness, the number of questions, and the information provided in advance of requests.

In several studies, researchers have correlated shared mental model measurements to performance (Blickensderfer et al., 1997c; Cannon-Bowers et al., 1998; Marks et al., 2000; Mathieu et al., 2000; Minions et al., 1995; Stout et al., 1999). Although the shared mental model theory states that this relationship is fully mediated by team processes, only one study found support for this statement (Marks et al., 2000). In a few studies, correlations were calculated to investigate the relationship between teamwork and performance (Cannon-Bowers et al., 1998; Marks et al., 2000; Mathieu et al., 2000). The results are mixed. Whereas in the studies of Marks et al. (2000) and Mathieu et al. (2000) teamwork was positively related to performance, Cannon-Bowers et al. (1998) found no relationship between teamwork and performance. Correlations were also calculated to investigate the relationship between the provision of information in advance of requests and performance (Blickensderfer et al., 1997c; Cannon-Bowers et al., 1998; Marks et al., 2000; Mathieu et al., 2000; Schaalstal & Bots, 1997; Stout et al., 1999). With the exception of the Cannon-Bowers et al. study, in all studies this relationship was positive.

2.4 Conclusions

The review of team performance factors shows that team performance can be related to many factors. Although the research is growing, many factors have yet to receive empirical examination. In this thesis, we will investigate, first, communication in relation to team performance and, second, the role of knowledge or shared mental models herein.

With respect to the shared mental model theory, several issues must be addressed. First, the empirical research shows conflicting results. This applies especially to the theoretically important relationships among shared mental models, team processes, and performance. A problem in interpreting the results is the inconsistent way researchers have defined and measured shared mental models. It is not clear whether the same construct is investigated across the various studies. Moreover, the effect of shared mental models is investigated on different team processes. It is not always clear how these are influenced by shared mental models. The differences among the various studies may explain the conflicting results. Nevertheless, it is of concern that the research so far has not been able to bring forth a coherent picture of what shared mental models are, how they are measured, and how they operate. If this will not be reconciled in future research, construct validity is at stake, and the construct loses its explaining and predictive power.

More clarity is also needed whether shared means that team members must have common knowledge, distributed knowledge, or both. Taking this a step further, it is also important to investigate in detail what knowledge is important and how this influences team processes. In this thesis, we will partially
address this sharedness issue. For the purposes of experimentation we developed an experimental team task (see chapter 3) for which we determined not only which teamwork members have to perform, but also which knowledge and cognitive tasks team members perform to engage in this teamwork (see chapter 4). This can be viewed as a case study in which we analyzed in detail what knowledge is important, and to what extent this needs to be shared among team members. Although this analysis is applied to a very specific domain, we expect that this analysis gives more insight in the issue of which and how knowledge is distributed among team members. In our empirical research, we will measure team members' knowledge using a questionnaire in which different types of knowledge will be addressed (see chapter 6 and 8). By using these questionnaires, we will also attempt to determine the distribution of knowledge among team members.

The support for the hypothesized relationship between shared mental models and implicit coordination is mixed. Whereas in one study this relationship was supported by the results (Blickensderfer et al., 1997c), in two other studies this was not supported (Cannon-Bowers et al., 1998; Stout et al., 1999). A problem in these studies is the limited measurement of implicit coordination. This was measured only by the amount of providing information in advance of requests. Nevertheless, other measurements are also important. Therefore, we used several communication measurements. We measured implicit coordination not only by the amount of necessary information provided in advance of requests, but also by the total amount of communication, timeliness of necessary information, number of questions, and proportion of necessary information of the total communication (see chapter 5 and 6). This way we attempted to reconcile the issue of limited implicit coordination measurements.

A final issue is that the research so far has focussed mainly on team knowledge in shared mental models developed before task execution. There is no research that investigated shared mental models concerning the situation or that team members must develop “on the fly” and have to maintain up-to-date. The hypotheses that team members must develop shared problem models (Orasanu, 1990, 1993) or strategic knowledge (Stout et al., 1999) of the conditions in which team members are engaged in, to keep up the teamwork and solve problems jointly and, in turn, maintain the performance are not investigated. The role of communication herein also requires further study. Communication can be viewed as an antecedent because it is expected that it supports the development of shared mental models during task execution. In this thesis, we will focus on the development and maintenance of knowledge during task execution (see chapter 7 to 9).

In conclusion, many issues concerning the shared mental model construct need to be investigated further. Although not all will be addressed in this thesis, we attempt to contribute to several ones. More specifically, we will empirically investigate the role of communication both as a result as well as antecedent of shared mental models. In the next chapter, we will describe the methodology used toward that end.