Communication and performance in teams

Peter Rasker

STELLINGEN

Behorende bij het proefschrift:

COMMUNICATION AND PERFORMANCE IN TEAMS

van Peter Rasker

1. In een goed team hebben de teamleden aan een half woord genoeg.

2. Het gezegde "spreken is zilver en zwijgen is goud" gaat niet op voor teams die moeten werken in onbekende situaties.

3. Directe instructie van teamleden over elkaars taken en informatiebehoefte is een effectieve methode om communicatie in teams te verbeteren.

4. Communicatie in teams verbetert de prestatie omdat het de ontwikkeling van team- en situatiekennis stimuleert en teamwerk bevordert.

5. Teams die werken onder hoge tijdsdruk aan cognitief belastende taken moeten zo min mogelijk communiceren. De tijd die beschikbaar is om te communiceren moeten teams gebruiken voor het uitvoeren van teamwerk, zoals het gezamenlijk bepalen van een goede strategie.

6. Het concept *shared mental model* lijkt veelbelovend voor het verklaren en voorspellen van teamprocessen, maar zal zijn waarde verliezen indien niet meer duidelijkheid komt over wat het is, hoe het werkt, en hoe het moet worden gemeten.

7. Het in werking stellen van een kennismanagementsysteem in een organisatie leidt zelden tot optimale kennisoverdracht bij medewerkers: het overdragen van kennis is namelijk een kwestie van mensenwerk en niet van techniek.

8. Tijdens een crisis kan kostbare tijd worden bespaard wanneer de leden van een crisisbeheersingsteam precies weten wie verantwoordelijk is voor welke taak en welke informatiebehoeften de teamleden hebben.

9. Telefoneren in de auto leidt de aandacht af, of het nu *handsfree* gebeurt of niet. Het propageren van *handsfree* telefoneren door de overheid geeft daarom een valse illusie van veiligheid.

   Strayer, D.L., & Johnston, W.A. (2001). Driven to distraction: Dual-task studies of simulated driving and conversing on a cellular phone. *Psychological Science, 12*(6), 462-466.

10. In veel *usability* onderzoek wordt ten onrechte meer belang gehecht aan de subjectieve mening van toekomstige gebruikers dan aan objectieve metingen van de prestatie.

11. Het hebben van een goede technische beheersing van een muziekinstrument is slechts een bijzaak als het gaat om het overbrengen van emotie in de muziek.

12. Voor klussen in huis geldt: alles wat kan tegenzitten, zit tegen.

COMMUNICATION AND PERFORMANCE IN TEAMS

Peter Rasker

The research described in this thesis was performed at TNO Human Factors,
P.O. Box 23, 3769 ZG Soesterberg, The Netherlands

ISBN: 90 6464 758 5
Printed by Ponsen & Looijen BV, Wageningen, The Netherlands

COMMUNICATION AND PERFORMANCE IN TEAMS

ACADEMISCH PROEFSCHRIFT

ter verkrijging van de graad van doctor
aan de Universiteit van Amsterdam
op gezag van de Rector Magnificus
Prof. mr. P.F. van der Heijden
ten overstaan van een door het college voor promoties ingestelde
commissie, in het openbaar te verdedigen in de Aula der Universiteit
op donderdag 18 april 2002, te 14:00 uur

door

Peter Christian Rasker

geboren te Schiedam

Promotiecommissie

Promotores:
Prof. dr. J.G.W. Raaijmakers
Prof. dr. C.K.W. de Dreu

Co-promotor:
Dr. J.M.C. Schraagen

Overige leden:
Prof. dr. P.L. Koopman
Dr. B.A. Nijstad
Prof. dr. J. van der Pligt
Dr. P.H.M.P. Roelofsma

Faculteit der Maatschappij- en Gedragswetenschappen
Afdeling Psychologie

VOORWOORD

Communicatie is voor de mens als sociaal wezen belangrijk en onmisbaar om samen met zijn soortgenoten te kunnen bestaan en te kunnen overleven. Communicatie is het middel bij uitstek om dat sociale aspect te voeden. Vaak verloopt communicatie vanzelfsprekend, maar in bijzondere situaties kan communicatie problemen geven. Dan kan het beter zijn om zo veel mogelijk je mond te houden en met zo min mogelijk woorden zoveel mogelijk te zeggen. In die zin kan het voorwoord ook efficiënt en kort. Simpelweg door te volstaan met: bedankt! Toch kan dat niet. Hoewel in één woord de kern van de boodschap wordt uitgedrukt is het kil en onpersoonlijk. Meer woorden zijn nodig om alle mensen die betrokken zijn geweest bij de voltooiing van dit proefschrift te bedanken met een persoonlijke noot. Zogezegd, zogedaan.

Het meest betrokken bij het onderzoek was Jan Maarten Schraagen in de rol van copromotor. Hem wil ik bedanken voor zijn hulp bij het bedenken, begeleiden en bekritiseren van het onderzoek. Zijn enthousiasme stimuleerde mij om steeds een stapje verder te gaan. Dat enthousiasme was overigens soms moeilijk in te tomen; de actielijst werd vaker langer dan korter. Op iets meer afstand, maar niet minder belangrijk, was er de begeleiding van beide promotoren. De kritische noten van Jeroen Raaijmakers en Carsten de Dreu gingen gepaard met opbouwende en ter zake kundig commentaar. Hen wil ik bedanken voor deze belangrijke bijdrage.

Teamonderzoek is tijdrovend. Vele uren heb ik besteed aan het doorgronden van het teamwerk, de analyses en het scoren en coderen van de verbale communicatie. Gelukkig was ik daarin niet alleen. Alle collega's van TNO Technische Menskunde, die hebben meegewerkt aan het onderzoek of mij anderszins hebben gesteund, wil ik daarom bedanken. Ook ben ik dankbaar voor de hulp van drie stagiaires die ieder hun licht over de materie hebben laten schijnen. Zo heeft Erwin Koster een belangrijke rol gespeeld bij het vernieuwen van de taakopzet en de eerste experimenten over de verbale communicatie in teams. Simone Stroomer heeft als kampioen in het verwerken van verbale protocollen ook een flinke "boost" aan het onderzoek gegeven. Tot slot heeft Mark Heijligers vanuit zijn marine ervaring mij laten inzien dat het onderzoek een duidelijk link heeft met de praktijk.

Twee collega's wil ik in het bijzonder bedanken. Ten eerste Wilfried Post, mijn kamergenoot, die ik vaak deelgenoot kon maken van zowel de inhoudelijke als de persoonlijke strubbelingen die je zoal tegenkomt bij het schrijven van een proefschrift. Met charmante en creatieve inslag gaf hij altijd weer een andere kijk op de zaken. Ten tweede Otto van Verseveld die als vierde programmeur de elegante maar soms ondoorzichtige nalatenschap van zijn voorgangers naar zijn eigen hand moest zetten. Tot wanhopen toe kwam ik steeds weer met ideeën voor de experimentele taak: of hij die "even" wilde implementeren. Het is gelukt.

De inhoudelijke bijdragen van collega's en betrokkenen waren niet mijn enige steun. Evengoed belangrijk was de persoonlijke steun van mijn vrienden en familie, waarvoor ik hen zeer dankbaar ben. Mijn ouders, Roel en Heidi, wil ik bedanken voor alles wat zij voor mij hebben gedaan. In de kiem hebben zij een omgeving gecreëerd voor een fijne jeugd waar ik kon leren en studeren. Zonder deze basis was het met dit proefschrift niets geworden. Het was ook zeker niets geworden zonder de steun en liefde van Sandra. Niet alleen nam zij ettelijke huishoudelijke taken voor mij waar, maar beurde zij mij ook keer op keer op wanneer het weer eens niet opschoot. Zij bleef een continue bron van warmte en gezelligheid. Hoewel "dank je wel" nu kil en onpersoonlijk lijkt, weet zij wat ik bedoel. Soms kun je met weinig woorden namelijk *wel* veel zeggen. Want het *ene* woord dat mijn liefde voor haar bevestigd komt nu snel. Communicatie in optima forma.

CONTENTS

1 INTRODUCTION

In many critical environments, teams have to do the job while work conditions change rapidly and time is limited. This puts great emphasis on the ability of teams to perform effectively. Among others, an important factor that influences team performance is communication. Communication can be problematic because there is too little time to communicate or it distracts team members from performing their tasks. However, teams need communication to exchange the necessary information, to preserve up-to-date knowledge of the situation, and to determine strategies to cope with the changes in the situation. These paradoxical demands of a team to communicate or not to communicate are the topic of this thesis.

The ability of teams to work effectively is a prerequisite in a number of critical work environments. From military command and control centers to aircraft cockpits to emergency medicine, from fire fighting to air traffic control to crisis management, teams carry out much of the work. In these environments, teams have to perform under complex and dynamic circumstances that can be characterized by time pressure, heavy workload, deadlines, ambiguous information presentation, and a rapidly changing environment. Furthermore, teams have to deal with high stakes and poor performance may have considerable consequences. Despite the reliance on teams to carry out their work successfully in such critical environments, there is still much to learn about the factors that make teams successful.

To illustrate the importance of effective teamwork, consider the following studies. In the aviation domain, many accidents involving aircraft damage were mainly due to the actions of the flight crew. A central theme in these cases was that human error resulted from failures in interpersonal communications (Helmreich & Foushee, 1993). Heath and Luff (1992) demonstrated that effective crisis management in the London underground line control room depends on how operators monitor each other and exchange information. Flin, Slaven, and Stewart (1996) describe the disastrous fire at the oil platform *Piper Alpha*. One of the reasons that lives could not be saved was that the chain of command had broken down and that there was no one in charge to lead people to safety. In the medical world, ineffective teamwork has led to a considerable number of incidents in anesthesia (Howard, Gaba, Fish, Yang, & Sarnquist, 1992). Finally, probably more lives could have been saved after the crash of a Hercules military transport aircraft of the Belgian air force had team members exchanged all information concerning the total number of passengers (Van Duin & Rosenthal, 1996).

These studies show that "human error" is not exclusively a matter of individual task performance but also of team performance. Even when a team consists of members with the finest skills or expertise, it is not said that one can speak of a skilled or expert team. Teams, in which members do not communicate, coordinate, cooperate, provide back up to each other or, in other words, do not engage in teamwork, will have a hard time getting good results. The interest of this thesis is in those factors that make a team effective. More specifically, this thesis focuses on the relationship between communication and team performance in time-pressured and dynamic situations. Insight in how teams perform in such situations helps to understand how team members can be supported by means of technical systems, procedures, and work organization and how team members can be trained effectively. We hope that this will give a contribution to teams operating more successfully in critical environments.

1.1 Team performance in time-pressured and dynamic situations

This thesis focuses on teams defined as follows. Teams consist of at least two people that work together toward a common goal, who have been assigned to specific roles or tasks to perform, and where the completion of the goal requires dependency among team members (Dyer, 1984; Salas, Dickinson, Converse, & Tannenbaum, 1992). Other researchers have used similar definitions in which the elements described above are all acknowledged as important ingredients for the definition of a team (Cannon-Bowers, Salas, & Converse, 1993; Duffy, 1993; Orasanu & Salas, 1993). There is discussion among researchers whether teams can be differentiated from groups. The central issue in this discussion is whether high interdependency, unique roles, distributed expertise, and specific needs for coordination are more typical for teams than for groups (Cannon-Bowers et al., 1993; Dickinson & McIntyre, 1997; Dyer, 1984; Guzzo, 1995; Orasanu & Salas, 1993). To further differentiate, several researchers even use specific terminology such as *command and control teams* (Rasker, Post, & Schraagen, 2000a), *tactical decision-making teams* (McIntyre & Salas, 1995), *action teams* (Klein, 2000), or *complex decision-making teams* (West, Borrill, & Unsworth, 1998), that all appear to refer to teams as defined previously. We view teams as a special instance of groups. In groups, members typically have less specialization, and less interdependency to reach their goal. In addition, the objective in groups is frequently to reach consensus, whereas this is not the case for teams.

We focus further on teams that have to perform in conditions characterized by high time pressure or excessive workload and in dynamic situations that change rapidly and contain novel or unexpected events. The demands for teams to perform effectively in such conditions are high. Team members not only have to perform well on their individual tasks; so-called taskwork, but also on the tasks needed to act as a team; so-called teamwork (Baker, Salas, & Cannon-Bowers, 1998; Dyer, 1984; Fleishman & Zaccaro, 1993; McIntyre & Salas, 1995). One demanding element of teamwork is communication. Communication is needed because the interdependency among team members requires that information exchange takes place. In addition, communication is needed because it helps team members to evaluate and improve task performance, to jointly determine strategies, and keep each other up-to-date with the changes in the situation (Blickensderfer, Cannon-Bowers, & Salas, 1997b; Orasanu, 1990, 1993; Rochlin, LaPorte, & Roberts, 1987; Seifert & Hutchins, 1992; Stout, Cannon-Bowers, & Salas, 1996). Nevertheless, notwithstanding the need for communication, potential problems are that there may be too little time to communicate and that communication may disrupt the individual task performance of team members.

In conditions of high workload and time pressure, communication problems occur when team members have to discuss extensively about "who is responsible for what task" or "who needs what information and when." Not only is there too little time for such discussions, there is also a potential danger that team members are too late with exchanging the necessary information because of attending such discussions. A study of Kleinman and Serfaty (1989) suggests that ineffective teams frequently engage in this type of communication, which the authors labeled as *explicit coordination*. Team performance can be maintained if teams adapt to high time pressure by anticipating on each other's informational needs and providing each other relevant information in advance of requests. This is called *implicit coordination*, because team members exchange the necessary information and perform their tasks without the need for extensive communications to coordinate explicitly. The blind pass in basketball, where a player passes the ball over his or her shoulder to another player without looking and talking, is an example of implicit coordination.

Although several studies show that performance decreases because communication is inefficient and disrupts the workflow during high-workload periods or after critical, rare events (Hollenbeck, Ilgen, Tuttle, & Sego, 1995; Hutchins, 1992; Johnston & Briggs, 1968), other studies point to the benefits of communication. In the aviation domain it was found that 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). Based on observations in a full-mission simulated flight, Orasanu (1990, 1993) concluded that team performance in cockpit crews was positively related to the amount of task-oriented communication including situation updates and the formulation of plans or strategies. Observations by military teams have led McIntyre and Salas (1995) to conclude that in effective teams, members communicate to monitor the performance of each other, provide feedback, and prevent each other from making errors. Finally, Rochlin et al. (1987) concluded that the redundancy in verbal communication, such as crosschecks on decisions made, was partially responsible for the reliability in the complex and high-risk operation of bringing in an aircraft on a flight carrier.

Three things can be learned from these studies. First, communication is potentially problematic when teams work in time-pressured and dynamic situations. Team members cannot exchange the necessary information in time and extensive communications distract team members from their taskwork. Second, although communication may be problematic, there are ways to work around it. Performance can be maintained if team members adapt to the situational demands by limiting the communication through implicit coordination. Third, communication is not necessarily a bad thing at all times. Communication to monitor each other's performance, provide feedback, and exchange information about the situation, is positively associated with performance. The obvious conclusion is that teams should restrict their communication as much as possible, and communicate only if it is necessary or contributes to performance. However, less obvious is how teams can achieve this. Thus, the questions raised here are "how can teams limit their communication?" and "when is communication needed?"

1.2 Explaining communication in teams: shared mental models?

Recent literature has advanced the construct of shared mental models among team members as an underlying mechanism of team processes and performance in teams (Cannon-Bowers et al., 1993; Rouse, Cannon-Bowers, & Salas, 1992). This construct has emerged from the literature on individual mental models (Rouse & Morris, 1986; Wilson & Rutherford, 1989) that are organized knowledge structures that allow individuals to describe ("what is it?"), explain ("how does it work?"), and predict system functioning ("what is its future state?"). Bringing the mental model construct to a team level, *shared* mental models are organized knowledge structures that allow team members to describe, explain, and predict the teamwork demands. The knowledge that is shared comprises the internal team (e.g., knowledge about the tasks, roles, responsibilities, and informational needs of the team members, interdependencies in a team, and the characteristics of the team members) and the external situation (e.g., cues, patterns, and ongoing developments). The explanations and expectations generated by this knowledge allow team members to anticipate on each other's task-related needs by providing each other information, resources, or other support in time (Cannon-Bowers et al., 1993).

With respect to communication, it is hypothesized that shared mental models allow team members to explain and predict the informational needs of teammates. Because team members rely on their shared mental models, communication takes place efficiently and effectively. Efficiently, because 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. Effectively, because 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). In other words, shared mental models allow team members to coordinate implicitly. The result is the smooth team functioning of team members who are in sync with each other, and who know exactly when to talk and what to say.

Although shared mental models may result in efficient and effective communications, it is also hypothesized that communication is important for the development and maintenance of shared mental models (Orasanu, 1990, 1993; Stout et al., 1996). Communication during task execution refines team members' shared mental models with contextual cues. This may result in more accurate explanations and predictions of the teamwork demands (Stout et al., 1996). For maintenance purposes, communication is needed to keep the shared mental models up-to-date with the changes that occur during task execution. Especially in dynamic or novel situations, communication is needed to preserve an up-to-date shared mental model of the situation and to adjust strategies or develop new ones to deal with the situation (Orasanu, 1990, 1993). 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 in that particular situation. In contrast to implicit coordination, which implies that mature teams are silent teams, this emphasizes the need for explicit communication to arrive at a joint interpretation of the situation and the generation of strategies to deal with that situation.

The potential power of shared mental models to explain and predict team processes in general and, more specifically, communication in teams, has appealed many researchers. This resulted in a tremendous growth of research, as evidenced by the overview described in the next chapter (see section 2.3). In the early nineties, shared mental models were mainly conceptually explored and used to explain team processes a posteriori. At the time the research for this thesis started, in the mid nineties, there were still few empirical studies that had investigated team processes in relation to shared mental models. The main reason for this paucity in the empirical work is that there were no adequate measures of shared mental models (see also Mohammed & Dumville, 2001). Recent work has attempted to measure and investigate shared mental models more directly (Cannon-Bowers, Salas, Blickensderfer, & Bowers, 1998; Marks, Zaccaro, & Mathieu, 2000; Mathieu, Goodwin, Heffner, Salas, & Cannon-Bowers, 2000; Stout, Cannon-Bowers, Salas, & Milanovich, 1999).

To date, the empirical research has concentrated mainly upon the question how team processes and performance can be improved by fostering team members' shared mental models. Several antecedents of shared mental models including various types of cross and team training (Blickensderfer, Cannon-Bowers, & Salas, 1997c, 1998b; Cannon-Bowers et al., 1998; Entin & Serfaty, 1999; McCann, Baranski, Thompson, & Pigeau, 2000; Minionis, Zaccaro, & Perez, 1995; Schaafstal & Bots, 1997), leader briefings (Marks et al., 2000), team planning (Stout et al., 1999), and experience within the team (Mathieu et al., 2000; Rentsch, Heffner, & Duffy, 1994) were investigated. In these studies, shared mental models were measured in various ways (if at all). Some studies investigated the knowledge content of individual team members (Cannon-Bowers et al., 1998), whereas in other studies the similarity among team members' mental model was measured (Marks et al., 2000; Mathieu et al., 2000). Team processes were also investigated differently. Some studies assessed team processes by rating teamwork behaviors observed by subject matter experts (Cannon-Bowers et al., 1998; Entin & Serfaty, 1999; Marks et al., 2000; Mathieu et al., 2000; Volpe, Cannon-Bowers, Salas, & Spector, 1995), whereas in other studies the provision of information in advance of requests was used as a measure of implicit coordination (Blickensderfer et al., 1997c; Cannon-Bowers et al., 1998; Entin & Serfaty, 1999; Schaafstal & Bots, 1997; Stout et al., 1999; Volpe et al., 1995). All studies included measurements of team performance.

Despite this research interest, many issues have to be addressed to ensure that the shared mental model construct is a valid psychological construct. The main concern is that the research so far does not give a clear picture of the effect of shared mental models on team processes and, in turn, performance. Although some studies established a positive relationship between shared mental models and performance (Blickensderfer et al., 1997c; Marks et al., 2000; Mathieu et al., 2000), this relationship was not established in other studies (Cannon-Bowers et al., 1998; Minionis et al., 1995; Stout et al., 1999). Especially the effect of shared mental models on communication shows inconsistent results. Similarly, the results with respect to the relationship between team processes and performance are conflicting. Only one study demonstrated that team processes mediated the relationship between shared mental models and performance (Mathieu et al., 2000). The problem that underlies these conflicting empirical results is that researchers have not been consistent in the way shared mental models are defined, manipulated, and measured. In other words, there is no shared understanding among researchers what shared mental models are and how they operate.

In this roaring field of shared mental model research, the research described in this thesis was conducted. The above-described issues with respect to the shared mental model construct will not all be addressed. For one part, because we were mainly interested in the optimization of communication and performance in teams. Hence, we gained the most insight in this area. For another part, because we too had no adequate measures of shared mental models. Nevertheless, the knowledge content of shared mental models is analyzed in detail and measured at several points. In addition, we describe how this knowledge influences communication processes and vice versa. This way we address several issues with respect to the shared mental model construct that may serve future research. We will return to these issues in the concluding chapter 10.

1.3 Research questions

The shared mental model construct explains how communication can be limited. Team members that rely on their mental models provide each other the necessary information in time, that is, in advance of requests. It also explains why and when communication is needed: to develop shared mental models and to keep them up-to-date. These notions inspired us to perform the research described in this thesis. The main objective was to investigate empirically the relationship between communication and performance in teams. This was investigated from two different perspectives. First, we were interested in how communication can be limited by communicating as efficiently and effectively as possible. The basic idea is that antecedents (such as training) foster the knowledge in team members' mental models. In turn, this has a positive effect on the effectiveness and efficiency of the communication. The research question for this first perspective was:

> *How can communication and performance be improved by fostering the knowledge team members have in their mental models?*

From the second perspective, we were interested in how team members can use their communication to improve their performance. In contrast to the first perspective, we were now interested in how performance can be improved by expanding the communication. The basic idea is that communication fosters the development and maintenance of the knowledge in team members' mental models. Hence, from this perspective, communication is viewed as a team process that is not only influenced by shared mental models, but also is an antecedent of shared mental models.

The research question for this second perspective was:

> *How and when does communication improve performance by fostering the knowledge team members have in their mental models?*

The answers to the two research questions should provide more insight in how and when communication influences team performance. Given the limited room for communication due to high time pressure or excessive workload, it is essential that the room left to communicate is used as effectively as possible. In this thesis we examined how this communication room can be used optimally.

1.4 Organization of this thesis

As described above we focus on teams that perform in time-pressured and dynamic situations. The reader that is unfamiliar with this field of small-group research will find an overview of what it entails in chapter 2. In this chapter, we also describe in detail the theory and research concerning shared mental models. Chapter 3 addresses the method used throughout this thesis. It delineates how we developed an experimental team task for two team members based on methodological considerations, requirements extracted from the literature, and an analysis of command and control tasks. In chapter 4, a cognitive team task analysis is applied to the experimental team task. In this chapter, we determine the teamwork, the knowledge team members need to perform this teamwork, whether this knowledge is important for shared mental models, and the knowledge that is transferred when team members communicate in this particular team task.

After the theoretical, methodological, and conceptual examination of team processes and performance in chapter 2 to 4, the thesis turns to the empirical work. Chapter 5 and 6 comprise the first perspective in which we investigate how communication and performance can be improved by fostering the knowledge team members have in their mental models. In chapter 5, two experiments are described that investigate the effect of cross training on communication and team performance. Chapter 6 continues with the investigation of how communication and performance can be improved. This time, a different method is employed and a questionnaire is used to measure the team knowledge of the members.

Chapter 7 to 9 comprise the second perspective in which we investigate how and when communication improves performance by fostering the knowledge team members have in their mental models. The two experiments described in chapter 7 investigate the effect of communication on team performance. In the first experiment, the question is addressed whether team performance improves when teams can communicate freely compared to a restricted type of communication in which team members can exchange only the necessary information. In the second experiment, the opportunity to communicate freely is varied systematically during and between task execution. In the experiment described in chapter 8, we again focus on the effect of communication on team performance. This time, we are interested in whether communication is beneficial when team members have worked together for a longer period. The final experiment of this thesis is described in chapter 9 in which the effect of communication on team performance is investigated in routine as opposed to novel situations.

Chapter 10 concludes with a summary of the main results, a discussion of the theoretical implications, the limitations and strengths of the research, and the practical implications.

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.

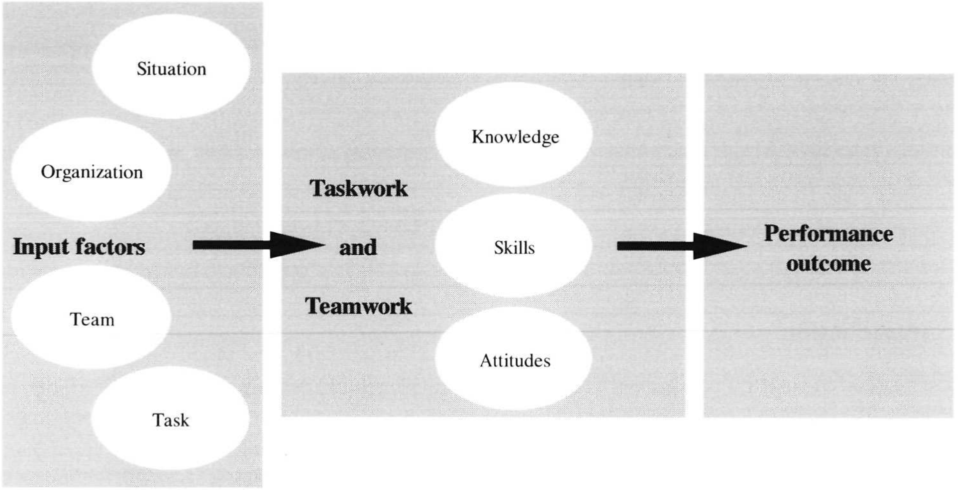

Figure 2.1: A framework for team performance factors

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 (Helmreich & Foushee, 1993; Salas et al., 1992; Serfaty et al., 1998). Orasanu 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, & Reick, 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.

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 Phandi (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.

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 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 posses 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

Implicit coordination	**Communication features**
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).

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.

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

	Declarative	**Procedural**	**Strategic**
Team	• Goals • Members' tasks, roles and responsibilities • Members' interdependencies and informational needs • Members' characteristics • Equipment and system functioning	• Plans and procedures • Members' task sequence • When members are interdependent, need information, and interaction is needed	• Strategies, action plans, and solutions • Members' task execution • Priorities • Adjusted task execution • Adjusted informational needs • Taking over tasks, roles, and responsibilities
Situation	• Environmental features • Features of elements	• Timing and sequences of environmental elements	• Ongoing developments • Cues and patterns • Problems

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.

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

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.

Schaafstal 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 Schaafstal 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 Schaafstal 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.

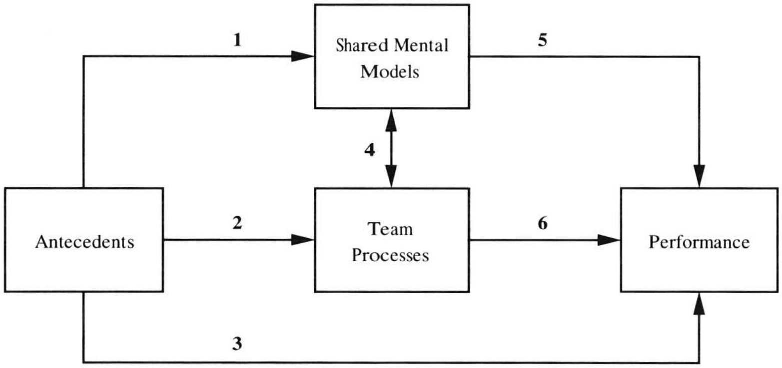

Figure 2.2: Shared mental model dimensions and relationships

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; Schaafstal & 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; Schaafstal & 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, Schaafstal 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; Schaafstal & 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 Schaafstal 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. Schaafstal 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 2.3: Overview of the empirical research on shared mental models

Author	Antecedent	Shared mental model	Team processes	1	2	3	4	5	6	Comment
Volpe et al., 1995	Cross training (videotaped explanation and written instructions)		• Teamwork • Providing information in advance of requests • Acknowledgements • Questions • Irrelevant remarks		+ + 0 0 +	+				
Cannon-Bowers et al., 1998	Cross training (positional rotation)	• Objective IPK • Subjective IPK	• Teamwork • Providing information in advance of requests • Acknowledgements • Questions • Commands, replies, planning statements • Irrelevant remarks	+ +	+ + 0 0 0 0	+	+/0 0/0	+/0	0 0	Objective/ Subjective IPK
Schaafstal and Bots, 1997	Cross training (positional rotation and explicit written instructions concerning team interdependencies)		• Requests • Responses • Providing information in advance of requests		0 0 +	+			- - +	Positive relations only for explicit written instructions
McCann et al., 2000	Cross training (positional rotation)		Communication (number of utterances)		0	-				
Minionis et al., 1995	• Team interaction training • Training in a team setting	Mental model similarity (team interaction model)	• Coordination • Communication (seven content categories)	+ 0			+ 0	+		
Blickensderfer et al., 1997c	Team self-correction training	Overlap in expectations (team roles, strategy, communication patterns)	• Team self-correction score • Providing information in advance of requests	+	+ +	0	 +	+	 +	Relationship 6: moderate positive relation

Author	Antecedent	Shared mental model	Team processes	1	2	3	4	5	6	Comment
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		+ 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 Schaafstal 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 Schaafstal 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 then 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; Schaafstal & 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 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; Minionis 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; Schaafstal & 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.

3 EXPERIMENTAL TEAM TASK

This chapter describes the experimental team task that we used for the research described in this thesis. First, we describe the methodological considerations and requirements that are extracted from the literature. Subsequently, we describe a task analysis that provides insight in whether the task contains command and control tasks, team members have specific roles and responsibilities, are interdependent, and to what extent tasks have to be performed in parallel. Finally, an experiment is outlined testing the hypothesis that a team of two members performs the task better as compared to a single person.

3.1 Introduction

The understanding of team processes has improved greatly in recent years. There is a need, however, to gain a better understanding of how these processes are affected by various factors (Salas, Bowers, & Cannon-Bowers, 1995). Team assessment methodology in the past has largely focused on observable behavior. Although observational studies yield insight in the composite set of factors, they provide less insight as to what extent particular factors affect the team performance. Therefore, we developed an experimental task for teams in the form of a low-fidelity simulator to investigate various factors systematically. With the help of this task, we attempt to develop an understanding of how these factors affect team processes, so as to be able to improve team performance. The purpose of this chapter is to give a description of the task that is used for the research described in this thesis. Furthermore, we describe on what grounds the task is developed and what lessons we learned from developing this experimental team task.

The use of an experimental task in the laboratory has particular advantages in the evaluation of theories of team performance, because it allows researchers to exercise more strict control over extraneous variables than is possible in the field (Driskell & Salas, 1992a). There are several advantages in using low-fidelity simulations for the investigation of team performance (see also Bowers, Salas, Prince, & Brannick, 1992). First, the technology is available at relatively low cost. Second, low-fidelity simulations possess the characteristics needed to investigate teams. Third, low-fidelity simulations give experimental control of independent variables. Finally, people can be relatively easily trained to perform a low-fidelity simulation. Consequently, it is possible to invite unpracticed participants instead of fully trained persons that are often difficult to recruit.

One complicating factor in studying teams using a laboratory task is that it can be argued that the generalisability to real-world environments is limited. This critique is based on the misconception that the goal of laboratory research is to predict real-world behavior. Instead, we believe that the goal of most research in the laboratory is to test a theory (Driskell & Salas, 1992a). It is the theory that is applied to the real world, not the task. In order to test a theory, it is important that an experimental task contains an environment in which theoretically relevant phenomena can be investigated. In our case, the experimental task must provide an environment in which team processes such as communication and coordination are elicited and can be investigated in relation to shared mental models and performance.

This chapter describes the requirements for such an environment. In order to find out whether this environment indeed elicits the team processes we are interested in, we performed a cognitive team task analysis which is described in chapter 4.

In this chapter, we also want to demonstrate that a task analysis based on a generic command and control model supports the development of an experimental team task. A task analysis method is used that provides not only a task hierarchy, but also describes the information dependency among tasks and the sequence of tasks for each team member. Based on this analysis, the different roles of the team members and the information dependency between them are specified. In addition, by showing that the specified tasks have to be performed in parallel, we demonstrated that the experimental task is a task for two team members, which cannot be performed well enough individually. This is also demonstrated by an experiment in which teams are compared with individuals. With the use of the task analysis method, we attempted to develop an environment in which the theoretically relevant team processes can be investigated under experimentally controlled conditions.

The development of an experimental team task was an iterative design process. We ended up with three different versions. Version 1 was developed based on methodological considerations and requirements extracted from the literature (Schraagen, 1995). Although Version 1 fulfilled these considerations and requirements, we felt that not all relevant command and control tasks were addressed, and we doubted to what extent team members were dependent on each other's information, and to what extent the task allowed us to investigate the teamwork we were interested in. Therefore, we conducted a task analysis that supported the development of Version 2. Finally, a third version was developed that improved Version 2 in such a way that it refined the performance measurements, and allowed us to conduct an experimental session in a shorter period of time.

In the next section, the requirements considered for the development of the experimental team task are outlined. This is followed by a description of Version 1 of the task and the lessons learned from the first two experiments described in chapter 5 (Schraagen & Rasker, 1995, 1996). Subsequently, a task analysis of the task is presented, followed by a description of Version 2 of the task. Version 2 of the task is used for Experiment 4 and 5 described in chapter 7 (Post, Rasker, & Schraagen, 1997; Rasker et al., 2000a). Next, the changes for Version 3 are described. Version 3 is used for Experiment 3, 6, and 7 described in chapter 6, 8, and 9 respectively (Rasker, Schraagen, & Stroomer, 2000b; Rasker, Schraagen, & Van der Kleij, 2000c). This chapter ends with a description of an experiment testing the hypothesis that the task is a team task.

3.1.1 Requirements for an experimental team task

The teams of interest in this thesis perform command and control tasks in time-pressured and dynamic situations. Therefore, an experimental task requires at least two people that work together towards a common goal who have been assigned to specific roles and tasks and who are dependent of each other for the completion of the goal (Dyer, 1984; Salas et al., 1992). The notion that an experimental task must provide a condition in which team members are required to interact in an interdependent manner is viewed as one of the most important requirements (Bowers et al., 1992; Weaver, Bowers, Salas, & Cannon-Bowers, 1995). The reason is that interdependency requires team members to engage in teamwork such as communication and implicit coordination.

Interdependency between team members is required not only to investigate team processes such as communication and coordination, it is also an important characteristic of real world command and control tasks. When teams perform command and control tasks, each team member is assigned to one or more tasks. Furthermore, there is a dependency of information between these tasks. That is, the completion of one task results in information that is needed for the completion of the next task. For a successful completion of the tasks, team members must exchange this information in a coordinated manner. This means that, apart from information content, team members should also consider the moment when information needs to be exchanged. Because tasks in command and control situations must often be completed before a deadline, it is important that team members offer each other relevant information in time.

For the type of teams under investigation in this thesis, it is important that team members execute relevant command and control tasks such as situation assessment and resource allocation. For the completion of these tasks team members need specific expertise and information sources that define their roles. In teams, tasks are often performed in parallel. Team members work simultaneously at their own set of tasks, which makes it impossible to perform all tasks by one individual. The command and control tasks comprise the individual taskwork. For an understanding of real-world team performance it is also important to investigate teamwork among interdependent team members performing different types of tasks (Bowers et al., 1992; Weaver et al., 1995). We expand on this view with the notion that team members perform tasks in parallel.

In the preceding paragraphs, we discussed the requirements of an experimental team task in terms of the activities team members have to perform. The way these activities are executed is affected by the specific situation in which teams perform (Orasanu & Connolly, 1993; Zsambok, 1997). The situation is often characterized as dynamic in that it can change over time autonomously, because of a completed action, or both. In dynamic situations, teams have to consider the dimension of time explicitly because there is a deadline before a decision or action has to be made. It is not enough to know *what* should be done, but also *when* it should be done (Brehmer, 1992; Kerstholt, 1996). Command and control situations are also characterized as complex and rapidly changing and the situation often changes within the period a decision or action is required (Orasanu & Connolly, 1993; Zsambok, 1997). In addition, teams have to perceive and exchange a great amount of (ambiguous) information while there is limited time available. The importance for a team task to contain such situation characteristics is that team processes such as implicit coordination are expected to be especially advantageous in such situations.

There are also requirements from a methodological perspective. First, an experimental team task must measure the performance of a team objectively. Such a measure must express the performance of a team, its taskwork, as well as its teamwork tasks. Second, to collect as much data as possible, and to reduce the error variance, repeated measurements are favored. Third, the task must be designed in such way that it can be easily trained.

In sum, an experimental team task for command and control situations must contain a dynamic and rapidly changing situation with limited time available, relevant command and control tasks, specific roles and tasks for at least two team members, and information dependency among team members. In addition, it must be made possible to train participants easily, and measure objectively team performance.

3.1.2 Overview of experimental team tasks

Given the preceding discussion, the question arises whether there are already tasks developed that answer the formulated requirements. Weaver et al. (1995) provided an overview of experimental team tasks in a plea for the use of networked paradigms for investigating team performance. The first task described by Weaver et al. is the *Team Performance Assessment Battery* (TBAP). The TBAP consists of a monitoring task in which team members must monitor a simulated radar display and detect deviations from normal states and a resource management task in which team members are required to utilize information from their computer displays to coordinate resources and take countermeasures. The advantages of TBAP are that team members have specific roles and tasks to perform and situational characteristics such as uncertainty and workload can be employed easily. It is not clear, however, to what extent the team members are interdependent.

The TANDEM task provides a low-fidelity simulation of a command and control environment similar to that of the TBAP, but with higher face validity to real-world combat information centers. The task was developed to investigate factors such as task interdependence, time pressure, task load, and ambiguity and could be performed by a maximum of three team members. Team members performing the TANDEM task are required to make decisions regarding unknown targets represented on a simulated radar display by consulting the targets and integrating pieces of information that are distributed over team members. Based on this decision, targets are either cleared or shot. The TANDEM system can be used to investigate situational factors such as ambiguity and time pressure as well as teamwork processes such as communication and coordination. The largest shortcoming of the TANDEM system is that the task is only moderately dynamic in that the information to be integrated remains constant throughout the scenario.

Another task described by Weaver et al. (1995) is the *Team Interactive Decision Exercise for Teams Incorporating Distributed Expertise* (TIDE^2) developed by Hollenbeck, Sego, Ilgen, Major, Hedlund, and Phillips (1991). TIDE^2 was developed especially for the investigation of distributed decision making in complex, uncertain, and ambiguous situations. The task consists of a command and control scenario that requires four team members to query nine attributes in order to determine the threat of incoming targets. This threat could be determined by five decision-making rules that describe how the attributes should be combined. Distinct roles and expertise is incorporated by giving each of the team members either the ability to measure target attributes, knowledge of rules, or opportunity to combine the target attributes and the rules in order to determine the threat. The utility of TIDE^2 can be found especially in how structural factors such as the distribution of information or decision-making authority can be manipulated. Nevertheless, TIDE^2 is a rather static task and lacks several dynamic elements such as a scenario that develops (in)dependently of the tasks of team members.

The fourth task that is described by Weaver et al. (1995) is the *C3 Interactive Task for Identifying Emerging Situations* (CITIES) developed by Wellens and Ergener (1988) to investigate situations characterized by distributed information, ambiguity, and time pressure. In the CITIES task, two teams consisting of two members perform either as police or as fire rescue teams in order to react upon emergency events in a computer-simulated city. Each of the teams has a number of resources that must be allocated to the emergencies that vary in location and intensity. According to Weaver et al. (1995), the CITIES task is the best task of the reviewed tasks for investigating teams in command and control situations. It is possible to manipulate situational factors such as time pressure, severity, and ambiguity and to use the CITIES task for the investigation of teamwork (including team-to-team communication). Nevertheless, because of the technology used, the CITIES task might be more costly than the other tasks discussed.

The preceding discussion shows that several researchers have made an attempt to develop an experimental team task suitable for the investigation of command and control teams, thereby indicating that developing an experimental team task is not an easy job to perform. Although each task appears to be (and also proved to be) useful to investigate teams, there are several shortcomings. Especially the dynamic nature of real world command and control environments appears to be difficult to obtain. In addition, because of technology involved, not all tasks can be developed easily elsewhere than the place where the tasks were originated. In an attempt to overcome the mentioned shortcomings and to investigate teams in our own laboratory, the fire-fighting task was developed.

3.2 Outline of the fire-fighting task

3.2.1 The fire-fighting task: Version 1

We used Version 1 of the fire-fighting task for Experiment 1 and 2 described in chapter 5.

The experimental task is a low-fidelity simulation of a dispatch center representing a fire-fighting organization in a city. The fire-fighting team consists of an observer and a dispatcher. In order to keep the number of casualties as low as possible, which is the goal of the task, the team is required to fight fires. The system with which the team works consists of two linked computers. The observer and the dispatcher each have their own graphical interface. By pointing and clicking with a mouse, team members can interact with the system. In order to accomplish the goal, the observer has to assess the situation in the city and inform the dispatcher about the status of the buildings. The dispatcher has to assign a number of resources (i.e., fire-fighting units) to the buildings to extinguish fires. Different types of buildings in the city are associated with different numbers of potential casualties. The number of units needed to extinguish a fire is related to the type of building. Because the number of units (only six) is limited, scenarios can be developed in which more units are needed than are available. Consequently, team members must prioritize and decide upon the buildings that need to be extinguished. Team members can exchange the necessary information by sending standardized electronic messages.

On the display of the observer, a map of a city containing the buildings is presented. Figure 3.1 depicts the screen display viewed by the observer. Fires are indicated by a flashing red contour, a green contour indicates a fire is extinguished, and a black contour, with crossed black lines, indicates a building is burned down. A building can also be "in danger," which indicates a possible upcoming fire. By pointing and clicking on buildings the observer can gather information concerning the identification (house, school, etcetera), status (fire, extinguished, burned down, in danger), period in which the building will burn when it is in danger, and number of units needed. The information that is displayed in the outbox window, can be sent to the dispatcher by clicking the send button. At the same time, this information is displayed in the message overview window. By clicking the present button (a question mark appears), the observer requests the dispatcher how many units are present at a building. The observer receives this information from the dispatcher in the inbox window. This information can be forwarded to the message overview window by clicking the button *to overview*.

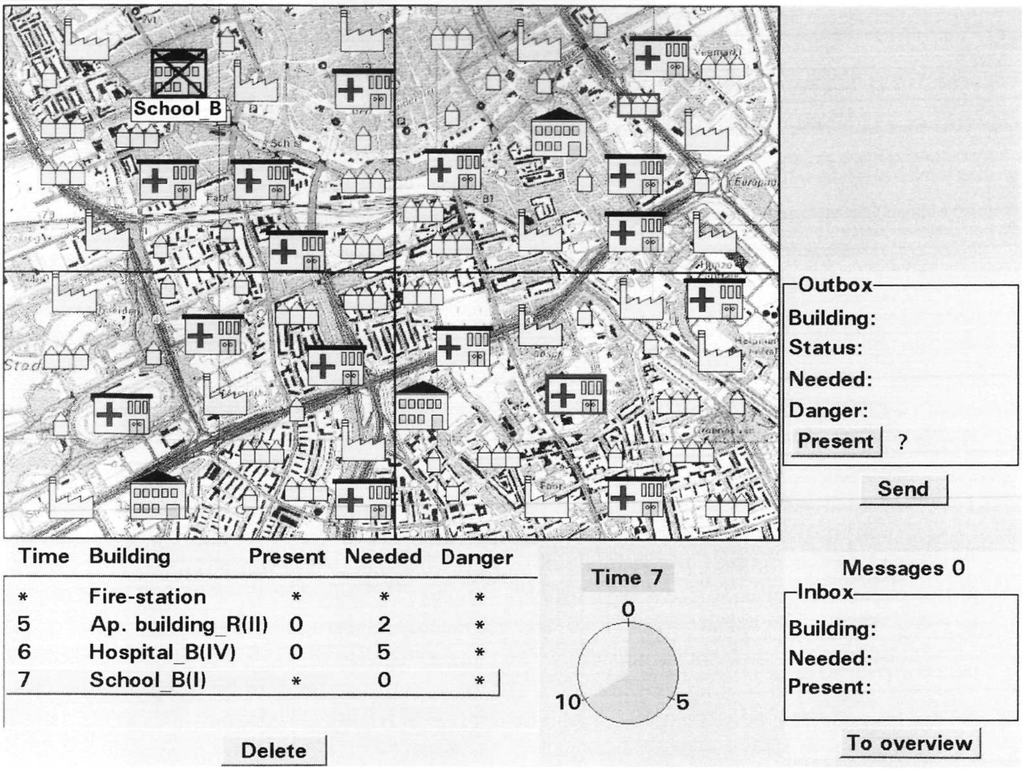

Figure 3.1: Screen display of the observer in the fire-fighting task

On the display of the dispatcher, a message overview window is presented in which the dispatcher can add or pull back units from buildings by manipulating the "+" or "-" buttons. Figure 3.2 shows the screen display viewed by the dispatcher. When the dispatcher points at and clicks on a line in the message overview window, the information of this line is displayed in the outbox window and can be sent to the observer by clicking the send button. By clicking the needed button (a question mark appears), the dispatcher requests the observer how many units are needed at a building. The information that the dispatcher receives from the observer is displayed in the inbox window. This information can be forwarded to the message overview window by clicking the button *to overview*.

The dispatcher display also contains a fire station window in which the number of units available is listed. The team plays several scenarios containing a number of periods in which different buildings are set on fire. At the end of each period, the status of buildings can change from *no fire* to *fire*, *in danger* to *fire*, or *fire* to *saved* or *burned down*. In addition, the number of units needed during the fire can change, depending on the match between the number of units needed and the number of units allocated. A clock is displayed on the screen of each team member, showing the seconds left to play within the period. After each period, the clock resets and starts to countdown automatically. Once a fire is started, it takes several periods before the fire is extinguished, depending on the number of units present and the period they arrived (and stayed) at a building. When a building burns down, a number of lives are lost. A house has two potential casualties, an apartment ten, a school one hundred, a factory five hundred, and, finally, a hospital, one thousand. To save the lives, units are needed. For a house, one unit suffices, an apartment needs two units, a school three, a factory four, and a hospital five.

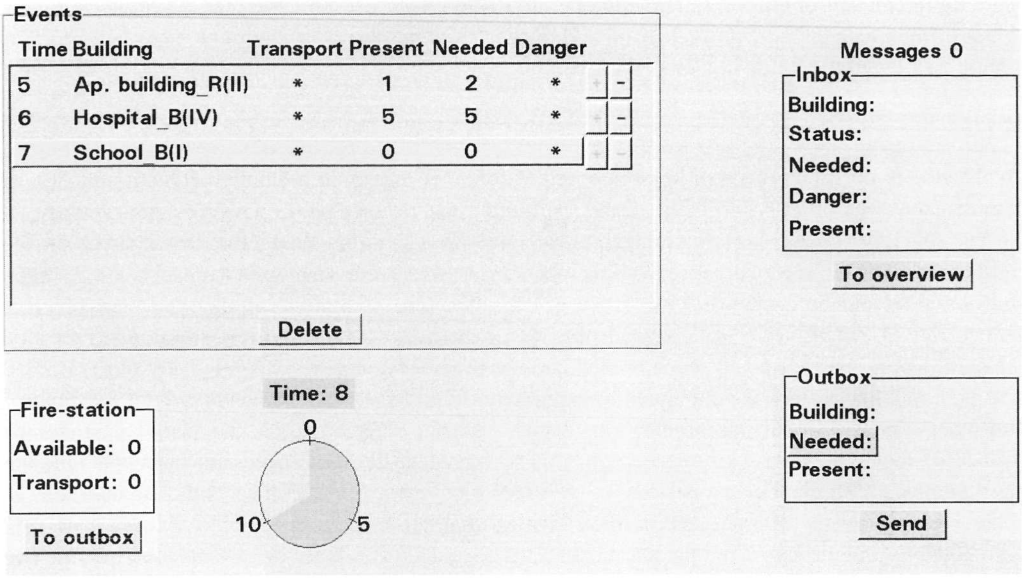

Figure 3.2: Screen display of the dispatcher in the fire-fighting task

The events in scenarios (e.g., which building is set on fire in which period) are pre-programmed. Once a fire is started, pre-programmed algorithms (so-called state transition diagrams) determine how the fire develops in reaction to the deployment of units by the team. The allocation of units takes some time. The allocation commands of the dispatcher become effective at the change of each period. Units allocated from the fire station to a building need one period to reach their destination. Since units always have to come back to the fire station before they can be allocated to another building, it takes longer to allocate units from one building to another than directly from the fire station.

Performance measurement

The performance is measured by the ratio between the number of possible casualties threatened and the number of casualties saved. This ratio is expressed by the percentage of potential casualties saved. In order to obtain a high percentage of potential casualties saved, team members must perform accurately on their taskwork, such as situation assessment and decision making. Because team members are dependent on each other's information, it is important that team members perform accurately on their teamwork that consists of the exchange of relevant information in a coordinated and timely manner.

3.2.2 Lessons learned

The fire-fighting task appeared to be a promising experimental task to investigate team performance (Schraagen, 1995; Schraagen & Rasker, 1995). In the first two studies, the fire-fighting task was used to investigate the effects of cross training on team performance (see chapter 5). We expected that team members that were cross-trained developed better mental models containing knowledge of their teammates' roles and tasks, than team members that were not cross-trained. Because this allowed the cross-trained teams to anticipate on the informational needs of their teammates and coordinate their tasks implicitly, their performance should improve. The results of the first two studies, however, showed smaller effects of cross training on team performance than expected. Although our expectations regarding the impact of cross training could be unjustified, it is also possible that the fire-fighting task did not differentiate enough between good and poor performing teams. A thorough analysis of the fire-fighting task led to the following lessons learned.

Time pressure

When trying to obtain an effect of implicit coordination, it is important not only that team members are dependent on each other's information, and therefore must interact with each other substantially, but also that this must be accomplished under considerable time pressure. Being able to anticipate on each other's informational needs (because team members know which information to exchange and when that information should be exchanged) has more effect when time is limited, as time pressure precludes explicit, that is, extensive, coordination. In the first experiment using the fire-fighting task, scenarios contained several periods of 30 seconds each and the time between fires was relatively large. Looking back, we think that there was not enough time pressure. Even when team members did not anticipate on each other's informational needs and did not provide each other with the necessary information in advance of requests, there was still enough time to complete the task successfully. In the following experiments, we shortened the periods in the scenarios from 30 to 15 seconds. In addition, the successive fires were programmed in such a way, that team members should inform each other continuously about the status and the number of units allocated. This way, we attempted to provide team members with such time pressure that the use of efficient coordination strategies would be beneficial.

Dynamic scenarios

The second lesson we learned is related to the use of dynamic scenarios. The advantage of using dynamic scenarios is that it has high face validity with real-world dynamic situations. That is, scenarios develop over time autonomously (buildings are set on fire) and because of a completed action (allocated units extinguish fires). The disadvantage of using dynamic scenarios is that a minor mistake at the beginning of a scenario may have serious consequences for the further progress of that scenario. For example, when team members are one period too late with the withdrawal of units at the beginning of the scenario, it is difficult to be on time during the remainder of the scenario. Even when team members performed well during the remainder of the scenario, they would still be penalized for their mistake at the beginning. The consequence is that effective and ineffective teams are not differentiated when using those types of scenarios. When using dynamic scenarios in that they develop as a result of a completed action, they should be programmed in such a way that minor mistakes at the beginning of a scenario do not outweigh the results of effective performance on the remainder of the scenario.

Both lessons learned were taken into account in the development of a new version of the fire-fighting task. Nevertheless, besides the lessons learned, we were uncertain as to whether the requirements formulated previously are completely addressed. We had limited insight in whether the fire-fighting task addressed relevant command and control tasks. The roles and expertise team members had, and how they were dependent on each other were also unclear. Finally, we had limited insight in whether tasks had to be performed in parallel. To ensure that Version 2 of the fire-fighting task fulfilled the formulated requirements, we performed a task analysis of the fire-fighting task, based on a generic command and control model.

3.3 Task analysis of the fire-fighting task

To ensure that Version 2 of the fire-fighting task would contain command and control tasks, the fire-fighting task was further developed based on a generic command and control model. The model presented in Figure 3.3 is adapted from Passenier and Van Delft (1997) and is centered on four generic command and control tasks at two levels of information processing (see also Adams, 1995).

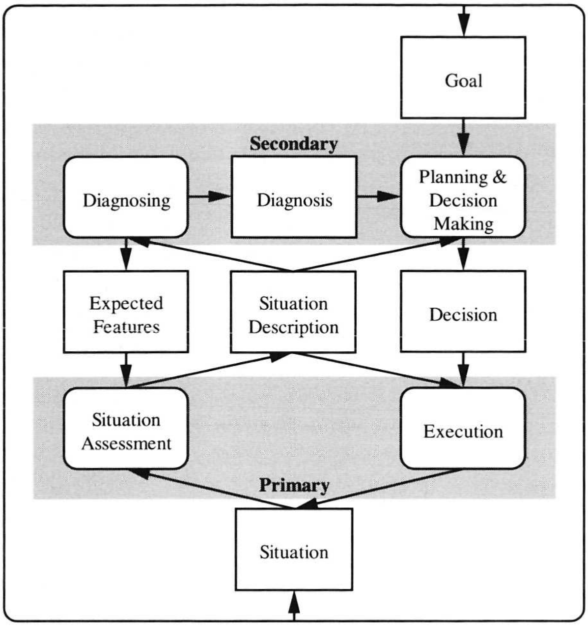

Figure 3.3: Model of generic command and control tasks to be performed by teams

The primary level represents a direct response to a monitored event. At this level, the situation is directly recognized and action is taken by applying a pre-defined rule. When the identity of detected objects is not directly clear, and their intentions must be investigated in more detail, then the secondary level of information transfer is invoked. At this level, plans are developed in the light of the goal that must be accomplished. The current situation is the input for the command and control process. *Situation assessment* consists of assembling and maintaining a picture of the actual situation, which results in a description of that situation. In terms of Endsley (1995), the objective of this task is "developing an awareness of the elements of the situation within a volume of time and space" (p. 36). When the situation is recognized, a team can respond by executing a pre-defined plan. At the secondary level, *diagnosing* of the situation takes place when a situation is encountered that is not directly clear. It concerns what Endsley (1995) calls "a comprehension of the meaning of the perceived elements in the environment, and the projection of their status in the near future" (p. 36) *Planning and decision making* encompasses the initiation of tasks in order to achieve the desired goal. At the secondary level, higher-order objectives, determined by the goal, and the type of tasks, are translated by the planning and decision-making task into plans or rules for executing the task at the primary level. At this level, *execution* takes account of the accomplishment of tasks.

When applying the generic command and control model to the fire-fighting task, we noticed that Version 1 misses several important command and control tasks. In particular, tasks that are concerned with the secondary level seemed to be missing. Because the situation was directly clear (e.g., there is a fire or not), there was no need for team members to diagnose. The scenario presented offered no possibilities to comprehend the meaning of the perceived elements and project their status on the near future. In order to remedy this, a situation was developed that was not directly clear and in which team members had to conduct a diagnosis. In the following section, this situation is outlined, followed by the description of the adjusted displays and the command and control tasks that are specified for the fire-fighting task.

3.3.1 The fire-fighting task: Version 2

We used Version 2 of the fire-fighting task for Experiment 4 and 5 described in chapter 6.

Situation

As with Version 1, the fire-fighting task is situated in a city where different buildings are set on fire. This time, the city consists of 76 buildings that are located in one of the four sectors. To have different sectors, the map was divided into four quadrants (sector I to IV). The scenarios that are developed for Version 2 are based on a prototypical scenario that consists of 12 periods of 15 seconds each (three minutes real time). In this scenario, first a house catches fire, next a school, then two apartments and a house, and finally a factory. Table 3.1 shows how a scenario develops over time.

Table 3.1: A prototypical scenario of 12 periods representing the situation that has to be dealt with

Period	1	2	3	4	5	6	7	8	9	10	11	12
Building (74)		house		school	ap. building	ap. building	house			factory		
Sector (4)		II		III	IV	IV	IV			I		
Potential casualties		2		100	10	10	2			500		
Units needed		1		3	2	2	1			5		

The scenario in Table 3.1 shows that the most important building to save is the factory. This fire can be prevented when sufficient units are located at the factory at the beginning of the fire. Each scenario contains a series of fires in small buildings that can be used to predict the sector and the type of a large building that will catch fire later in the scenario. When three small buildings in one sector catch fire (in the example scenario, two apartment buildings and a house in sector IV), a large building will catch fire in the opposite sector three periods later (in this scenario, a factory in sector I). When teams are able to comprehend this pattern in the series of fires and make a prediction of the expected large fire, a team can allocate units in time. Since the large building has proportionally the highest number of potential casualties within a scenario, this is crucial for a good performance. Predicting the building type and the sector helps to search the large building more closely. That is, instead of a random search across the map and clicking 32 buildings, the search can be directed to four buildings in one of the four sectors. Time is limited. The units need one period for transportation between the fire-fighting station and a particular building. Thus, to allocate sufficient units in Period 10, a team must have sufficient units available in Period 8.

There are also scenarios in which the pattern in a series of small fires follows different rules than usual. In routine scenarios, the pattern in a series of small fires always predicted the large fire in the way team members would expect based on the pattern they learned in their training. In novel scenarios, however, the large building is set on fire in another sector, building, or both, than team members would expect based on the pattern they learned in their training. If, for instance, a hospital was expected in the diagonally opposite sector, a factory would in fact be in danger next to the diagonally opposite sector. Scenarios are developed with different patterns in a series of fires. However, all scenarios can be considered as variations on the same theme.

In conclusion, the situation of the fire-fighting task corresponds to the situational characteristics of real-world command and control teams. The situation is rapidly changing and team members have to perform under time pressure. Furthermore, the scenarios represent a dynamic situation in that decisions made by the team (i.e., the allocation of units to buildings) influence the way scenarios develop. The scenarios of Version 2 are shortened and programmed in such a way that they are under higher experimental control than in Version 1. This way, minor mistakes of team members at the beginning of a scenario have less influence on performance during the remainder of the scenario.

Command and control tasks

Based on the command and control model, fire fighting is decomposed into a task hierarchy presented in Figure 3.4.

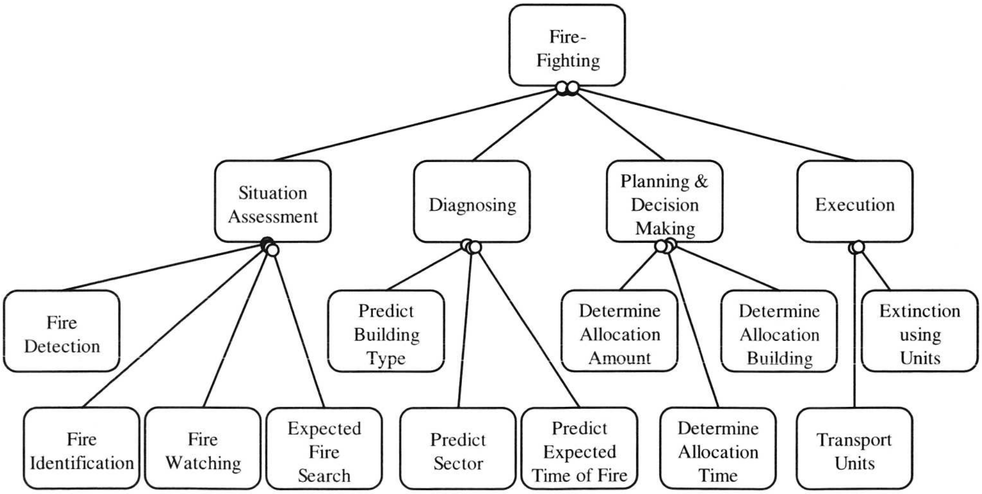

Figure 3.4: Hierarchy of tasks used in the fire-fighting task

The task hierarchy presented in Figure 3.4 shows that the fire-fighting task contains command and control tasks. Besides a decomposition of the command and control tasks, it is also important to describe the information needed to perform the tasks and the information dependency among tasks. This is important, because when tasks are assigned to team members, we can determine whether team members depend on each other's information. In the following paragraphs, the tasks of fire fighting are modeled in such a way that it gives a description of the information dependency between tasks. A more detailed description of the modeling approach used can be found in Essens, Post, and Rasker (2000). The representation language and graphics used in the models consist of a restricted set of descriptors with a consistent form and a consistent meaning. An arrow means data dependency, a small circle with a line represents a part-of relationship, a rounded box represents a task, and a square box represents an information entity.

Situation assessment

The first phase in fire fighting is to build an accurate and up-to-date situation picture. Figure 3.5 gives a model of the tasks and information used during situation assessment in the fire-fighting task.

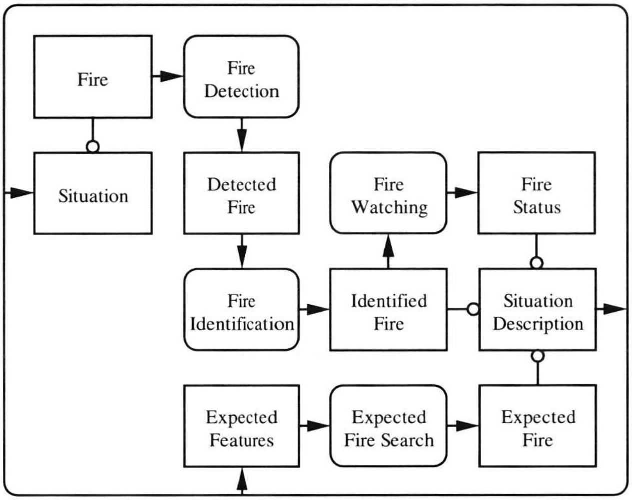

Figure 3.5: Model of the tasks and information used during situation assessment in the fire-fighting task

Fire detection uses information of the city and takes place by perceiving the colored contour that appears around a building. *Fire identification* describes the detected fire in terms of sector, type of building (whether it is a house, a hospital, etcetera) and units needed. Fire identification is performed by pointing and clicking on the buildings, which results in information about an identified fire that is displayed in the message overview window. *Fire watching* is performed in the same manner as fire detection. This task uses the identified fire information in order to determine whether a building is still on fire, burned down, or extinguished. A burning building needs to be watched each period to find out whether there are more or less units needed. *Expected fire search* takes place by searching for a potential fire in a hospital or factory based on the information concerning the expected features (i.e., the expected sector and building type). In Period 7, in which the last building of the pattern in a series of fires starts to burn, the four buildings in danger have to be checked out by pointing and clicking on the buildings on the map. When the expected fire is found, a building message appears in the inbox window, indicating "danger," the period in which the building will catch fire, and the number of units needed. Altogether, the information concerning the identified fires, the status of these fires, and the expected fire, specifies the situation description.

Diagnosing

In Version 2 of the fire-fighting task, it is important to determine the pattern in a series of small buildings in order to detect the large building in danger (i.e., hospital or factory) that is going to be set on fire later in the scenario. Figure 3.6 gives a model of the tasks and information used during diagnosing in the fire-fighting task.

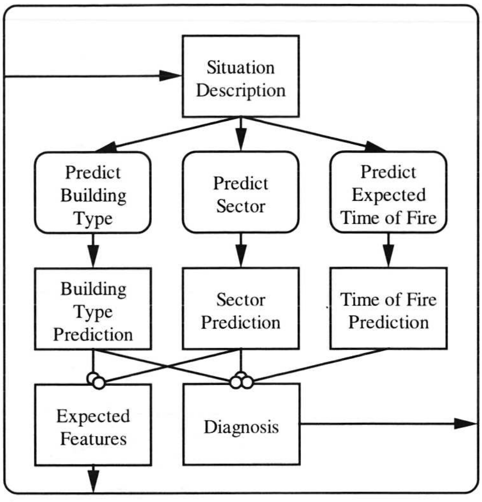

Figure 3.6: Model of the tasks and information used during diagnosing in the fire-fighting task

Predict building type describes whether the large building in danger is a hospital or factory. This task is performed by perceiving the pattern in a series of fires, from which the large building in danger can be derived. *Predict sector* describes in which sector the large building in danger is going to be set on fire. This task is performed by perceiving the sector in which the pattern of a series of fires takes place, from which the sector can be derived. Together, the information concerning the expected sector and the expected building type form the expected features that are used to search the expected fire during situation assessment. *Predict expected time* of fire describes at which period the large building in danger is going to be set on fire. This can be derived from the period at which the last building of a series completes the pattern. Altogether, the information concerning the predicted sector, building, and the expected time of fire comprise the diagnosis.

Planning & decision making

Because there are not enough units available to extinguish all fires, team members must decide to which buildings the units should be allocated to achieve the goal (i.e., save as many potential casualties as possible). Figure 3.7 gives a model of the tasks and information used during planning and decision making in the fire-fighting task.

Determine allocation building describes to which building a unit should be allocated or withdrawn from. This task uses situation information concerning the identified and expected fires and is performed by considering the importance of buildings in terms of the number of potential casualties. *Determine allocation amoun*t is performed by deciding how many units should be allocated or withdrawn. This task uses situation information concerning the fire status that specifies the number of units needed. *Determine allocation time* is performed by deciding on the period a unit should be allocated or withdrawn. Altogether, the information concerning the allocation building, number, and time, specifies the decision. The decision that is made can be effected by pointing and clicking on the function buttons on the screen display of the dispatcher. This contains a messages overview window in which the number of units can be allocated to the buildings by manipulating "+" or "-" buttons. The screen display of the dispatcher also contains a fire station window in which the number of units available is listed.

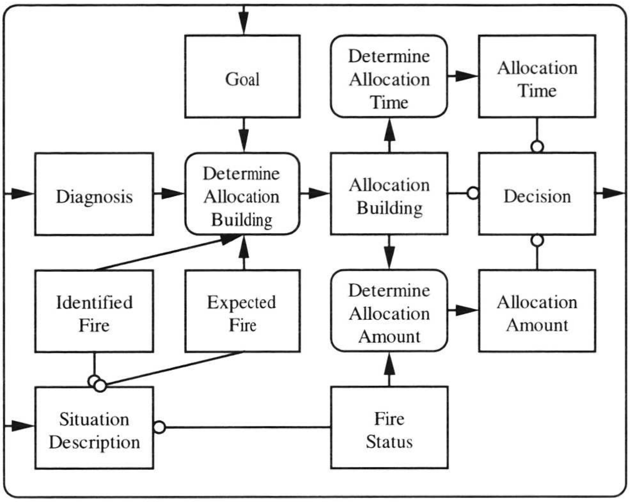

Figure 3.7: Model of the tasks and information used during planning and decision making in the fire-fighting task

Execution

The decision is executed in order to achieve the goal. Figure 3.8 gives a model of the tasks and information used during execution in the fire-fighting task.

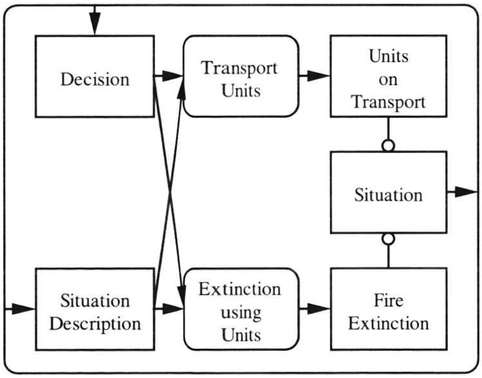

Figure 3.8: Model of the tasks and information used during execution in the fire-fighting task

Transport is performed when a unit is allocated and on the road. *Extinction* is performed when a unit is present at a building. Both tasks use decision information that specify the building, number of units, and time to allocate, and situation information that specify the identified and expected building, and status. The information concerning the transported units and the fire extinction are part of the information that specifies the situation.

Team member roles

In the fire-fighting task, the tasks are assigned to two team members (an observer role and a dispatcher role) and the system. The observer takes account of fire detection and identification of the buildings in the situation. Information on buildings must be provided to the dispatcher, who determines the type of building, number, and time of the allocation of units. Subsequently, the system takes care of the transport of units and the extinction of fires. When a building is on fire, the observer watches the building for possible status changes. When a series of fires in small buildings takes place, both the dispatcher and the observer will attempt to predict the building type (whether it is a hospital or factory) and the sector. This generates information of the expected features of the large building that is in danger. Based on that information, the observer will perform a search for the expected fire. In the meantime, the dispatcher predicts the time of the expected fire and determines the number of units needed. When the large building in danger is found, the observer must exchange this information to the dispatcher. Along with this information, the dispatcher transfers the decision to the units.

Information dependency

As described above, we determined for each task, the information input, output, and the information dependency among tasks. When the tasks are assigned to the team members, we can specify the information dependency of team members. Therefore, we developed a so-called *Team Operational Sequence Diagram* (TOSD). A TOSD is a diagram that represents the flow of tasks performed successively and in parallel by the team members as a response to an external event (such as a fire). TOSDs are also employed by Schaafstal and Van Berlo (2000) and Van Berlo (1998), and their representational format is similar to the event sequence diagrams (Essens et al., 2000) and the sequence and timing (SAT) diagrams (Beevis, Bost, Döring, Nordø, Oberman, Papin, Schuffel, & Streets, 1992). With the help of a TOSD, the information interdependency between team members can be determined normatively. Figure 3.9 shows a sample of a TOSD of Period 2 to 4 of the prototypical scenario.

Based on TOSD that we made for the entire scenario, we determined that the observer must inform the dispatcher about the new fires, the changes in the number of units needed, and the large building in danger. Without this information, the dispatcher cannot allocate units and save potential casualties when a building is on fire. The dispatcher must provide information about the allocation decision. The observer uses this information to watch the buildings. For a successful completion of the fire-fighting task, this is the necessary information exchange. Although additional information exchange may be beneficial, the TOSD shows that it is not necessarily needed to complete the tasks. The necessary information can be exchanged by the standardized electronic messages.

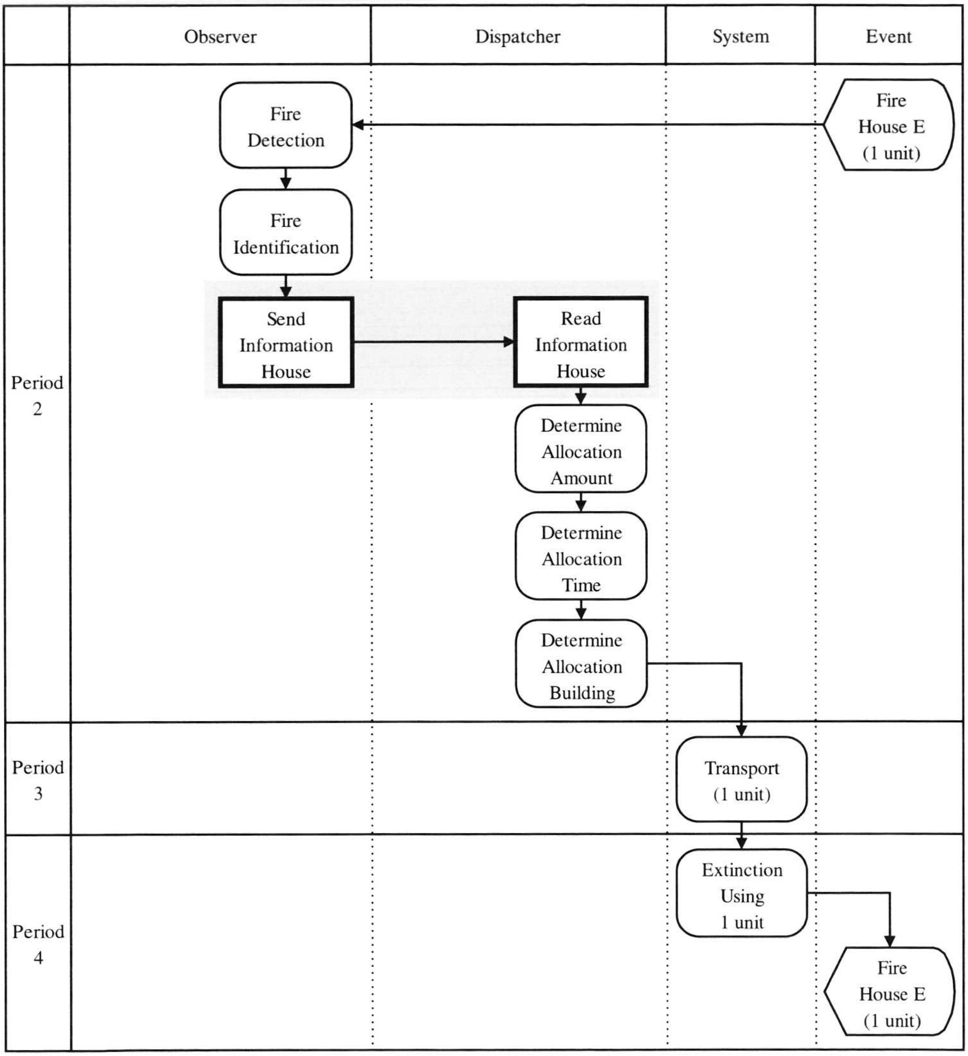

Figure 3.9: Sample of a TOSD; the diagram shows the flow of tasks team members perform as a response to a fire in Period 2 to 4 of the scenario

Screen displays

With respect to Version 1, the displays of the observer and the dispatcher are adjusted in Version 2 of the fire-fighting task. The display of the observer and the dispatcher are elaborated with two panels: one with four fields denoting the sectors and one with four fields denoting the large buildings. The panels for the dispatcher are button panels. When the dispatcher pushes a button in one of the two panels, the corresponding field is highlighted on the panel at the screen display of the observer. This way, the dispatcher is able to help the observer in predicting the sector and the building type of the large building in danger. The highlighted sector and building type represents the dispatcher's prediction. Figure 3.10 shows the panels placed on the screen display of the observer and the dispatcher.

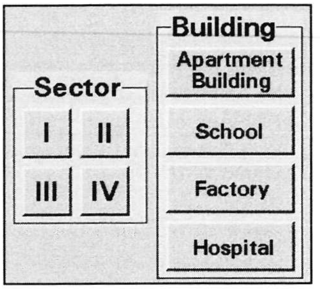

Figure 3.10: Panels placed on the screen display of the observer and the dispatcher in Version 2 of the fire-fighting task

Task parallelism

The TOSD shows that team members must perform tasks in parallel. This is especially true for Period 7 to 9. In these periods, task performance is most critical. Team members must obtain the pattern in a series of fires, exchange the electronic message of the large building in danger, withdraw and allocate units within the limited time frame of three periods. Diagnosing the threat and finding the large building in danger too late delays (re)allocation of the units, which has serious consequences for being in time to rescue the large building. For these periods a time-line analysis is performed. With this analysis, we attempt to demonstrate that the tasks have to be performed in parallel by two team members. In addition, the timeline analysis demonstrates that team members are able to exchange critical information in time with the use of the standardized electronic messages. Figure 3.11 and 3.12 present the time-line analysis for two different conditions. In the first condition, a single person carries out fire fighting, while in the second condition two team members carry out fire fighting.

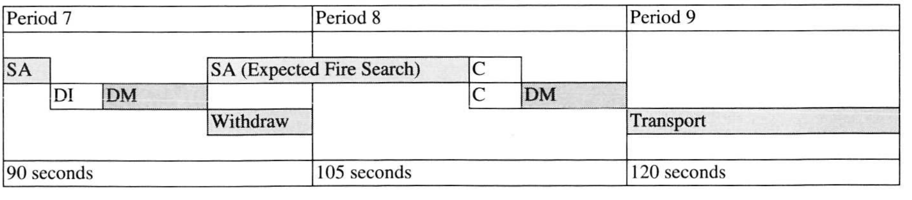

Figure 3.11: Timeline analysis of the critical periods in the fire-fighting task when tasks have to be performed by a single person (top row: observer tasks; middle row: dispatcher tasks; bottom row: system tasks)

In the first condition, the person starts, at the beginning of Period 7, with a situation assessment task (denoted by "SA"). He or she detects a building on fire and identifies the building type. Knowing what the previous buildings were, the person diagnoses a pattern in a series of buildings (denoted by "DI"), and is now able to predict the building type and the sector of the fire that is expected to start in Period 10. Next, the person starts to determine how many units need to be sent to the fire, and, if not enough are directly available in the fire station, from which buildings they need to be withdrawn (denoted by "DM," meaning decision making). Now, the search for the expected fire begins. After the expected fire has been found, the building is transferred from one screen to the other (denoted with "C," meaning communication). Finally, the available units can be allocated and transported.

The person has to work with two deadlines. It is essential that decisions about withdrawing units (in Period 7) and about allocating units (in Period 8) are performed in time, that is, before the start of a new period. Otherwise, transport is delayed with a full period. The most critical task is the search of the expected fire (the second SA task in the figure). When the expected fire is not found in time, the units will arrive too late at the building, causing many casualties. Therefore, it is important to start this task as soon as possible. The length of the expected fire search task represents the available time for searching. How much time this task takes, depends on the chance of finding the expected fire. The duration of the other tasks is always the same.

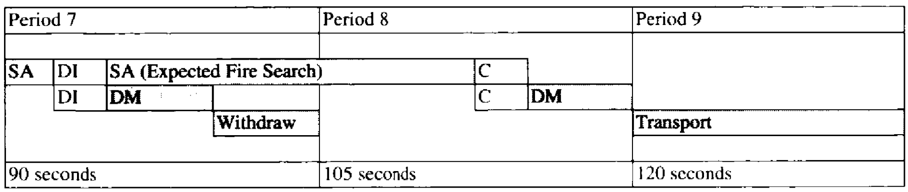

Figure 3.12: Timeline analysis of the critical periods in the fire-fighting task when tasks have to be performed by two team members (top row: observer tasks, middle row: dispatcher tasks, bottom row: system tasks)

Figure 3.11 clearly shows that several tasks are carried out sequentially. One way to start earlier with the search for the expected fire is to carry out tasks in parallel. To do this, a second person is needed. Figure 3.12 shows this condition. The observer starts with situation assessment. The last piece of the pattern in a series of fires is communicated to the dispatcher, and the observer can continue directly with diagnosing and searching for the expected fire, once the building type and sector is determined. In parallel, the dispatcher diagnoses the expected building and withdraws units.

Performance measurements

In Version 1 of the fire-fighting task, performance was expressed by the percentage of potential casualties saved. In Version 2 of the fire-fighting task, this measure was not suitable. The most important building to save in the scenario is the large building that is set on fire in Period 10, which is two periods before the scenario finishes. Even when team members perform well and are in time with sufficient units, the state transition diagrams are programmed in such a way that a fire is not extinguished before the scenario ends, which results in a low percentage of potential casualties saved. Consequently, this performance measure does not differentiate between well and poor performing teams. In order to reconcile this, a new performance measure is defined. The most important building to save is the large building in danger. Because this is crucial for accomplishing the goal (i.e., rescue as many lives as possible) of the task, having sufficient units allocated in Period 10 is defined as the new performance measure for Version 2 of the fire-fighting task.

3.3.2 The fire-fighting task: Version 3

We used Version 3 of the fire-fighting task for Experiment 3, 6, and 7 described in chapter 5, 8, and 9.

In Version 3 of the fire-fighting task, the state transition diagrams are adjusted in such a way that the percentage of potential casualties saved differentiates well between good and poor performing teams. When team members are in time with sufficient units, the fire in the large building is extinguished before the scenario ends. When team members are too late or have insufficient units, the fire in the large building cannot be extinguished before the scenario ends. The advantage of using the percentage of potential casualties saved when compared to the measurement of having sufficient units allocated is that it takes into account the small fires extinguished at the beginning of the scenario. Therefore, it measures more accurately team members' performance on the complete scenario. In addition, the scenarios of Version 3 are shortened with one period (the first period of a scenario) in order to shorten the duration of an experimental session. With respect to the prototypical scenario presented in Table 3.1, this means that all fires take place one period earlier (e.g., a large fire in Period 9 instead of Period 10).

3.4 Testing the fire-fighting task

With the help of the TOSD and the time-line analyses, we attempted to demonstrate that the fire-fighting task could be accurately performed only when more than one person executes the task. In order to test whether this is a valid assumption, an experiment is performed in which a single person condition is compared to a condition where two team members execute the fire-fighting task. Based on the task analysis, it is hypothesized that two team members perform the fire-fighting task better than a single person.

3.4.1 Method

Participants

The data were obtained from 33 students of Utrecht University. Eleven participants were assigned to the single person condition (seven males and five females) and 22 participants were assigned to the teams condition. Each team consisted of two participants of the same sex (six male and five female teams). Participants that formed the team were not acquainted to each other. The participants were paid Dfl. 60, = and were informed that they had a chance of receiving a bonus of Dfl. 40, =

Design

Between teams. Two conditions were compared: a *single person* and a *team* condition.

Within teams. The presence of novel scenarios was a within team manipulation. Routine and novel scenarios were equally present and were presented in a fixed order (i.e., first eight routine scenarios, followed by eight novel scenarios).

Task

In this experiment, Version 2 of the fire-fighting task was used.

Manipulation

In the single person condition, participants could control the features with the mouse on the observer as well as the dispatcher screen display with the help of specially designed software. By sending and receiving the standardized electronic messages, participants could transfer the necessary information from one screen display to the other. In the team condition, team members were placed in the same room and communication was made possible face-to-face. In addition, team members could exchange the necessary information by sending and receiving the standardized electronic messages.

Scenario type was manipulated as follows. In the routine scenarios, the pattern in a series of small fires predicted the large building in danger as learned during the training. For example, participants could predict a fire in a hospital in sector IV when they recognized the pattern of small fires that consisted of "apartment building-house-apartment building" in sector I. In novel scenarios, the sector of the large building in danger was different than participants would expect based on the pattern learned during the training. That is, instead of occurring in the diagonally opposite sector, the fire occurred in the sector underneath or above the sector with the pattern. The prediction with regard to the building type (factory or a hospital) remained intact.

Measure

Performance was measured by the number of scenarios in which team members allocated a sufficient number of units to the large building in danger in Period 10.

Procedure

In the team condition, participants were randomly assigned to the role of dispatcher and observer. In both conditions, participants were instructed to read the instruction manual supplied by the experimenter. Subsequently, they trained with the fire-fighting task in two training sessions, consisting of 16 scenarios each.

The instruction first explained the fire-fighting task in general, followed by specific instructions for the respective roles. The instruction contained a systematic explanation that described how to manipulate the interface and the standardized electronic message facility. This was accompanied by small tasks that had to be carried out by the participants. Subsequently, there was a training session of 16 scenarios. After the first training session, participants were asked to continue to read the instruction. In this instruction, it was explained how they could predict, based on a pattern in a series of small fires, the sector, type, and time of a large fire later in the scenario. These instructions were followed by another training session of 16 scenarios that contained such a pattern in a series of fires. Participants were allowed to ask questions at any point during reading. At the end of the break after the last training session, participants were instructed on the experimental condition they were assigned to.

During the training, the two members of the team played the same scenarios at the same time. The dispatcher played with a computer program that simulated observer behavior (e.g., sending messages and so forth) and the observer played with a computer program that simulated dispatcher behavior. The programs, or "agents" as they were called, displayed ideal observer and dispatcher behavior. That is, the agents were always in time with the right information. The participants were informed of this. Participants were also informed that in the experimental session they would play with their actual teammate. The choice for this technique was made, to ensure an equal level of expertise at the end of the training by controlling the teammate's behavior.

After this instruction, the experimental session of 16 scenarios started. Participants were allowed to use the manual during the experimental session.

3.4.2 Results and discussion

Participants could perform either sufficiently or insufficiently on the performance measure allocation. The scores can be found in Table 3.2.

We fitted three log-linear models to the data. The first model included the general mean and the design (i.e., sufficiency, condition * scenario type). The second model included the general mean and the design and the main effect of condition (i.e., sufficiency, condition * scenario type, condition * sufficiency). For both models Pearson's Chi^2 was calculated. To test the main effect of condition, the Chi^2 of the first model minus the Chi^2 of the second model was tested. The degrees of freedom for this test were the ones of the first model, minus the ones of the second model. The third model included the general mean and the design and the main effects of condition as well as scenario type (i.e., sufficiency, condition * scenario type, condition * sufficiency, scenariotype * sufficiency). To test the interaction effect of condition and scenario type, the Chi^2 and the degrees of freedom of this model were tested. To test the differences between conditions on either the routine or novel scenarios, a Chi^2 for each separate two-way table was calculated and tested.

Table 3.2: Performance measure allocation; total number of scenarios in which participants had allocated a sufficient number of units during Period 10 for each condition and scenario type ($N = 352$)

Condition	Scenario type	Allocation	
		Sufficient	Insufficient
Single person	Routine	5	83
	Novel	16	72
Team	Routine	23	65
	Novel	28	60

The comparison between the single person versus team condition yielded significant results. As can be seen in Figure 3.13, teams perform better than single persons. The teams allocated sufficient units in more scenarios (29%) than single persons (12%), $\chi^2(1, N = 352) = 13.38, p < .01$. Teams also allocated sufficient units in more routine scenarios (26%) than single persons (6%), $\chi^2(1, N = 176) = 13.76, p < .01$, and in more novel scenarios (32%) than single persons (18%), $\chi^2(1, N = 176) = 4.36, p < .05$. There was no interaction between condition and scenario type, $\chi^2(1, N = 352) < 1$.

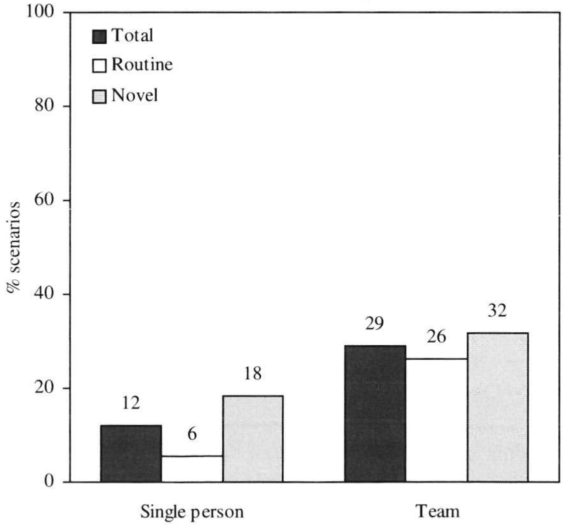

Figure 3.13: Performance measure allocation; percentage of scenarios in which participants had allocated a sufficient number of units during Period 10 for each condition and for the total number of scenarios as well as for the routine and novel scenarios separately

Based on this result we conclude that two team members perform the fire-fighting task better than a single person does. The task and the timeline analysis show that teams can perform tasks in parallel so that each team member has more time to perform the tasks accurately. We think that this explains the performance increase for teams. In other words, the present experiment demonstrated that the fire-fighting task needs the capacity of two team members. Although the fire-fighting task was better performed by a team than a single person, we cannot conclude that the fire-fighting task is a team task. A team task implies, among other things, that members perform teamwork such as communication and coordination. In chapter 4, we describe a cognitive team task analysis that is performed to answer the question whether the fire-fighting task is actually a team task and not only a task that is better performed by teams.

3.5 Conclusions

The objective of this chapter was to give an outline of the task that is used throughout this thesis and to describe on what grounds the task is developed and what general lessons we learned. The development of an experimental team task is a complex matter that took us several iterations before the design fulfilled the requirements we extracted from the team literature. In order to investigate teamwork, a task must comprise at least two people that work together towards a common goal and who have been assigned to specific roles and tasks. One of the most important requirements is that team members interact interdependently. Interdependency requires team members to engage in teamwork behaviors such as communication and coordination which is of particular interest in our research. Furthermore, team members must perform relevant command and control tasks in a situation that is dynamic and rapidly changing with limited time available.

A task analysis based on a generic command and control model supported the development of the experimental team task to fulfil the requirements. With the use of the described task analysis method, we specified relevant command and control tasks, a dynamic situation, and the information needed to perform these tasks accurately. Furthermore, the sequence of tasks for each team member is determined in a TOSD. Based on this, we specified the different roles and expertise of the team members and the information dependency between them. In addition, the task analysis showed that tasks have to be performed in parallel, which demonstrates that the fire-fighting task is a team task for two members. An experiment in which teams were compared with individuals showed that teams performed the task better, indicating that fire fighting needs the capacity of two team members.

Based on the task analysis we conclude that the fire-fighting task provides an environment in which team processes can be elicited and investigated. However, it is not clear to what extent team processes or teamwork are present and what knowledge is needed to perform the teamwork. We determined that team members have specific roles and are interdependent. Although this means that team members need to interact, we have no clear picture of the importance to communicate efficiently and effectively or coordinate implicitly. In other words, it is unclear to what extent communication in relation to the knowledge team members have in their shared mental models can be investigated with the fire-fighting task. With respect to our goal to test a theory, this means that we need a better understanding of whether such theoretically relevant aspects are present in the fire-fighting task. In the next chapter, a cognitive team task analysis is described that we performed to determine the teamwork and the knowledge needed to accomplish the fire-fighting task. With the help of this analysis we attempt to answer the question whether the fire-fighting task contains the theoretically relevant aspects to test the shared mental model theory empirically.

4 COGNITIVE TEAM TASK ANALYSIS

This chapter describes a cognitive team task analysis of the fire-fighting task. We performed this analysis to determine the teamwork and the knowledge needed to perform the fire-fighting task. In addition, we examined the way communication may foster the knowledge in shared mental models. We performed a qualitative analysis of the verbal communication that took place in the teams that participated in Experiment 5 (see chapter 7). Altogether, the cognitive team task analysis gives a description of the relationships between team processes, knowledge in shared mental models, and performance in the fire-fighting task.

4.1 Introduction

In chapter 3, the fire-fighting task was introduced as an experimental team task. We performed a task analysis to determine to what extent the fire-fighting task contains command and control tasks, team members have specific roles and responsibilities, are interdependent, and to what extent tasks have to be performed in parallel. Nevertheless, this is only one part of the picture. What is missing is an analysis of the teamwork and knowledge team members need in order to perform the fire-fighting task effectively. In terms of Potter, Roth, Woods, and Elm (2000), the task analysis of chapter 3 provides an analysis of the domain in which the focus is on developing an understanding of the way the world works and what it requires of the team members. Here, we provide an analysis of the teamwork and the knowledge needed for the fire-fighting task.

The cognitive team task analysis is important for the research questions formulated in the introduction of this thesis. To investigate these questions, the fire-fighting task must contain the relevant psychological aspects concerning the theory under investigation (Driskell & Salas, 1992a). For the shared mental model theory, these aspects are knowledge and teamwork. More precisely, it is hypothesized that team and situation knowledge in shared mental models influence the way team members communicate, coordinate implicitly, and determine strategies together and, the other way around, communication influences team members' team and situation knowledge in shared mental models. Thus, the psychological aspects that must be present in the fire-fighting task are communication, implicit coordination, and team and situation knowledge. When these aspects are present in the fire-fighting task, we have greater confidence that we can test the shared mental model theory empirically. In line with Driskell and Salas (1992a), we assert that, in turn, the theory, not the task, can be generalized to real world teams in which these aspects are also present. The main purpose of the analysis is, therefore, to reveal to what extent teamwork and knowledge are present in the fire-fighting task.

The analysis serves several other purposes as well. First, the analysis must make clear whether the knowledge needed for the teamwork in the fire-fighting task has to be shared among team members. Therefore, the description of the knowledge needed to accomplish the teamwork must be examined in relation to the knowledge that researchers have hypothesized to be important in shared mental models. This way, the issue of sharedness (i.e., whether knowledge is overlapping or distributed among team members) will be, at least for the fire-fighting task, resolved. Second, the analysis must make clear how communication can be used to foster the knowledge of team members in a mental model. Therefore, it must be determined how team members communicate and what knowledge is transferred. Third, the analysis must make clear what the relationship is between the knowledge, teamwork, and the performance measurements. This can be used to determine to what extent the performance is an indication of effective teamwork and having shared mental models. Finally, the analysis must make clear what teamwork and knowledge can be measured in the fire-fighting task.

Because it is not an easy task to provide a complete analysis of the teamwork, knowledge needed, and communication, we analyzed this step-by-step. The strategy we adopted was to begin with the relatively simplest condition, and subsequently add more complexity. Therefore, the first step was to describe normatively the teamwork and the knowledge needed for the condition in which teams have *no* opportunity to communicate verbally. In this condition, the information exchange needed to accomplish the tasks takes place by using the standardized electronic messages. Team members can only send each other messages and cannot speak freely to, for example, determine strategies cooperatively or to transfer knowledge about the teamwork demands. Because team members are restricted in their opportunities to communicate, this condition is referred to as the restricted condition. The task analysis of chapter 3 is taken as a starting point to determine what teamwork is needed in the fire-fighting task when teams communicate restrictedly. Subsequently, we described for each task, including the teamwork tasks, the knowledge needed. Based on this description, we linked the teamwork in the fire-fighting task to the generally formulated teamwork concepts. Likewise, we linked the knowledge needed for the teamwork in the fire-fighting task to the knowledge that is expected to be important in shared mental models. Finally, we related this to the performance measures. Section 4.2 describes the first step of the analysis.

The second step was to analyze the condition in which teams have the opportunity to communicate verbally. In this condition, team members must also exchange the information that is needed to accomplish the tasks using the standardized electronic messages. However, on top of that, team members are allowed to communicate verbally and are free to exchange any information they like. Verbal communication can be viewed as an additional opportunity team members have to optimize their task performance. Team members may use this opportunity to transfer knowledge, perform the command and control tasks jointly, or to perform teamwork. Because team members are unrestricted in their opportunities to communicate, this condition is referred to as the unrestricted condition. For this condition, we also described normatively the teamwork that can be performed when team members can communicate unrestrictedly and the knowledge needed for that purpose. Based on the literature we developed a model in which the relationships between the knowledge in shared mental models, task performance and teamwork is illustrated. We used the model to describe the knowledge that is expected to be transferred between team members and to define categories in which the communication can be classified.

The last step in the analysis was to examine the verbal communication in order to get a better picture of the knowledge that is transferred between team members and how team members use their communication opportunity to optimize task performance. The communication that took place during Experiment 5 (see chapter 7) was transcribed into verbal protocols. Based on the verbal protocols we examined how team members communicated and whether this could be linked to the communication categories we normatively defined. Subsequently, a detailed description is provided of the knowledge that is transferred in each of the categories. This is linked to the knowledge that we normatively determined to be needed to perform teamwork in the fire-fighting task. Altogether, this must provide a good understanding of how communication may foster the knowledge team members have in their mental models. Section 4.3 describes the second and the third step of the analysis.

The advantage of analyzing the restricted and unrestricted condition separately is that it gives a clear description of what happens when team members have the opportunity to communicate unrestrictedly compared to the team members that do not have this opportunity. Note, however, that the normative analyses of the restricted communication condition can also be applied to the teams that communicated unrestrictedly. In both conditions, the command and control tasks are similar and teams *must* exchange the information needed to accomplish the tasks by using the standardized electronic messages. Unrestricted communication is not needed to perform the fire-fighting task successfully. However, it may help team members to perform additional tasks and optimize their task performance. In chapter 5 and 6, which comprise the first perspective in this thesis, teams are investigated that could only communicate restrictedly. From this perspective, we are interested in the communication as a result of shared mental models. Therefore, we analyzed whether the standardized electronic messages reflect implicit coordination as a result of shared mental models. In chapter 7 to 9, which comprise the second perspective in this thesis, the opportunity to communicate unrestrictedly was varied in several ways. From this perspective, we are interested in communication as antecedent of shared mental models. Therefore, in various conditions, teams had the opportunity to communicate unrestrictedly either during scenarios, between scenarios, or both. To test the effect of communication on shared mental models and performance these teams were contrasted with teams that could only communicate restrictedly.

4.2 Restricted communication

In this section, we are interested in two questions. First, what teamwork tasks must team members perform to accomplish the tasks in the fire-fighting task successfully, and, second, what knowledge do team members need to perform the (teamwork) tasks? The starting point of the cognitive team task analysis is the TOSD of the prototypical scenario of the second version of the fire-fighting task (see chapter 3). For each coherent series of tasks (e.g., from detecting a fire to sending information about that fire) a specific TOSD is developed. This can be viewed as a snapshot of a task sequence that shows when and which tasks, including the teamwork tasks, have to be performed to be in time in the fire-fighting task and to accomplish the tasks successfully. For each task in the TOSD, we determined the cognitive tasks or critical decisions team members have to perform and the knowledge that is needed (Potter et al., 2000). This is described in separate tables that are linked to the TOSDs. Each task in the TOSD is labeled with a number that corresponds to the row in the table. Subsequently, the row describes the cognitive tasks or critical decisions, and the knowledge. The complete set of TOSDs and the corresponding tables in this section represent all task sequences that are present in Version 2 and 3 of the fire-fighting task. TOSD 1 and 2 and the corresponding tables can be applied to Version 1. However, the difference is that in Version 1 a period lasts 30 seconds, whereas in Version 2 and 3 a period lasts 15 seconds.

4.2.1 Restricted communication, teamwork, and knowledge

Team operational sequence diagram 1

The first task sequence begins when a building is on fire. The observer detects and identifies fires and sends the information to the dispatcher. Figure 4.1 presents a TOSD of these tasks. In Table 4.1, a description is provided of the cognitive tasks versus critical decisions and the knowledge needed to perform the tasks presented in Figure 4.1. To perform fire detection and identification, the observer needs declarative knowledge about the city, building types, and potential casualties associated with each building type.

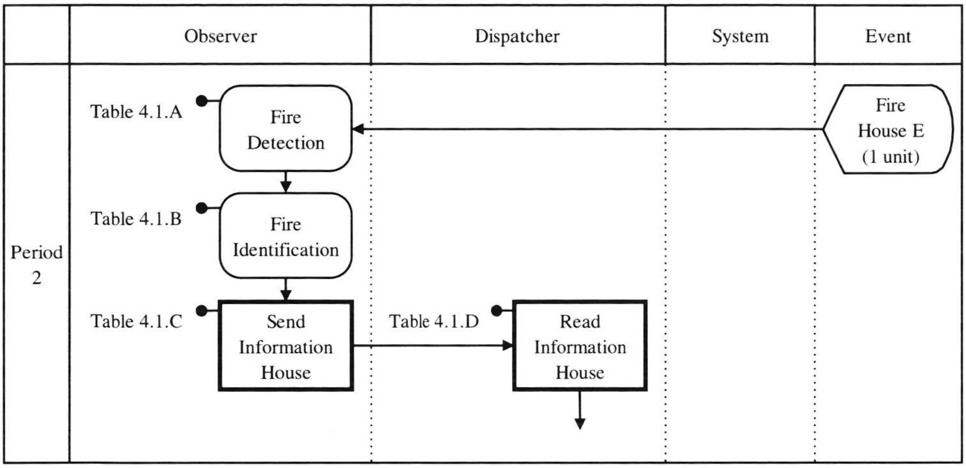

Figure 4.1: TOSD 1; from fire detection to read information

In all subsequent TOSDs, teamwork tasks are marked in boldface. Teamwork in TOSD 1 is the communication task *send information*. The observer must send the information about the fires to the dispatcher. The standardized electronic message facility can be used for that purpose. Therefore, the observer needs procedural knowledge of how to use this facility. To decide that the information about fires is important for the dispatcher, the observer must know that the dispatcher uses this information to decide on the allocation of units. To read the message about the fires, the dispatcher must know that messages contain information about new fires. To coordinate implicitly, the information about fires must be sent in time and without requests by the dispatcher. Therefore, the observer must know *when* this information is important to give to the dispatcher (i.e., within one period). The knowledge needed to perform the tasks of TOSD 1 can be obtained from the instructions that are developed to train team members in the fire-fighting task. The instructions describe how team members can use the standardized electronic message facility to exchange the necessary information. The roles and responsibility of the team members are also explained. There is no explicit description of how to coordinate implicitly. However, the instruction does emphasize the importance to exchange information in time.

TOSD 1 shows that teamwork, namely communication and implicit coordination, is included. Table 4.1 shows further that to perform this, the observer needs knowledge about the dispatcher's task and team interaction knowledge of when information must be provided.

Table 4.1: Cognitive tasks versus critical decisions and the knowledge needed for fire detection and identification, and send and read information

	Task	Cognitive tasks/ critical decisions	Knowledge
4.1.A	Fire detection (observer)	• Monitor the map of the city • Detect fires by perceiving a flashing red colored contour around buildings	• The city contains buildings which can catch fire • A flashing red colored contour around a building means fire
4.1.B	Fire identification (observer)	• Decide on clicking on the building when a fire is detected • Read information about the building • Determine building type • Determine potential casualties • Determine the number of units needed to extinguish the present fire	• Clicking on a building gives information about the building type • Different buildings in the city represent different building types (house, apartment building, school, factory, and hospital) • Different building types have different numbers of potential casualties • Different building types need different numbers of units to extinguish the fire
4.1.C	Send information (observer)	• Decide that the information of the building on fire is needed by the dispatcher • Decide that this information must be sent at this time • Decide to put information in the outbox window • Decide to send information to the dispatcher	• The dispatcher needs information of buildings on fire to decide on the allocation of units • The sooner the dispatcher receives this information, the sooner the fire can be extinguished • Information of fires should be sent within one period • Information can be sent using the outbox window • Information is sent to the dispatcher by clicking the send button
4.1.D	Read information (dispatcher)	• Decide on reading the message in the inbox • Read information about the building	• Messages in the inbox contain information of the observer about new fires

Team operational sequence diagram 2

After reading the information about the fire, the dispatcher decides whether units will be allocated to that fire. Therefore, the allocation amount, time, and building must be determined. These tasks are represented in TOSD 2 depicted in Figure 4.2. In Table 4.2, the cognitive tasks versus critical decisions and the knowledge needed are described. First, the dispatcher determines the number of units needed to extinguish the present fire and compares this number with the units available in the station. The dispatcher must know that there is a limited number of units and that there are different building types that need different numbers of units to extinguish the potential fires. To determine whether units can be withdrawn, the dispatcher needs knowledge about when and how withdrawal must take place. The dispatcher can obtain this knowledge from the instructions that describe the allocation procedure in detail. The instruction of the observer does not contain such detailed information about the allocation procedure. However, the instruction of the observers does contain information about that different building types need different numbers of units and that the number of units available is limited.

To determine the best time to allocate units, the dispatcher needs procedural knowledge that describes that the sooner units are present, the sooner the fire will be extinguished. For large buildings (i.e., factories and hospitals), this procedural rule is slightly different. Units have to be present at the onset of the fire. Otherwise, the building cannot be saved. Note that the sector and the type of fires in large buildings can be predicted by determining a pattern in small buildings at the beginning of a scenario. Thus, when a pattern is determined in time, the dispatcher can allocate units at the beginning of a fire. In combination with the knowledge about the number of units available and the opportunities to withdraw units, the dispatcher can determine whether it is possible to allocate units in time to the present fire. In the instructions of the observer as well as the dispatcher, it is highlighted that fires must be extinguished as soon as possible. With respect to the large building in danger, the instructions explain explicitly that units have to be present at the onset of the fire.

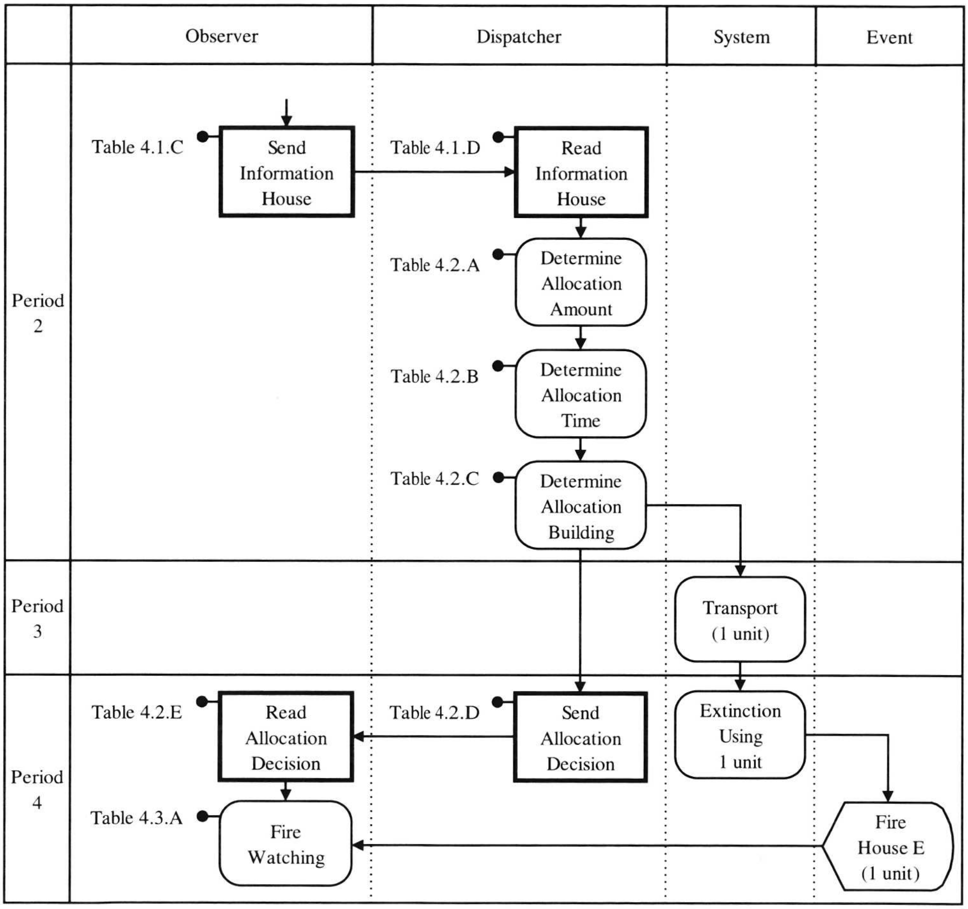

Figure 4.2: TOSD 2; from send information to fire watching

Finally, the dispatcher determines whether the present fire has more priority over the fires that started earlier. Declarative knowledge is needed about the number of potential casualties associated with each building type. For both team members the instructions include a table that gives an overview of the building type, number of potential casualties, and number of units needed in case of a fire. Strategic knowledge describes whether the fire in the present situation has priority over fires that started earlier. The knowledge elements needed to determine the allocation time and building are task related.

When the allocation decision is made, the dispatcher may fulfil his or her teamwork and send this information to the observer. Just as with the observer, the dispatcher needs procedural knowledge about how to send the standardized electronic messages. To decide that the information of the allocation decision is important for the observer, the dispatcher must know that the observer uses this information to decide on which fire has higher priority to watch. The instruction informs the dispatcher about the responsibility of the observer to watch fires. To coordinate implicitly, the information about the allocation decision must be sent in time and without requests by the observer. Therefore, the dispatcher must know when this information is important for the observer. Although the instruction of the dispatcher does not include an explicit explanation of how to coordinate implicitly, the importance to be in time is emphasized.

Table 4.2: Cognitive tasks versus critical decisions and the knowledge needed for determine allocation amount, time, and building, and send and read allocation decision

	Task	Cognitive tasks/ critical decisions	Knowledge
4.2.A	Determine allocation amount (dispatcher)	• Determine the number of units needed to extinguish the present fire • Determine the number of units available in the station • Determine whether there are sufficient units available to allocate to the present fire • Determine the number of units that are in transport to a building • Determine the number of units present at a building • Determine the building types where units are allocated • Determine the number of periods that units are present when a building is on fire	• Different building types need different numbers of units to extinguish the fire • The number of units is limited (six units available) • Units in transport cannot be allocated or withdrawn • Units that are present cannot be allocated • Units must first be withdrawn to the station, before they can be allocated • Different buildings in the city represent different building types (house, apartment building, school, factory, and hospital) • The more periods units are present, the more the fire is extinguished
4.2.B	Determine allocation time (dispatcher)	• Determine whether the time to allocate is in time to extinguish the fire	• The more periods units are too late, the smaller the chance that a building can be extinguished • If a sufficient number of units is not available at the beginning of a predicted fire in a large building, then the fire cannot be extinguished • Present fire can be extinguished in time
4.2.C	Determine allocation building (dispatcher)	• Decide on the withdrawal of units • Decide on the allocation of units to the present building	• Different building types have different numbers of potential casualties • Present fire has more priority than previous fire
4.2.D	Send allocation decision (dispatcher)	• Decide that the information of the allocation decision is needed by the observer • Decide that this information must be sent at this time • Decide to put information in the outbox window • Decide to send information to the observer	• The observer needs information of the allocation decision to decide which fire has higher priority to be watched • The sooner the observer receives this information, the sooner the fire can be watched • Information of the allocation decision should be sent within one period • Information can be sent using the outbox window • Information is sent to the observer by clicking the send button
4.2.E	Read allocation decision (observer)	• Decide on reading the message in the inbox • Read information about the building	• Messages in the inbox contain information of the dispatcher about the allocation decision

The dispatcher needs mostly task-related knowledge to perform the tasks described TOSD 2. To perform the teamwork (i.e., communication and implicit coordination), Table 4.2 shows that the dispatcher needs declarative knowledge about the task of the observer and procedural knowledge of when information must be provided.

Team operational sequence diagram 3

When there are buildings on fire, the observer must monitor the status (i.e., fire, saved, or burned down) of the buildings and watch he number of units needed. TOSD 3 depicted in Figure 4.3 represents these tasks. In Table 4.3, the cognitive tasks versus critical decisions and the knowledge needed are described. Dependent on the number of units present, the number of units can be different each period. That is, fewer units are needed when a building is about to be saved and more units are needed when a building is about to be burned down. Knowledge is needed to know when the number of units is most likely to change (i.e., *not* during a period, but after the clock resets and the new period begins) and a building is saved or burned down. The observer can obtain this knowledge from the instruction that describes how a fire typically evolves.

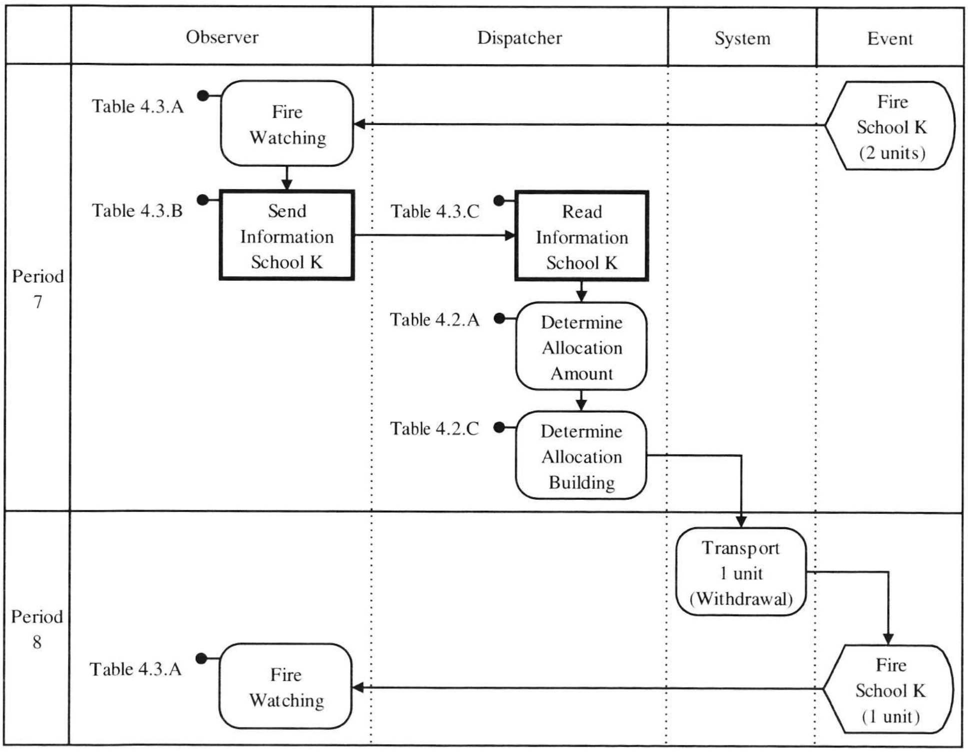

Figure 4.3: TOSD 3; from fire watching to fire watching

Again, the observer must perform teamwork by giving the information about the building (including the number of units needed) to the dispatcher. Knowledge about how to send standardized electronic messages is needed and can be obtained from the instructions. To decide that the information about the number of units is important for the dispatcher, the observer must know that the dispatcher uses this information to decide on the allocation amount and building. Note that it is inefficient for the observer to send continuously information about the buildings on fire. Implicit coordination implies that the observer *only* sends information about a building on fire when the number of units needed is changed. Therefore, the observer must know that only the information about changes in the number of units needed to extinguish a fire is important for the dispatcher. The instruction of the observer provides a description of the role and informational needs of the dispatcher. Although the instruction describes that the dispatcher needs information about new fires and the changes in the number of units, there is no explicit instruction of how to coordinate implicitly and provide the necessary information in advance of requests.

TOSD 3 shows that this task sequence contains teamwork. To communicate effectively and engage in implicit coordination, the observer needs declarative knowledge about the dispatcher's task and procedural knowledge of when information must be provided.

Table 4.3: Cognitive tasks versus critical decisions and the knowledge needed for fire watching, and send and read information

	Task	Cognitive tasks/ critical decisions	Knowledge
4.3.A	Fire watching (observer)	• Determine when a building on fire needs more or less units • Detect extinguished fires by perceiving a flashing green colored contour around a building • Detect burned fires by perceiving a black colored contour around a building • Decide on clicking on a building • Read information about the building	• Within a period the number of units needed remains the same • Dependent on the number of units allocated, buildings on fire need more or less units • Green colored contour means a building is extinguished and the potential casualties are saved • Black colored contour means a building is burned down and the potential casualties are expired • At the beginning of each period the number of units may change
4.3.B	Send information (observer)	• Decide that the information about the number of units needed to extinguish the fire is needed by the dispatcher • Decide that this information must be sent on this time • Decide to put information in the outbox window • Decide to send information to the dispatcher	• The dispatcher needs information about the number of units needed to extinguish the fire to determine the allocation amount and building • The dispatcher needs information about the changes in the number of units needed to extinguish the fire • The sooner the dispatcher receives this information, the sooner the dispatcher can allocate or withdraw units • Information of fires should be sent within one period • Information can be sent using the outbox window • Information is sent to the dispatcher by clicking the send button
4.3.C	Read information (dispatcher)	• Decide on reading the message in the inbox • Read information about the building	• Messages in the inbox contain information of the observer about the number of units needed to extinguish fires

Team operational sequence diagram 4

In the previous paragraphs, we described how team members react on a detected fire and allocate units. Efficient and timely communication is important to be on time to extinguish the fires and save the buildings. The tasks and knowledge elements that are involved are typical for the first six periods of a scenario. From the seventh period, team members must predict the type and sector of a large building based on a pattern in fires of small buildings. This is important because in order to extinguish a fire in a large building (i.e., a factory or a hospital) units must be present at the beginning of that fire. It is essential that the observer finds the expected fire in a large building before it starts to burn and provide this information to the dispatcher. If the dispatcher does not receive this information in time (i.e., before Period 9), then the dispatcher cannot allocate units in time and save the large building. Recall that predicting the building type and the sector helps the observer to search the large building more closely, whereas the dispatcher uses this to withdraw units in time and reallocate them to the large fire in danger.

Predicting the building type begins with the observation that a series of fires in one sector forms a pattern. After the detection and identification of the fire that forms the last part of a pattern, both team members start to predict the building type. TOSD 4 depicted in Figure 4.4 represents these tasks. In Table 4.4, the cognitive tasks versus critical decisions and the knowledge needed are described. Declarative knowledge is needed to know that there are patterns in a series of small fires in each scenario. Procedural knowledge is needed to know how the various patterns predict a fire in one of the two large building types (i.e., a factory or hospital). The instructions of both the observer and the dispatcher contain the procedural rules that describe how a large building in danger can be predicted from a series of fires in small buildings.

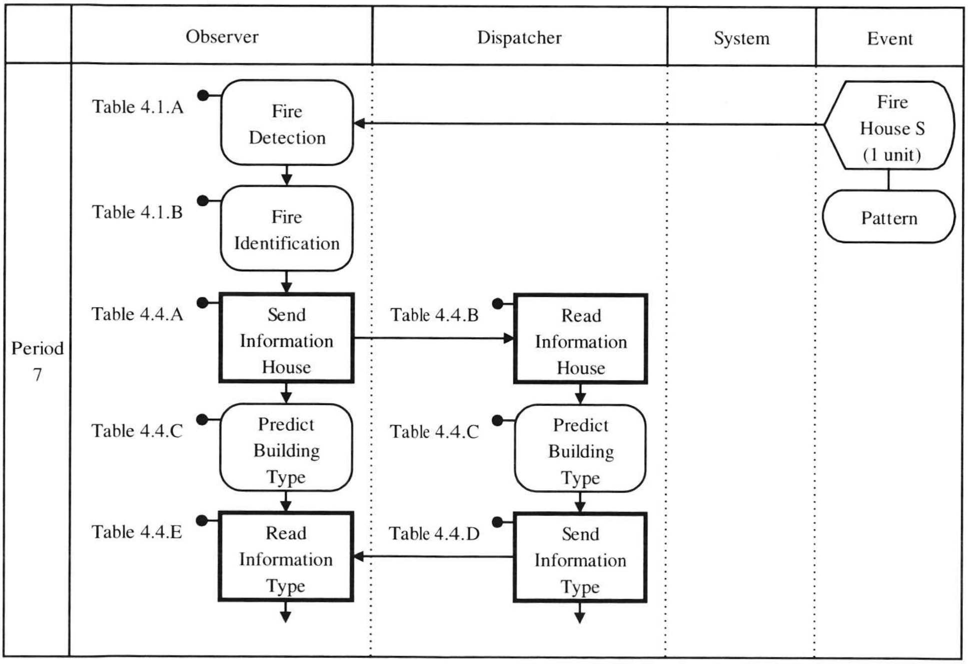

Figure 4.4: TOSD 4; from fire detection to read information type

Teamwork in this TOSD 4 begins with the observer that must send the information of the building on fire to the dispatcher. We already outlined that the observer must provide timely information about the detected and identified fires to the dispatcher (see TOSD 2). In this case, the knowledge needed to provide this information is slightly different. Instead of knowing that the dispatcher uses information of the fires to (re)allocate units, the observer must know that the dispatcher also uses this knowledge to predict the building type. This may seem look unimportant because the information of fires will be sent anyhow. However, because this is the last fire of a pattern and there are insufficient units to extinguish this fire anyway, the observer might think that the dispatcher does not need this information. To ensure that this information will be sent, it is important that the observer knows that the information of the last fire of a pattern is important for the dispatcher to predict the building type, and hence the number of units that need to be withdrawn from other buildings. To provide this information in time and without requests by the dispatcher (i.e., implicit coordination), the observer needs procedural knowledge about when in the dispatcher's task sequence this information must be provided (Period 7). The instruction provides the observer with general information that describes that the dispatcher is responsible for the timely withdrawal of units.

Table 4.4: Cognitive tasks versus critical decisions and knowledge needed for predict building type, and send and read information

	Task	Cognitive tasks/ critical decisions	Knowledge
4.4.A	Send information (observer)	• Decide that the information of the building on fire is needed by the dispatcher • Decide that this information must be send on this time • Decide to put information in the outbox window • Decide to send information to the dispatcher	• The dispatcher needs information of buildings on fire to determine a pattern in a series of fires • The sooner the dispatcher receives this information, the sooner a pattern can be determined • Information of fires should be sent within one period • Information can be sent using the outbox window • Information is sent to the dispatcher by clicking the send button
4.4.B	Read information (dispatcher)	• Decide on reading the message in the inbox • Read information about the building	• Messages in the inbox contain information of the observer about new fires
4.4.C	Predict building type (observer and dispatcher)	• Decide that there is a pattern in the fires of small buildings • Determine the building types of the small fires in the same sector • Determine the type of building that is expected to be set on fire	• A series of three fires in small buildings in one sector forms a pattern • Different sequences of building types in a series of three fires in small buildings determine the fire in a large building: • The pattern: "apartment building-house-house" predicts a fire in a factory • The pattern: "apartment building-apartment building-house" predicts a fire in a factory • The pattern: "apartment building-house-apartment building" predicts a fire in a hospital • The pattern: "apartment building-apartment building-apartment building" predicts a fire in a hospital
4.4.D	Send information type (dispatcher)	• Decide that the information of the predicted type is important for the observer • Decide that this information must be sent at this time • Decide to push the building type button	• The observer may need information of the building type to direct his or her search • The sooner the observer receives this information, the sooner the observer can start the fire search • When the building type button is pushed, the building in the panel on the observer's display is highlighted
4.4.E	Read information type (observer)	• Decide on reading the building panel	• Highlighted buildings on the panel, is a message of the dispatcher about his or her prediction of the building type

Another teamwork task concerns the backup of the observer by the dispatcher with information about the predicted building type. With the help of a button panel, the dispatcher can inform the observer about the building type that is expected to be on fire. When the dispatcher pushes the button that corresponds to the predicted building, this building is highlighted on the display of the observer. The information about the predicted building type is not necessarily needed. The observer is able to predict the building type by him or herself. Nevertheless, the dispatcher can backup the observer by performing this task and providing the information about the expected building type. In other words, this task sequence shows that the dispatcher can perform a teamwork task by backing the observer up. In order to backup, the dispatcher must know that the observer uses the information about the predicted building type to direct his or her search. Both the observer and dispatcher are instructed upon the functionality of the button panel and the way to use it. The instruction of the dispatcher describes that the observer uses the information of the type of the large building in danger in order to direct his or her search.

To predict the building type, the observer and the dispatcher need knowledge about the patterns in a series of small fires. Both team members can obtain this knowledge from the instructions that describe the procedural rules of how a large building can be predicted. Teamwork is present in two ways. First, the observer must provide the information of the fire that forms the last part of a pattern. The observer must know that the dispatcher uses this information to predict the building type. Second, the dispatcher can help the observer by providing his or her prediction concerning the building type. To perform this backup behavior, the dispatcher must know that the observer uses the predicted building type to direct his or her search for the expected large fire. For both teamwork tasks, declarative knowledge about each other roles, responsibilities, and tasks is important. Procedural knowledge about when information must be provided is also important.

Team operational sequence diagram 5

After predicting the building type, both team members must predict the building sector and time. TOSD 5 depicted in Figure 4.5 represents these tasks. In Table 4.5, the cognitive tasks versus critical decisions and the knowledge needed are described.

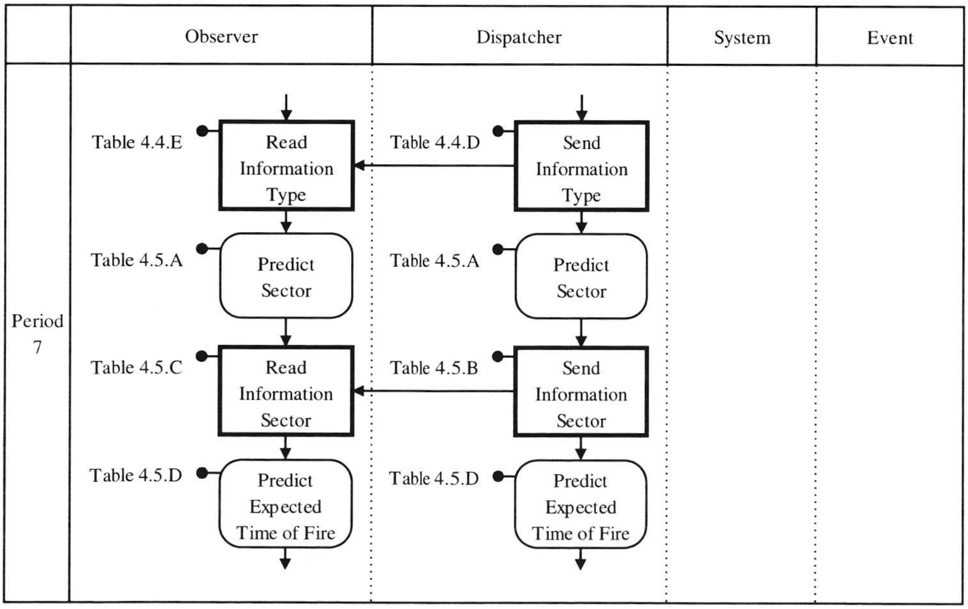

Figure 4.5: TOSD 5; from send information type to predict expected time of fire

The city map on the screen display of the observer contains four sectors. Based on the pattern in the series of fires in the small buildings, each team member can predict in which sector a large building will be set on fire. Declarative knowledge is needed to know that there are patterns in a series of small fires in each scenario. Procedural knowledge is needed to know how the various patterns predict a fire in one of the sectors. The expected time of fire can also be predicted from the pattern. Declarative knowledge is needed to know that when a pattern is completed, the expected fire starts to burn after three periods (i.e., Period 10). The instructions of both team members explain in detail how the sector, type of building, and time of fire of the large building in danger can be predicted from a series of fires in small buildings.

Table 4.5: Cognitive tasks versus critical decisions and knowledge needed for predict sector and expected time of fire, and send and read information

	Task	Cognitive tasks/ critical decisions	Knowledge
4.5.A	Predict sector (observer and dispatcher)	• Determine the number of small buildings on fire in the same sector • Determine the sector of the building that is expected to be set on fire	• A series of three fires in small buildings in one sector forms a pattern: • A pattern in sector I predicts an expected fire in sector IV • A pattern in sector II predicts an expected fire in sector III • A pattern in sector III predicts an expected fire in sector II • A pattern in sector IV predicts an expected fire in sector I
4.5.B	Send information sector (dispatcher)	• Decide that the information of the predicted sector is important for the observer • Decide that this information must be sent at this time • Decide to push the building type button	• The observer may need the information of the sector to direct his or her search • The sooner the observer receives this information, the sooner the observer can start the fire search • When the building sector button is pushed, the sector on the panel on the observer's display is highlighted
4.5.C	Read information sector (observer)	• Decide on reading the building panel	• A highlighted sector on the panel, is a message of the dispatcher about his or her prediction of the sector
4.5.D	Predict expected time of fire (observer and dispatcher)	• Determine in which period the pattern of a series of fires in small buildings is established • Add three periods to the period number when a pattern is established	• The expected fire will burn after three periods from the period when the pattern is completed (Period 10)

Teamwork concerns the information about the predicted sector. As with the building type, the dispatcher can backup the observer with information about the expected sector with the help of a button panel. When the dispatcher pushes the button that corresponds with the predicted sector, this sector is highlighted on the screen display of the observer. Providing the information of the sector serves the same purpose as with the provision of information concerning the building type. Although the observer does not necessarily need this knowledge, the dispatcher can help the observer by providing this information. Again, the dispatcher can perform a teamwork task by backing the observer up. To perform this task, the dispatcher must know that the observer uses the sector information to direct his or her search for the expected large fire. The instruction of the dispatcher describes that the observer uses the information of the sector of the large building in danger to direct his or her search.

To predict the sector, both the observer and the dispatcher need knowledge about the patterns in a series of small fires. TOSD 5 shows that teamwork is present when the dispatcher helps the observer by providing his or her prediction regarding the sector. To engage in this backup behavior, the dispatcher needs to know that the observer uses the sector to direct his or her search for a large building. For this teamwork task, knowledge about each other's roles, responsibilities, and tasks is important.

Team operational sequence diagram 6

When the observer and the dispatcher have determined the expected type of building and the sector, then the dispatcher must withdraw the units that are currently allocated to other fires. The observer must, based on the prediction of the building type and sector, start a search for the building that is expected to be on fire. Figure 4.6 shows TOSD 6 of these tasks. In Table 4.6, the cognitive tasks versus critical decisions and the knowledge needed are described.

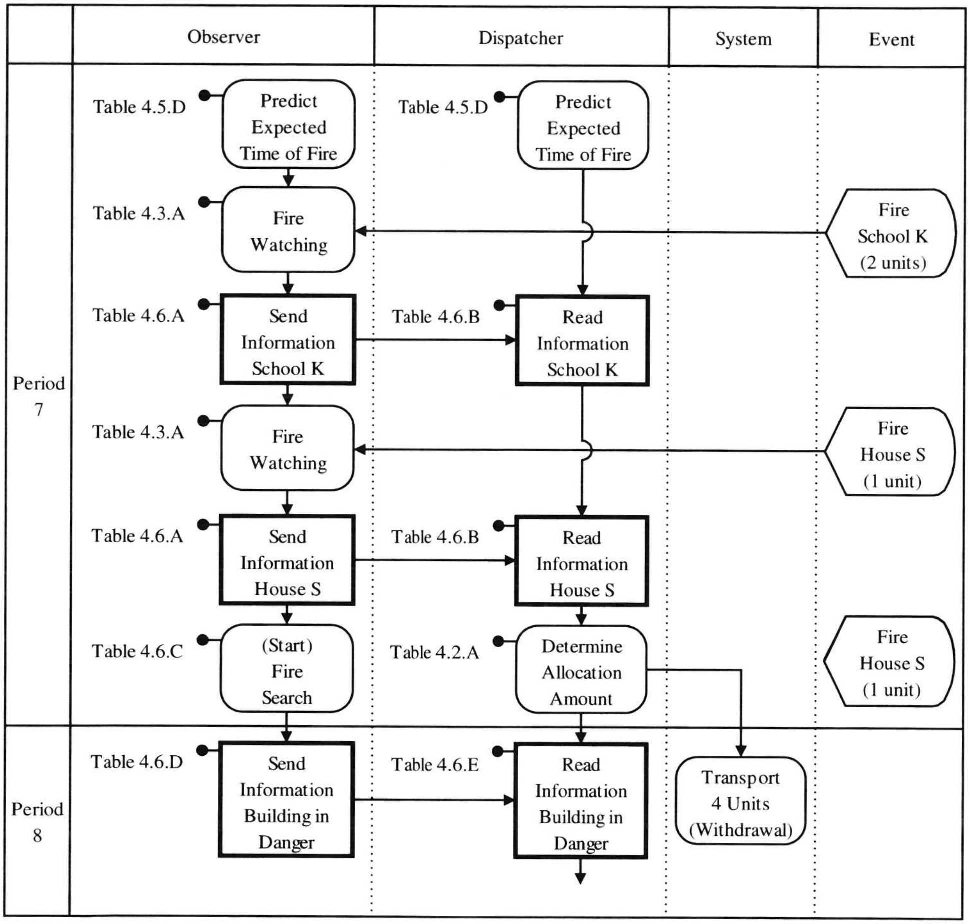

Figure 4.6: TOSD 6; from predict expected time of fire to read information large building in danger

To find the building that is expected to be on fire or, in other words, in danger, the observer must search by clicking the large buildings in the expected sector that correspond to the expected type. The observer must know that the large building in danger can be found by clicking on the buildings and that clicking on a building yields information that describes whether it is in danger. The instructions describe how the observer can find the large building in danger once a pattern is recognized.

Table 4.6: Cognitive tasks versus critical decisions and knowledge needed for fire search, and send and read information

	Task	Cognitive tasks/ critical decisions	Knowledge
4.6.A	Send information (observer)	• Decide that this information must be send on this time • Decide to put information in the outbox window • Decide to send information to the dispatcher	• The sooner the dispatcher receives this information, the sooner units can be withdrawn • Information of fires should be sent within one period • Information can be sent using the outbox window • Information is send to the dispatcher by clicking the send button
4.6.B	Read information (dispatcher)	• Decide on reading the message in the inbox • Read information about the building	• Messages in the inbox contain information of the observer about fires
4.6.C	(Start) Fire search	• Decide on clicking on the predicted large buildings in the predicted sector on the map of the city • Read information about the building • Determine whether the building is in danger	• A building that is about to be on fire can be found by clicking on the buildings • Clicking on a building gives information whether or not a building is about to be on fire ("in danger") • A building that is about to be on fire is labeled with "danger"
4.6.D	Send information (observer)	• Decide that the information of the large building in danger is needed by the dispatcher • Decide that this information must be sent at this time • Decide to put information in the outbox window • Decide to send information to the dispatcher	• The dispatcher needs information of buildings in danger to decide on the allocation of units • The sooner the dispatcher receives this information, the sooner the fire can be extinguished • Information of the large building in danger must be provided early in Period 8, because the dispatcher needs time to allocate units • Information can be sent using the outbox window • Information is sent to the dispatcher by clicking the send button
4.6.E	Read information (dispatcher)	• Decide on reading the message in the inbox	• Messages in the inbox contain information of the observer about buildings in danger

The observer must perform several teamwork tasks in TOSD 6. First, before the observer can start the search for the large building in danger, the observer must inform the dispatcher about the current fires. The dispatcher uses this information to decide on the withdrawal of units. Therefore, the observer must watch the fires and, subsequently, send the information about the fires. Besides procedural knowledge about how to send standardized electronic messages, the observer must know that this information is important for the task of the dispatcher. To provide this information in advance of requests, the observer must also know that it is important to send this information within one period.

The second teamwork task concerns the provision of information about the large building in danger. This is the most crucial teamwork task in the fire-fighting task. The dispatcher can only allocate units in time to a large fire in danger when the dispatcher receives this message from the observer. When the dispatcher does not receive this message, the dispatcher cannot put this information in the message overview window and is, therefore, not able to allocate units. Units are always one period in transit before they are present at a fire. Therefore, to be in time for the large fire (in danger) in Period 10, the dispatcher must allocate units in Period 8. This way, the units are in transit in Period 9 and present in Period 10. This means that the observer must give the information of the large building in danger at least in Period 8. Thus, to provide this information timely and in advance of requests (i.e., implicit coordination), the observer needs to know that this information is needed before Period 8 finishes. More specifically, the observer must know that the dispatcher uses this information to allocate units and that this activity takes some time. Therefore, the observer must not wait to the end of Period 8. The observer must know that the sooner in Period 8 the information about the large building in danger is provided, the more likely it is that the dispatcher can allocate the units. Note that to make sure that this information is provided in time, the observer must complete his or her task in time. In other words, the observer must tune his or her activities to those of the dispatcher. Declarative knowledge about each other's roles, responsibilities, and tasks as well as procedural knowledge of when information must be exchanged is, therefore, important for the observer to have. The instructions of the observer are very detailed on this point. It contains explicit information about the importance of this message. Moreover, the instruction includes an example that describes how the observer can be in time with the provision of the crucial information concerning the large building in danger.

TOSD 6 shows that the observer must perform teamwork. The most important teamwork task is the provision of information about the large building in danger in time. Table 4.6 shows that to perform this task, the observer needs declarative knowledge about the dispatcher's task and procedural knowledge of when information must be provided.

Team operational sequence diagram 7

After sending the information of the large building in danger by the observer, the last phase in fire fighting starts. The dispatcher must have sufficient units available and allocate these directly to the large building in danger. It is crucial that this is performed during Period 8. If this is accomplished, the units are in transport during Period 9 and present in Period 10, which is exactly in time. After that, the scenario proceeds relatively calmly. Team members can use the last periods to watch the fires and withdraw units. Sometimes, one or two units can be allocated to a small building that is still on fire. These tasks are shown in TOSD 7 depicted in Figure 4.7. As can been seen in Figure 4.7 these tasks, including the cognitive tasks and critical decisions and knowledge are described previously. Therefore, the cognitive tasks or critical decisions, and the knowledge can also be found in the previous tables.

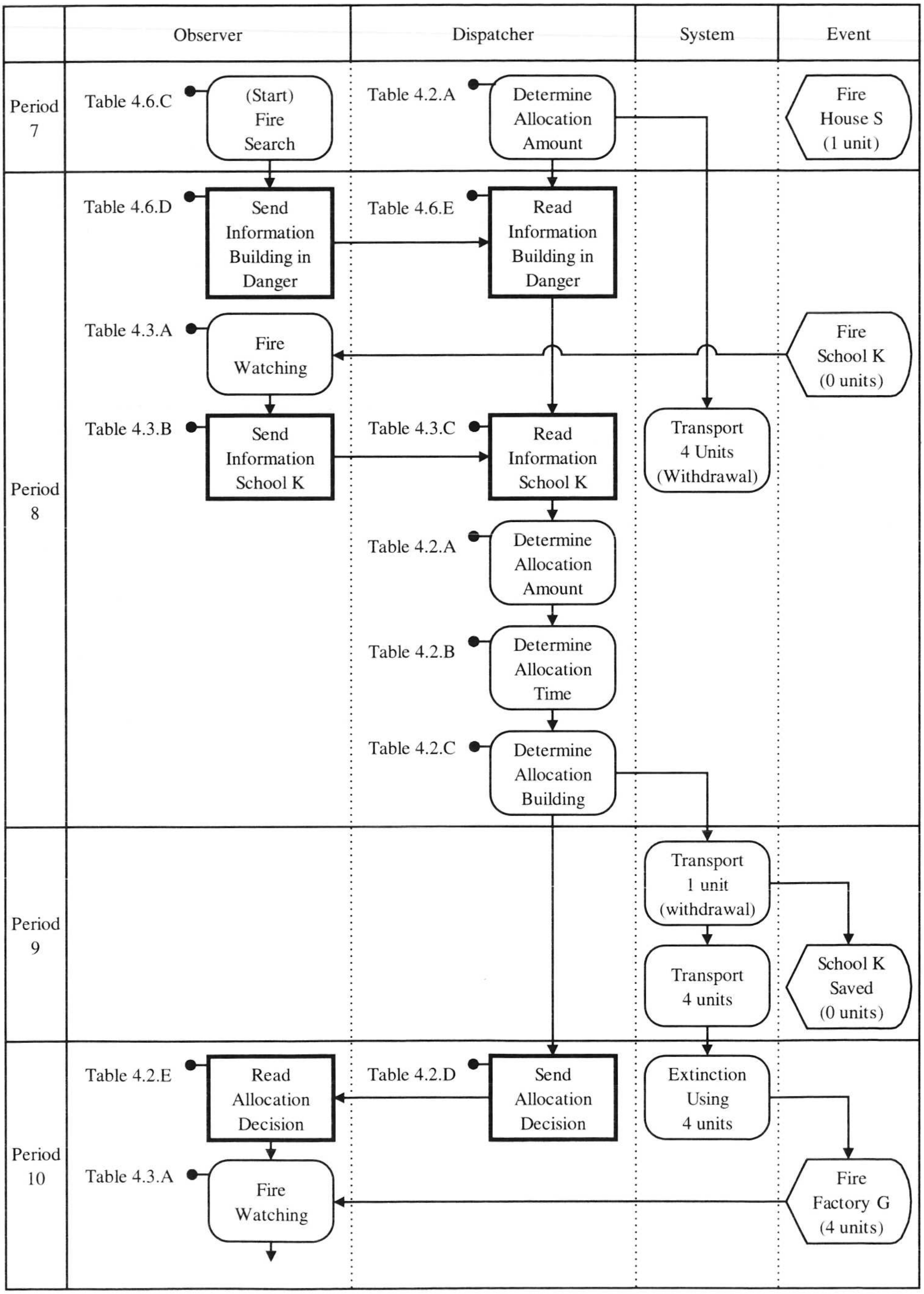

Figure 4.7: TOSD 7; from fire search to fire watching

Team operational sequence diagram 1 to 7

So far, we determined the teamwork and the knowledge by examining each TOSD separately. Consequently, we overlooked the teamwork and knowledge needed to handle the complete scenario. For example, teamwork depends on the strategy team members choose to fight fires. If team members choose to save only the large building in danger, the information exchange about the small fires at the beginning of the scenario is not needed any more. In this case, less teamwork is present which may have consequences for the knowledge of the team members. From a normative perspective, team members ought to save as many potential casualties as possible. The best strategy to achieve this goal is to save the first three small buildings at the beginning of the scenario and the large building in danger. To adapt this strategy, both team members need declarative knowledge of what the goal is. Strategic knowledge that includes action plans and priorities is also needed. This is related to teamwork and determines which information must be exchanged. For example, if both team members adapt the strategy to save the first three buildings, the dispatcher does not need to send information about the allocation decision to the observer. Based on the strategic knowledge that describes which buildings will be saved in a scenario, the observer knows which buildings have priority and, therefore, which fires need to be watched. In other words, strategic knowledge is important to develop accurate expectations of the information that is needed to exchange.

4.2.2 Summary and conclusions restricted communication

The purpose of the cognitive team task analyses in this section was to determine normatively a) what teamwork tasks team members have to perform and b) which knowledge team members need to perform the (teamwork) tasks in the fire-fighting task. In the following paragraphs, these subjects will be discussed separately. Subsequently, we outline the relationships between teamwork, knowledge, and performance in the restricted condition of the fire-fighting task.

Teamwork

Team members need to possess three teamwork skills to carry out the fire-fighting task effectively: information exchange, implicit coordination, and backup. These will be discussed in turn.

Information exchange. Team members are interdependent of each other's information to accomplish the tasks in the fire-fighting task. At several moments in the scenario, it is crucial that information is exchanged. That is, the observer must provide information about the new fires, the changes in the number of units needed, and the large building in danger. Without this information, the dispatcher cannot allocate units and save potential casualties when a building is on fire. The dispatcher must provide information about the allocation decision. The observer uses this information to watch the buildings. Hence, communication in order to exchange the necessary information is an important teamwork task that has to be performed in the fire-fighting task.

Implicit coordination. One of the most important teamwork skills that researchers expect to be influenced by shared mental models is implicit coordination. Implicit coordination is expressed by the communication of team members. That is, team members provide each other the necessary information only (i.e., the information needed to accomplish the tasks). Furthermore, this information is provided in advance of requests and on the time in a teammate's task sequence when this information is needed. It is expected that team members improve their performance when they coordinate implicitly. Especially in conditions of high time pressure, because in these conditions explicit coordination takes too much time. In the fire-fighting task, team members must perform their tasks under considerable time pressure.

Periods last just 15 seconds, in which tasks have to be performed and information must be exchanged. Moreover, to save the large building in danger, the observer must send the information of that building at least in Period 8. The TOSDs show that the timely exchange of information is important. Hence, we expect that implicit coordination is important teamwork that team members must perform in the fire-fighting task.

Table 4.7: Communication features when team members coordinate implicitly in general versus during fire fighting

General communication features	Communication features during fire fighting
Less communication	• Team members do not communicate to coordinate or to strategize • Observer does not send messages about buildings that are not burning or in danger • Observer does not send messages about a new fire after two or more periods when the fire started • Observer does not send the same message more than once • Dispatcher does not send the same message more than once
The exchange of relevant information only	• Observer sends only messages about new fires, changes in units needed, and large building in danger • Dispatcher sends only messages about the allocation decision
The exchange of information in advance of requests	• Both team members send relevant messages in advance of requests
Less requests	• Both team members send fewer messages with question marks
In case of requests, answers will be given	• In cases of messages with question marks, both team members give each other the answer
The exchange of relevant information in time	• Observer sends the relevant information of fires and changes in units needed within one period • Observer sends the relevant information of the large building in danger at least in Period 8 • Dispatcher sends the relevant information about the allocation decision within one period
In case of requests, answers will be given as soon as possible	• In cases of messages with question marks, both team members give each other the answer as soon as possible

We created Table 4.7 to determine how implicit coordination takes place in the fire-fighting task. This table is based on the communication features when team members coordinate implicitly, which we presented in section 2.3.1 (see Table 2.1). Based on the TOSDs we could specify for each communication feature how implicit coordination should take place in the fire-fighting task. In general, implicit coordination implies that team members exchange only the information needed to accomplish the tasks. In the restricted condition of fire-fighting task, team members can send each other only standardized electronic messages. Therefore, communication to coordinate, strategize, or to optimize task performance otherwise is not possible. However, it is not said that team members cannot exchange irrelevant information. Team members can send each other irrelevant messages when, for example, the observer continuously send messages about the status of fires instead of changes in the units only. Implicit coordination implies that team members refrain from this type of communication because this information is not needed by the dispatcher. Implicit coordination also implies that team members should provide each other with information in advance of requests. Thus, no messages are sent in which team members request each other for information. However, if there are any requests, team members will give each other the answer. Finally, implicit coordination implies that team members provide each other relevant information in time. In the fire-fighting task, this means that team members must exchange information within one period. Especially important is also the message of the observer about the large building in danger. It is crucial that this message is sent before Period 8 finishes. If the observer is not able to send this message in time, the dispatcher cannot allocate units to the large building. In case of requests, team members must give each other the answer as soon as possible.

Backup. The last teamwork task that can be found in the TOSDs is the information of the predicted building type and sector that the dispatcher can give to the observer. This information exchange is not strictly necessary. Observers can predict the building type and sector on their own. However, dispatchers may decide to help their teammate and send this information. This way, the dispatcher can back the observer up. Thus, although not necessarily needed, backup behavior can be considered as teamwork in the fire-fighting task.

In conclusion, the normative analysis of the unrestricted condition shows that teamwork is needed to perform the fire-fighting task successfully. Team members are interdependent of each other and information exchange is needed. Furthermore, because there is considerable time pressure and information must be exchanged before particular moments in the scenario, we expect that implicit coordination is important teamwork needed to perform effectively. Finally, backup behavior may be demonstrated by the dispatcher.

Knowledge

The TOSDs and tables show that team members need a considerable amount of task-related knowledge to accomplish the tasks. Declarative knowledge is needed and includes knowledge about the city, the buildings, and numbers of potential casualties. Procedural knowledge is needed and includes knowledge about sending messages, the allocation of units, and how a large building can be predicted from a pattern. The TOSDs and tables show that each team member has specific knowledge that is not needed by the other team member. For example, the observer needs to know that contours around buildings in the city mean that the building is on fire (red contour), extinguished (green contour), or burned down (black contour). This information is irrelevant for the dispatcher. Hence, several task-related knowledge elements are distributed among team members. In several cases, team members perform similar tasks (such as sending information or predicting sector and building type). Because the knowledge needed to perform these tasks is also similar, team members have several task-related knowledge elements in common. Nevertheless, within the context of shared mental models, this is not what is meant with shared knowledge. Although team members have certain task-related knowledge elements in common, the shared mental model theory asserts that team members must share those elements that improve teamwork.

Based on the TOSDs we concluded that three teamwork tasks are present in the fire-fighting task: information exchange, implicit coordination, and backup behavior. In addition, we determined what knowledge is needed to perform these tasks. In order to determine that the knowledge needed to perform the teamwork tasks in the fire-fighting task is similar to the knowledge from which researchers expect that it is important for shared mental models, we have compared this. In chapter 2 (section 2.3.1), we described four knowledge elements of shared mental models that are expected to be important for teamwork. These elements are equipment knowledge, task knowledge, team interaction knowledge, and knowledge of the characteristics of the team members (Cannon-Bowers et al., 1993). For each of these four elements, we described to what extent this is present in the fire-fighting task and important to perform teamwork:

1. *Equipment knowledge*. In order to perform teamwork in the fire-fighting task, team members must know how to use the standardized electronic message facility. Because the necessary information must be sent using this facility, team members need equipment knowledge about how to put information in the inbox and send it to the teammate.
2. *Task knowledge*. Task knowledge that is important to perform the teamwork in the fire-fighting task comprises knowledge of each other's tasks. The observer must know that the dispatcher is

responsible for the decisions regarding the allocation and withdrawal of units. The dispatcher must know that the observer is responsible for the assessment of the situation and the search to the large building in danger. Both team members must know the most optimal strategy to save the first two buildings and the large building in danger.

3. *Team interaction knowledge*. In the fire-fighting task, team interaction knowledge is concerned with team members' informational needs about the status of buildings and the way units are allocated. The observer must know that the dispatcher needs information about the number of units needed when a building starts to burn, changes in the number of units when a fire is about to be extinguished, and series of small buildings (i.e., in order to be able to determine the pattern). The dispatcher must know that the observer needs information about the allocation decision (i.e., the building were units are allocated to) and the building type and sector. Most important in the fire-fighting task is that information is exchanged in time. This procedural knowledge concerning the timing of activities and information exchange involves knowledge that information must be exchanged within one period and the sooner information is provided the sooner the teammate can perform his or her tasks. One piece of crucial information that concerns the large building in danger must be timely exchanged by the observer. Therefore, the observer must know that this information must be provided early in Period 8.
4. *Team members' characteristics*. The knowledge we determined for the fire-fighting task does not include knowledge of the characteristics of the team members. In order to perform the teamwork tasks in the fire-fighting task it is not necessary to know the skills, attitudes, or preferences of the teammate. This type of knowledge can be used by team members to tailor their behavior to their teammate. For example, team members can compensate for each other's deficiencies or provide information in a manner that is preferred by the teammate. In the fire-fighting task, the tasks and information exchange are fixed such that there is little room to perform such teamwork.

Besides these four knowledge elements, Blickensderfer et al., (2000) asserts that it is also important to have common knowledge of the goal. With respect to the fire-fighting task, team members must know that the goal is to save as many potential casualties as possible. Situation knowledge that concerns knowledge about the elements in the environment outside the team is not needed to perform teamwork in the fire-fighting task. Situation knowledge is especially important to determine strategies cooperatively (Orasanu, 1990, 1993; Stout et al., 1996). Since team members in the restricted condition cannot communicate freely, there is no teamwork involved in determining strategies.

In conclusion, based on the examination of the knowledge with the help of the TOSDs, we believe that to perform teamwork in the fire-fighting task, team members need knowledge that corresponds to the knowledge expected to be important for shared mental models.

Given the knowledge elements defined for the fire-fighting task, what can we conclude about the sharedness of this knowledge? The cognitive team task analysis shows that it is important to have knowledge of each other's tasks such that team members know what information must be exchanged and when. The question is to what extent this corresponds to the knowledge of that of the teammate. If it is sufficient to know what information must be exchanged when, it is not necessary that team members have this knowledge in common. After all, team members know when to provide the necessary information to their teammates. However, the shared mental model theory also asserts that it is important to know what information team members can expect of their teammates and when. When this is known, team members do not have to ask for information, but can just wait until the information is provided. This argues for commonly held knowledge about the content and timing of the information exchange. For the sender to know what information must be *provided* at what time, for the receiver to know what information can be *expected* at what time. Based on this knowledge team members can attune their information exchange on each other without the need for explicit coordination.

Although it can be argued that commonly held knowledge about the content and timing of the information exchange is important, the question remains whether it is important that team members have knowledge about each other's tasks. An important argument for having this knowledge is that it gives team members a better understanding of the information exchange that must take place. Team members not only know that information must be exchanged at certain points in time, but also for what reason. Knowledge of each other's tasks means that team members hold certain task-related elements in common. For example, the observer knows that the dispatcher needs information about new fires to decide on the allocation of units, whereas the dispatcher knows that he or she can decide on the allocation of units. This means that both team members have common knowledge about the dispatcher's responsibility for the decision to allocate units. Thus, it is important that team members hold the knowledge of each other's tasks, roles, and responsibilities in common.

In conclusion, many task-related knowledge elements are distributed among team members. Nevertheless, it can be argued that team members should have knowledge in common about the content and timing of the information exchange. Commonly held knowledge of each other's tasks seems also important, at least to the extent that it helps to develop an understanding of *why* information must be exchanged and *when*.

Knowledge, teamwork, and performance

Performance is defined in terms of achieving the task goal, which is to save as many potential casualties as possible. The best performance can be obtained when team members save the first two small buildings (e.g., an apartment building and a school) at the beginning of a scenario and the large building in danger (e.g., a factory). To accomplish this, team members must perform their taskwork accurately. Fires have to be detected in time, units must be allocated to fires with the highest priority, location and type of the large building in danger must be predicted well, and units have to be withdrawn and allocated in time to the large building in danger. The TOSDs show that these tasks can only be accomplished when information is accurately exchanged. That is, the information about the new fires, changes in the number of units needed, the large building in danger, and the allocation decision must be sent in time. In other words, performance depends on the teamwork of the team members. A link can also be established between the knowledge of the team members and performance. In the fire-fighting task, performance depends on the timely exchange of crucial pieces of information. Team knowledge is essential to understand when to send what information.

4.3 Unrestricted communication

In the previous section, we described the condition in which team members exchange the information needed to accomplish the tasks. It is clear that to perform effectively, information exchange is necessary and, therefore, one of the most important purposes of communication. However, communication may also serve several other purposes. On top of the communication needed to complete the tasks, which we define from now on as information exchange, team members may also communicate to fulfil other teamwork tasks and optimize task performance. In this section, we are interested in how this may take place. Therefore, we formulated three questions. First, what additional teamwork is introduced when team members have the opportunity to communicate unrestrictedly? Second, which knowledge is needed to perform this teamwork successfully? Third, what knowledge is transferred when team members communicate unrestrictedly and how does this foster the shared mental models of the team members and vice versa? To answer these questions, we first developed, based on the literature, a model in which we defined the teamwork that may take place when teams communicate unrestrictedly. Subsequently, we determined what knowledge is needed to perform this teamwork. Third, we described what knowledge might be transferred when team members communicate unrestrictedly. Finally, we analyzed qualitatively the verbal protocols of the teams that participated in Experiment 5 (see chapter 7). Altogether, this should give a good insight in the relationships between communication, knowledge, and performance in the unrestricted condition of the fire-fighting task.

4.3.1 Unrestricted communication, teamwork, and knowledge

To determine the teamwork, the knowledge needed, and the knowledge transferred when teams communicate unrestrictedly, we developed the model depicted in Figure 4.8. This model can be viewed as a specification of the model in chapter 2 (see section 2.3.3, Figure 2.2) in which the various dimensions and relationships of shared mental models are illustrated. In the model depicted in Figure 4.8 we set aside the possible antecedents of shared mental models and specified the team processes. We included implicit coordination, performance monitoring, evaluation, and determining strategies. As can be seen in Figure 4.8, we hypothesize that shared mental models influence implicit coordination as well as other teamwork (represented by the gray arrows from the shared mental model box into the boxes *implicit coordination* and *teamwork*). We also hypothesize that teamwork influences the development of shared mental models (represented by the black arrows from the box *performance monitoring* and *determining strategies* to the shared mental model box). In the following paragraphs, the different elements of the model are described in detail.

Implicit coordination

Central in the model is task execution (in our case fire fighting). A task can be decomposed into several subtasks. The completion of one task results in information that is needed for the next task. Because team members are interdependent of each other's information to complete their own tasks, information exchange between team members is needed. Furthermore, when teams have to perform tasks in dynamic and time-pressured situations, it is expected that this type of information exchange must take place without the need for explicit coordination. Thus, the box on top of the model represents the implicit coordination process that consists of the exchange of information in time, and without deliberations to coordinate or requests for information. This process is normatively described in the previous section with the help of the TOSDs. Team members can coordinate implicitly by exchanging the standardized electronic messages. Dependent on the necessity and timing of the messages and whether the messages are sent in advance of requests, team members coordinate more or less implicitly.

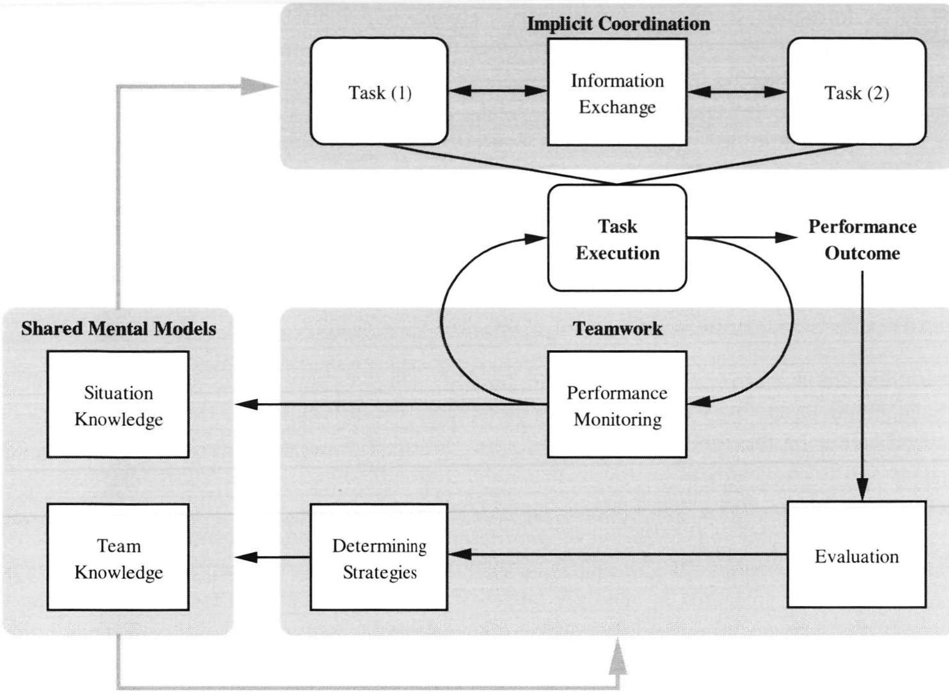

Figure 4.8: Fostering team members' knowledge in shared mental models by communication

Teamwork

Now we introduce the opportunity to communicate unrestrictedly. Team members can use this opportunity to exchange the necessary information verbally. Note, however, that in the fire-fighting task the necessary information *must* also be exchanged by using the standardized electronic messages. The opportunity to communicate unrestrictedly may also be used for other purposes. The box at the bottom of the model represents this process and shows which teamwork can be performed when team members have the opportunity to communicate unrestrictedly.

The first teamwork task that team members perform when communicating unrestrictedly is *performance monitoring*. Performance monitoring is the process in which team members watch each other's task execution, give information about the own task performance, and give feedback on each other's tasks execution. This takes place especially during the process of task execution. Observational studies have shown that effective teamwork requires team members to keep track of each other's task performance and, in turn, give each other feedback about it (McIntyre & Salas, 1995). Such feedback on each other's tasks can immediately be used to adjust the ongoing task execution. For example, team members may prevent each other from making errors.

Performance monitoring is a form of team self-correction that takes place based on events and performance during task execution. Team-self correction can also occur on the basis of the performance outcome or, when team members are still busy executing tasks, the *expected* performance outcome (Blickensderfer et al., 1997b). These team self-correction discussions contain two elements. First, team members look back, evaluate their performance, and analyze about the possible causes of the achieved performance. In our model, this is referred to as *evaluation*. Second, team members look ahead and communicate about strategies to optimize performance in the future, which we call *determining strategies*. Blickensderfer et al. (1997b) emphasize the importance of team self-correction in relation to teamwork. That is, team members evaluate and determine strategies to improve their teamwork. For example, team members clarify each other's tasks, roles, and responsibilities such that they increase their understanding of how to coordinate their actions efficiently and work with each other effectively. This fosters team knowledge in the mental models of team members.

The processes of evaluation and determining strategies can also be applied to the situation. Especially when problems occur or when the situation is novel and contains unexpected features, team members may evaluate their performance in terms of what was different in the situation than usual and to what extent the strategies are still appropriate. Team members interpret the situation cooperatively, provide each other with alternative explanations, employ their expertise, generate and test hypotheses, and offer information that is useful to solve the problems for the next time (Orasanu, 1990, 1993; Stout et al., 1996). Based on studies in a full-mission simulated flight, Orasanu (1990, 1993) concluded that effective teams engaged in more task-oriented communication than less effective teams including the formulation of plans and strategies. Stout et al. (1996) refer to the process of *strategizing* that includes the communication in which team members clarify, confirm and disseminate information, plans, expectations, roles, procedures, strategies, and future states. Orasanu as well as Stout reason that this type of communication is important for the development and maintenance of up-to-date knowledge and, therefore, improves teamwork and performance.

Knowledge

In the restricted communication condition, team members cannot perform the aforementioned teamwork. Because communication is only possible by exchanging the standardized electronic messages, there is no teamwork present to monitor the performance, evaluate, or determine strategies. When team members have the opportunity to communicate unrestrictedly, however, team members can perform this. It is hypothesized that in order to perform this accurately, team members need shared mental models with knowledge of the team and the situation. In the model depicted in Figure 4.8, the left-sided box and the arrow back into the box *teamwork* illustrates this hypothesized relationship. When team members have shared mental models of each other's task, team members are better able to monitor each other's performance, determine whether it went wrong, and provide feedback on it. Furthermore, shared mental models are important to ensure that team members interpret and evaluate the performance similarly and develop corresponding strategies (Orasanu, 1990, 1993). Especially in novel situations, it is important to preserve an up-to-date shared mental model because it enables team members to interpret the environment in a compatible manner and to take actions that are both accurate and expected by their teammates (Stout et al., 1996).

In order to determine the knowledge needed for performance monitoring, evaluation, and determining strategies in the fire-fighting task we created Table 4.8 and 4.9. In these tables, we determined for each task, the cognitive tasks or critical decisions and the knowledge needed to perform those tasks. This is described for the routine scenarios in Table 4.8 and for the novel scenarios in Table 4.9.

Table 4.8: Cognitive tasks versus critical decisions and knowledge needed for performance monitoring, evaluation, and determining strategies in routine situations

Task	Cognitive tasks/ critical decisions	Knowledge
Performance Monitoring (observer and dispatcher)	• Monitor the ongoing task performance • Predict the expected performance outcome • Determine whether the expected performance outcome meets the desired goal • Decide that the ongoing task performance needs to be adjusted to meet the desired goal	• Fire-fighting tasks • Ongoing task performance • The way units are currently allocated (e.g., number of units present, building type, time of allocation) will result in a certain performance outcome • The goal is to save as many potential casualties as possible • Norms about the way fire fighting (e.g., fire detection, information exchange, and allocation of units) should ideally take place
Evaluation (observer and dispatcher)	• After task performance (between scenarios): read performance (number of casualties saved) and determine whether this can be optimized • During task performance: predict the expected performance outcome • Compare performance outcome with desired goal • Cognitive "walkthrough" of the past scenario and analyze which activities led to good and which to poor performance • Decide that (predicted) performance outcome can be optimized	• Optimal performance is when three small buildings (at the beginning of the scenario) and the large building in danger are extinguished • The way units are currently allocated (e.g., number of units present, building type, time of allocation) will result in a certain performance outcome • The goal is to save as many potential casualties as possible • Past scenario and which activities have led to good or poor performance (good performance is: exchanging fire information within one period; saving the first three small buildings; searching the large building in danger before Period 8, exchanging the threat message before Period 8 ends; allocate sufficient units to the fires; withdraw units before Period 8 in order to re-allocate sufficient units to the building in danger in Period 10) Optimal performance is when three small buildings (at the beginning or the scenario) and the large building in danger are extinguished
Determining strategies (observer and dispatcher)	• Generate alternative strategies that might improve fire fighting • Consider the advantages and disadvantages of the alternative strategies in terms of expected outcome • Decide on which strategy is the best	• Past scenario and which activities have led to good or poor performance • Different strategies lead to different outcomes: • Exchange continuous (each period) information concerning the buildings, fires, and units • Exchange information only about the changes in fires and units as soon as possible • Allocate the number of units that a fire needs until there are no units left and withdraw units when a fire is extinguished • Keep units in the station until the threatened building is discovered and allocate units to this building only • Allocate units to the first three small buildings and withdraw units when the fire is extinguished or when there is another fire (or the large building in danger) that has higher priority

The knowledge needed for performance monitoring is task related. If team members have no opportunity to communicate unrestrictedly, team members can only monitor their own task performance and need, therefore, only task-related knowledge about their own tasks. However, in the condition in which unrestricted communication is possible, team members can also monitor each other's performance. In that case, knowledge is needed of each other's tasks. This includes procedural knowledge of when and how tasks have to be performed. Moreover, strategic knowledge about the teammate's ongoing task execution is needed. Team members must also have common knowledge of the goal and have similar norms of the way fire fighting should take place. This includes procedural knowledge of when and how tasks must be executed and strategic knowledge of the priorities. With the help of this knowledge team members can monitor each other's task performance and optimize when needed.

To evaluate the task performance, team members first need to know what the (expected) performance outcome is. When the performance outcome must be predicted, team members must know how the currently allocated units will result in a certain performance outcome. To compare the performance outcome with the desired outcome, team members must know that the goal is to save as many casualties as possible. The next step is to analyze the past scenario. In order to analyze which activities led to good or poor performance, team members must know what good performance is. This includes declarative knowledge about what tasks have to be performed and procedural knowledge of when and how tasks have to be performed in the fire-fighting task. In the unrestricted condition, team members are able to evaluate together. In that case, knowledge is needed about each other's tasks, roles, and responsibilities such that team members are able to analyze each other's performance and to determine were it went wrong or well.

To determine strategies, team members need knowledge about where it went wrong or well in the past scenario. Based on this knowledge team members can adjust strategies or develop new ones when necessary. For example, when team members know that it went wrong because the dispatcher was too late with the allocation of units to the large building in danger, team members can think about a strategy to be in time for the next time. Several alternative strategies can be developed that lead to different outcomes. Strategies can be related to teamwork and determine how to exchange information or allocate units. In both cases, it is important that team members have this knowledge in common. Based on this knowledge team members can develop accurate expectations of the information that is needed to exchange. For example, if team members decide to save the large building in danger only, then the dispatcher needs and expects only information about that building. Thus, commonly held knowledge of the strategies ensures that the tasks of the team members are attuned to each other.

In novel scenarios the large fire is set in another sector and in another building than team members would expect based on the pattern in a small series of fires they learned in their training. When teams are confronted with novel scenarios, team members must derive the new patterns. In other words, task optimizing must take place to handle novel situations. Team members must engage in performance monitoring, evaluation, and determining strategies in order to get the new patterns or develop other strategies to handle the situation. In Table 4.9, the cognitive tasks versus critical decisions and the knowledge needed for these tasks in novel situations are described.

Team members need situation knowledge to monitor the performance, evaluate, and determine strategies in novel scenarios. Performance monitoring to determine that the situation is different from usual is not necessarily teamwork. The observer as well as the dispatcher can obtain the information of the patterns from their screen displays. Both team members also have knowledge about the different patterns and how the large building in danger can be predicted from that. Nevertheless, team members can inform each other about the ongoing task performance. For example, the observer can inform the dispatcher that he or she is busy with the fire search and that the large building in danger cannot be found in the expected sector. This might trigger team members to think about the possibility that there are other patterns than the ones learned. For evaluation and determining strategies, situation knowledge is needed that helps team members to determine why it went wrong and what alternative strategies can be employed to reconcile this for the next time. When team members communicate unrestrictedly, strategies can be determined in cooperation. Therefore, team members need shared knowledge of the situation. When both team members have similar knowledge of how the situation developed, team members are able to give suggestions or generate alternative hypotheses that are appropriate for that situation. For example, if both team members know that the large building in danger could not be found because the pattern in a series of small buildings is changed, team members can give each other suggestions about other possible patterns. Thus, commonly held situation knowledge supports team members in determining strategies.

Table 4.9: Cognitive tasks versus critical decisions and knowledge needed for performance monitoring, evaluation, and determining strategies in novel situations

Task	Cognitive task/ critical decision	Knowledge
Performance monitoring (observer and dispatcher)	• Determine that the situation is different from the situation of the training	• Patterns of the training scenarios • The pattern of the current scenario does not predict the expected sector, building type, or both
Evaluation (observer and dispatcher)	• After task performance (between scenarios): read performance (number of casualties saved) and determine whether this can be optimized	• Optimal performance is when three small buildings (at the beginning or the scenario) and the large building in danger are extinguished
	• During task performance: predict the expected performance outcome	• The way units are currently allocated (e.g., number of units present, building type, time of allocation) will result in a certain performance outcome
	• Compare performance outcome with desired goal	• The goal is to save as many potential casualties as possible
	• Cognitive "walkthrough" of the past scenario and determine that performance was decreased because the situation changed compared to the situation team members were trained in	• Training scenarios: different sequences of building types in a series of three fires in small buildings determine the large building in danger • In novel scenarios the pattern does not predict the threatened building (whereas in the training scenarios the pattern does predict the threatened building)
	• Decide that performance can be maintained with adjusted or new strategies	• There are different patterns that determine the large building in danger
Determine strategies (observer and dispatcher)	• Form hypothesis or alternative strategies that might be appropriate for the novel situation faced with	• There are alternative patterns that might determine the threatened fire in a large building • The fires in small buildings of the past scenario • The sector in which the small buildings were set on fire in the past scenario • The building type of the large building in danger of the past scenario • The sector of the large building in danger of the past scenario
	• Test hypothesis of alternative strategies by predicting the threatened building based on a alternative pattern	• The pattern of the current scenario does not predict the expected sector, building type, or both

In conclusion, when team members have the opportunity to communicate unrestrictedly, additional teamwork tasks, besides the exchange of the necessary information, may be performed. For that purpose, team members need to have team and situation knowledge in common. For performance monitoring, evaluation, and determining strategies it also is important that team members have strategic knowledge. Based on that knowledge team members can adjust their performance and determine strategies "on the fly." When team members have this type of knowledge in common, it is ensured that strategies will be determined for the same situation.

Knowledge transfer

In the previous paragraphs, we determined the teamwork tasks and the knowledge needed when teams have the opportunity to communicate unrestrictedly. Here, we determine how the knowledge of the team members is fostered in a shared mental model by communication. Based on the model presented in Figure 4.8, we classified the communication into six categories. Table 4.10 shows these categories and their definitions. For each category, we determine what knowledge we expect that will be transferred between team members.

Table 4.10: Unrestricted communication; overview of the categories and their definitions

Category	Definition
Information exchange	Necessary information exchange about the status of buildings (i.e., fire, extinguished, burned down), number of units needed, units available, units in transport, the allocation decision, and the large building in danger
Performance monitoring	Communications about the tasks team members perform during the scenario. That is, explicitly telling each other what one is doing at that moment, giving each other advice what to do, giving each other feedback about each other's performance, and discuss the best course of action on that moment
Evaluation	Evaluative statements or judgements concerning the tasks of the scenario just played. Analyses of why things went well or wrong at particular times
Determining strategies	Information that expresses intentions to adjust the way the team should engage in the task, deliberations about alternative strategies, rationalizations of the strategy adopted so far
Team knowledge	Information about each other's tasks, roles, responsibilities, information dependency, and when and how information must be exchanged
Situation knowledge	Information about the situation, the pattern or changes in the pattern of a series of small buildings, and the prediction of the large building in danger

Information exchange concerns the information that is necessary to accomplish the tasks. This is information about the new fires, the changes in the number of units needed, the large building in danger, and the allocation decision. In the fire-fighting task, this information must be exchanged also with the standardized electronic messages. Communication in this category does not foster the knowledge of the team members in a mental model because no knowledge is transferred among the members.

Performance monitoring is communication about the tasks team members perform during task performance. Team members tell each other about the tasks they are performing and how their task execution develops. Furthermore, team members give each other advice, suggestions, or feedback about the best course of action. This type of communication may be especially important to develop specific procedural knowledge of how things work and when activities have to be performed. For example, based on the ongoing task performance, team members may clarify why and when certain information is important to exchange. When applying this example to fire fighting during Period 8, the dispatcher can tell the observer that the message about the building in danger has to be sent immediately, otherwise it is too late to allocate units. This type of performance feedback concerning the ongoing task may refine the knowledge of the team members about when interaction is needed. In other words, general background knowledge (e.g., I have to provide information in time to my teammate) is translated into specific knowledge that can be applied to that task (e.g., I have to provide information about the large building in danger before Period 8 finishes). We expect that, based on this knowledge, team members have better explanations and expectations of the teamwork, which increases performance.

During *evaluation*, team members judge the performance outcome and analyze what and in which way various factors were responsible for that outcome. Team members can evaluate their teamwork and determine, for example, that the necessary information was *not* provided or provided too late. By analyzing this, team members develop knowledge about when information exchange must take place. Team members may also clarify why it went well or wrong in each other's tasks, roles, and responsibilities such that team members increase their knowledge about how to coordinate their actions efficiently and work with each other effectively. With respect to the (changing) situation, team members may discover during evaluation that the performance decreased because, due to the changed situation, their strategies are not suitable any more. By analyzing situational elements, for example the pattern in a series of small fires in the fire-fighting task, team members develop common knowledge of that situation. Thus, evaluating in cooperation gives common knowledge of the teamwork, team strategies, and the role of members herein.

When team members *determine strategies*, alternative strategies to optimize task performance are discussed. The importance of determining strategies jointly is that team members develop shared team knowledge about the strategies, action plans, and priorities. For example, in the fire-fighting task, team members may develop a strategy to pay attention only to the first three small buildings and the large building in danger. When this strategy is commonly held among the two team members, the observer knows that the only important information to provide is about those buildings, whereas the dispatcher knows that that is the only information he or she can expect. Thus, communication about strategies fosters team members' strategic knowledge in a mental model.

Team members may also exchange information that contributes directly to the development of *team* and *situation knowledge*. With respect to team knowledge, team members inform each other about their tasks, timing, and sequences of their tasks. Furthermore, team members tell each other what information is necessary and at what moments. Finally, team members communicate about their own tasks. This type of communication fosters team members' knowledge of each other's tasks, task sequence, and informational needs. With respect to situation knowledge, team members communicate about the elements in the situation, features, and situational changes. This fosters team members' situational knowledge and ensures that team members develop common and up-to-date knowledge of the situation.

4.3.2 Verbal protocol analysis

In the previous section, we described normatively what type of communication is expected when team members communicate unrestrictedly and how this affects team members' knowledge in a mental model. We classified communication into seven categories and described what knowledge may be transferred. In this section, the communication of team members will be analyzed qualitatively. The main purpose is to gain a better insight in the knowledge that is transferred among team members. Furthermore, the analysis must give a better picture of whether the normatively described teamwork and communication actually take place.

The teams that participated in Experiment 5 (see chapter 7) were used for the analysis. These teams had to perform 16 scenarios of Version 2 of the fire-fighting task. The first eight scenarios consisted of routine scenarios and the second eight scenarios consisted of novel scenarios. There were two conditions. In the first condition, teams could communicate verbally during scenarios. In the second condition, teams could communicate verbally during the time between two subsequent scenarios. From these teams, the communication was taped and literally transcribed into verbal protocols. In total, 11 teams that communicated during scenarios (approximately one hour per team) and 11 teams that communicated between scenarios (approximately ten minutes per team) were transcribed. These protocols were then used to determine the type of communication that took place. The verbal protocols presented in this chapter are translated from Dutch.

We examined the verbal protocols in two ways. First, we selected the best performing team of the during and the between condition. For the teams that communicated during scenarios we selected the protocols of four scenarios: the first and the last routine scenario (Scenario 1 and 8), and the first and the last novel scenario (Scenario 9 and 16). For the teams that communicated between scenarios, we selected the protocols of the time after those scenarios (exception was Scenario 16, for which we selected the protocol between Scenario 15 and 16, also we added the protocol between Scenario 9 and 10). These protocols were subsequently translated, written down, and interpreted in terms of teamwork and knowledge transfer. Second, we examined the verbal protocols of all teams. For each communication category defined in the previous section, we selected several statements that are prototypical examples of that category. Again these statements were translated, written down, and interpreted in terms of teamwork and knowledge transfer. Altogether, this must provide a good insight in the teamwork and type of knowledge that is transferred.

Communication during scenarios

Team 6, routine Scenario 1. After starting the scenario, team members start to communicate (Period 1 to 3):

Observer:	Hello?
Dispatcher:	Hi!
Observer:	I will give you all the information, but I think that it is the easiest to neglect all small buildings
Dispatcher:	No, no, not at the beginning of a scenario. I have time to allocate some units, but please do give me all the information. This is particularly convenient to recognize the patterns
Observer:	Yeah, right. If apartment buildings are going to be on fire, then there will be a pattern
Dispatcher:	Yes
Observer:	Thus, if the second apartment building, or it is usually a house, is going to be on fire, then you must not allocate units anymore
Dispatcher:	Yes
Observer:	Otherwise the units are in transport and we are too late
Dispatcher:	No, no, it is possible. I am able to handle the first building and if there comes another apartment building, I will stop
Observer:	Exactly, the other two fires cannot be saved because you also have something like a school
Dispatcher:	Yes

Team members greet each other and directly begin to discuss the best strategies to fight fires. First, the observer and the dispatcher coordinate explicitly to agree upon which information is important to exchange. Second, team members jointly determine a strategy for the allocation of units. There is discussion whether units must be allocated to the small buildings at the beginning of a scenario. This indicates that both team members know that the most important building to save is the large building at the end of a scenario. Based on these commonly held expectations of how the scenario will develop (situation knowledge) team members discuss the best strategy. Knowledge is transferred concerning the pattern ("if apartment buildings are going to be on fire, then there will be a pattern"), the timing of tasks ("otherwise the units are in transport and we are too late"), and possible future fires ("you also have something like a school"). All these knowledge elements are important to determine the best strategy for allocating units. Team members continue to communicate (Period 4 to 6):

Observer:	Such as the school that is on fire now!
Dispatcher:	yes, units are on their way and units are present at the apartment building
Dispatcher:	I don't know what you see
Observer:	I see when fires start, now the second apartment building is started
Dispatcher:	Yes
Observer:	Thus, in a moment it will be a ...
Dispatcher:	Yes
Observer:	Now we get a house or an apartment building, and then we know what the large building is
Dispatcher:	No units will be allocated
Observer:	Usually, we have four periods, so we can be there on time

At this point in the scenario, a school is on fire. The observer gives information about the school and the apartment building, which also can be sent by the standardized electronic messages. Note that, to be able to allocate units, this information must also be sent electronically. Apparently, the observer feels the need to exchange this information verbally as well. The dispatcher responds to this information by informing the observer how many units are in transport and present at a building. This type of communication allows the observer to monitor the performance of the dispatcher. Because the pattern in a series of small buildings is almost complete, the observer begins to predict what the building type will be. Knowledge is transferred about the timing of tasks ("usually, we have four periods") which emphasizes the importance of being in time for the large building. From the seventh period, the team members must predict the building type and the sector of the large building in danger (Period 7):

Observer:	Well, I think it will be a factory
Dispatcher:	Yes? Are you sure, is there a house on fire?
Observer:	Yes, I found the factory, here it comes
Dispatcher:	Yeah, right. Back, and back
Observer:	By the way, you might save the school also
Dispatcher:	Yes, that might be possible. Units are on their way to the factory. That is, several units depart now, and one will be departing later

The observer informs the dispatcher about the predicted fire. In turn, the dispatcher checks whether the observer is confident about it. The observer gives advice (i.e., performance monitoring) about the school. Finally, the dispatcher gives information about how the units to the factory are allocated. This allows the observer to monitor the allocation and determine whether this goes right. Note that the observer is also interested in the task of the dispatcher and takes the initiative to think of the best way to allocate units. From Period 8 to the end of the scenario team members must handle the present fires, watch the number of units, and withdraw units when necessary (Period 8 to 12):

Dispatcher:	How many units are there needed for the school, still two?
Observer:	Yes, still two units
Observer:	Yes, now one unit!
Dispatcher:	Okay
Observer:	And now zero
Dispatcher:	In that case, I am able to...
Observer:	Factory needs four units
Dispatcher:	I can do something with the house. Oh, no I will never make it in time
Observer:	Yeah, it costs tree periods before the units will arrive
Observer:	Yes, the factory is..., and there goes an apartment building. School is saved

Information exchange takes place about the number of units needed for the school and the factory. The dispatcher is thinking aloud about the decision what to do with the house. The observer transfers knowledge about the number of periods that is needed before units arrive. This emphasis on the timing of events and activities may foster team members' procedural knowledge.

Team 6, routine Scenario 8. After a short break (about 30 seconds) between two scenarios (the headsets were switched off during the break) team members start to communicate (Period 1 to 4):

Dispatcher:	Hello?
Observer:	Hello, what was the score? I didn't pay attention to it
Dispatcher:	178 out of 624 or something like that
Observer:	Hmmm...
Dispatcher:	Yeah, right. It was the school that was still on fire
Observer:	Yes, that's right
Dispatcher:	Still nothing?
Observer:	Here it comes, an apartment building
Dispatcher:	An apartment building. It was really annoying that, because it was just in time before the clock resets. I wanted to correct and then I was just too late and two units went back and forth for nothing
Observer:	Oh, that is annoying indeed
Dispatcher:	So I had to withdraw units from the school, otherwise I was too late for the factory

Team members evaluate the performance outcome and analyze where it went wrong in the scenario. According to them, the school caused the relatively high number of potential casualties. The dispatcher informs the observer in detail why it went wrong and emphasizes the importance to be on time. Again, this may be important for team members' procedural knowledge. The scenario continues (Period 5 to 10):

Observer:	Another apartment building
Dispatcher:	Okay, I do nothing about it. It is in another sector isn't it?
Observer:	Yes, it is in another sector. Don't do anything about it
Dispatcher:	Okay, I won't. I don't make it anyway
Observer:	Another one in sector I. It is jumping around
Dispatcher:	I wonder, is it still the right pattern?
Observer:	Yes, I think so, because here I have a house. There is something coming up, I believe
Dispatcher:	Still no factory in sector IV?
Observer:	It is a factory
Dispatcher:	I though so
Observer:	In Period 10, you will manage that easily
Dispatcher:	Yes, units will be on their way in a moment, what about the apartment building of the beginning?
Observer:	Still two needed
Dispatcher:	Still two
Observer:	Indeed, still two
Dispatcher:	As soon as that becomes one, it is possible to save a house
Observer:	It is one now
Dispatcher:	The factory, units are present now
Observer:	That's great. Even one period too early

Team members communicate mainly about the ongoing situation and the best way to allocate units. At several times, the importance to be on time is highlighted ("in Period 10, you can manage that easily" and "even one period too early"). These cues may sharpen team members' procedural knowledge about when tasks (and thus information exchange) must be completed. In the last periods, the team members are examining the possibility to save a small building (Period 11 to 12):

Observer:	Apartment building is burned down and another one is repaired
Dispatcher:	Yes, I can see that
Observer:	Send the units to another apartment building
Dispatcher:	Yes
Observer:	There is still one
Dispatcher:	Yes, actually I had two available, but one was just...
Observer:	Oh, the apartment building is also burned down
Dispatcher:	Which one? Okay, then I can pull back units
Observer:	There are only a couple of houses
Dispatcher:	Well then I sent units over there. Are there extra houses left?
Observer:	No, there are no new fires, it will be too late anyway. It doesn't matter anymore
Dispatcher:	Okay, I am busy saving a house and a factory, so...
Observer:	Well, it doesn't matter anymore
Dispatcher:	How many units are there needed by the factory?

Because there is too little time (two periods) to allocate units, the effort of the team members to save a small building is not successful. Team members realize that and the dispatcher checks the balance ("I am busy saving a house and a factory"). These attempts to save as many buildings as possible give team members a good understanding of the best strategy possible.

When compared to Scenario 1, less knowledge is transferred about how to exchange information. There are also fewer discussions about how to save buildings in general. Instead, the communication is more aimed at the present performance and the best way to handle particular moments. In Scenario 8, team members are mainly busy with monitoring the performance and giving each other suggestions about how to act. In the following protocols, team members are confronted with novel scenarios in which the pattern in a series of small buildings does not predict the large building in danger as usual.

Team 6, novel Scenario 9. After the scenario starts, team members first begin to evaluate the past scenario (Period 2 and 3):

Observer:	Well, it is directly a house again, I see
Dispatcher:	Yes, the past scenario shows that if we are in time at the factory in Period 10, you get about 80 casualties
Observer:	Yes, exactly
Dispatcher:	Or something like that uh...
Observer:	So we can do better?
Dispatcher:	Maybe

The importance to be on time in Period 10 is highlighted. Nevertheless, team members do not go beyond that and determine, for example, the best way to achieve that. The scenario continues (Period 4 to 5):

Observer:	A school
Dispatcher:	A school
Observer:	It is in sector II
Dispatcher:	Well, what shall I say, it is not important
Observer:	Apartment building in sector III
Dispatcher:	I don't do anything about that
Observer:	And the house?
Dispatcher:	No, there is a unit present, but I can pull it back in time and save the house
Dispatcher:	If it is necessary, otherwise I leave it that way

The observer gives the dispatcher the necessary information. In turn, the dispatcher keeps the observer informed about the allocation of units. From Period 6, the search to the large building in danger can start (Period 6 to 8):

Observer:	Second apartment building, same sector, thus it will be a...
Dispatcher:	Another apartment building, okay
Observer:	And, again another apartment building
Dispatcher:	yes
Observer:	Let's see, it will be a factory again
Dispatcher:	Okay, which sector?
Observer:	Ooh, it is not in the right sector
Dispatcher:	Oh?
Observer:	Ah, I found it, it is in sector IV now
Dispatcher:	Yes, sometimes it is different

As usual, team members start to predict the expected building type and location. The observer soon finds out that the predicted location is not correct and informs the dispatcher about that. Thus, strategic knowledge of the situation is transferred. From now on, both team members know that patterns do not necessarily predict the expected sector. The observer is very lucky. By chance, the large building is found in danger in another sector. The observer informs the dispatcher about the sector. Both team members not only know that the pattern is changed, but also which sector it was this time. This common situation knowledge can be used to determine the new pattern jointly. Now team members are able to respond to the large building in danger (Period 7 to 8):

Dispatcher:	Can I pull back the unit from the house?
Observer:	Well, you have to
Observer:	Thus, that is very annoying, normally as the pattern develops in III then it is a factory in II, but this time not
Dispatcher:	Indeed

Team members start reallocating units and the observer again emphasizes the fact that the pattern was not correct. Probably because it is very busy in these periods, team members do not go a step further and determine what the new pattern is. The reallocation of units has the highest priority now (Period 8 to 12):

Dispatcher: Can I pull back one unit from the school?
Observer: yes, you can do that immediately
Dispatcher: I have three units ready
Observer: Yes, you can withdraw, yes
Dispatcher: Yes
Observer: But you have to do it right away
Dispatcher: Yes
Observer: The factory is of higher value
Dispatcher: Hmmm...
Dispatcher: Yes, but it is one round later than usual
Observer: School needs only one unit now
Dispatcher: Okay. Is the house burned down? It probably is
Observer: Yes and the school is saved
Dispatcher: Okay
Observer: Apartment building down
Dispatcher: Which apartment buildings are still out there? T and H?
Observer: Only H.
Dispatcher: Okay, I send some units to that
Observer: H is gone too
Dispatcher: Ah

In the last periods, the communication is mainly about the units needed by the present burning buildings. First, to determine where the dispatcher could pull back the units most effectively, second, to determine which small buildings could be saved at last.

Team 6, novel Scenario 16. Scenario 16 is the last scenario team members have to perform. Team members have received eight novel scenarios. When teams were able to grasp the new pattern, the novelty should be gone by now. Team members again start to evaluate the past scenario (Period 1 to 3):

Dispatcher: Again 80
Observer: A school is on fire
Dispatcher: Yes, that one we gonna save
Observer: But, indeed again 80, yes
Dispatcher: Just give me all fires, also the apartment buildings
Observer: Nothing is happening now
Dispatcher: I was thinking, maybe we can leave the units one period longer so that we can get less than 80 casualties
Observer: Hmmm...
Dispatcher: Well, it is just a idea, maybe it won't work

Although performing the last scenario, team members are still discussing alternative strategies to optimize task performance. This time, the dispatcher considers the possibility to wait one period with the withdrawal of units. The pattern in the series of small buildings is now starting (Period 4 to 7):

Observer: School still needs three units
Observer: Still three, and an apartment building starts
Dispatcher: Still three for the school?
Observer: Yes
Observer: Now a second apartment building, the pattern is beginning
Dispatcher: Yes
Observer: So, hold on
Dispatcher: And the school, still three?
Observer: No, two units now
Dispatcher: In that case, I pull one back

Observer: Watch, another apartment building, now we can search for the hospital
Dispatcher: And the school?
Observer: Wait a minute, I am busy looking for the hospital, that's more important now
Dispatcher: Yes, yes, yes
Observer: There it is, sector III

The observer attempts to discover the pattern. It is likely that the observer knows by now what the new pattern is. Otherwise, it would be fruitless to put effort in predicting the building type and sector. The observer manages to be on time with finding the large building in danger. In the meanwhile the dispatcher wants to know exactly the number of units needed for the school in order to withdraw as soon as possible. The dispatcher's request for information is disturbing. The observer gives her a reprimand that the search for the hospital is more important now. The dispatcher has to wait.

In conclusion, team members use their opportunity to communicate unrestrictedly during task execution to optimize task performance. Team members monitor their performance, evaluate, determine strategies, and transfer knowledge about the team and the situation. The communication is several times very precise with respect to the timing of events and actions. We think that communicating unrestrictedly during the scenarios helps team members to develop specific knowledge of the team and the situation.

Communication between scenarios

Team 16, between routine Scenario 1 and 2. Team members just accomplished the first scenario. The headsets are switched on and the team members start to communicate immediately:

Observer: Hello?
Dispatcher: Hi
Observer: If it is possible, I would like to receive information about when the units are present
Observer: And, if there are too many fires to extinguish, we just have to prioritize, I think
Dispatcher: Yes, I don't allocate units to houses anyway
Observer: No, not even at the beginning?
Dispatcher: No, there are only two buildings, and the units are gone, and it takes four periods to allocate them and then pull back
Observer: Okay, that's right
Dispatcher: It's only two humans
Observer: Yes
Dispatcher: However, they're still humans, of course
Observer: Yes. But what about an apartment building, do you allocate units to that?
Dispatcher: Yes, an apartment building surely, because that's ten
Observer: Exactly
Dispatcher: However, giving messages to you is sometimes difficult, because it happens all so fast, so...
Observer: Okay, I understand
Dispatcher: But, I will see to it

The observer directly starts to inform the dispatcher about the information she would like to receive. Later the dispatcher responds to her request and makes clear that it is difficult to give this information. In this type of communication, team members clarify each other's informational needs and tasks that may give a better understanding of why interactions are needed. The observer and the dispatcher jointly determine the best strategy to fight fires. Knowledge is transferred about the number of periods needed to allocate and withdraw units. Team members continue to communicate:

Observer: Okay, when a fire is extinguished, then it becomes green on my screen
Dispatcher: Hmmm...
Observer: Then I send you the message immediately. It is possible, however, that you get a lot of messages at once
Observer: I also check continuously whether a building still needs units, and if it is extinguished, then the number of units is zero I assume?
Dispatcher: Hmmm...

Observer:	So, that 's it
Dispatcher:	Yes, but the numbers of units count down don't they?
Observer:	Oh, yes indeed
Observer:	Okay, I just look ...uh... I have a map. Do you have a map?
Dispatcher:	No
Observer:	I have a map with buildings on it, and when I click on a building then I can see how many units there are still needed
Dispatcher:	If you just give me the information about the apartment buildings and the changes. That save us a lot of time and effort
Observer:	And it is more quiet for you also
Dispatcher:	Yes, indeed

Here, the observer informs the dispatcher about her task. This task-related information gives the dispatcher insight in the information that can be expected. Moreover, the dispatcher can verify the observer's knowledge about how fires develop and units that are dependent on that. Based on this, the dispatcher asserts that the number of units count down. This information makes the observer realize that it is important to check the fires regularly to determine the number of units needed. Team knowledge is further transferred when the dispatcher makes clear which information she needs. Based on this knowledge, team members can coordinate implicitly for the next time.

Team 17, between routine Scenario 8 and novel Scenario 9. By now, team members have performed eight routine scenarios:

Observer:	Okay, I think we have the best score possible
Dispatcher:	Yes, I do too
Observer:	Well, maybe we could save the second apartment building too. Two units are needed there
Dispatcher:	There were two units allocated to that building
Observer:	Oh, is it? Maybe it is still burning?
Dispatcher:	Yes maybe
Observer:	But, you had four units for the factory, so that leaves us with two for the apartment building
Dispatcher:	No, there were four units in the station
Observer:	In the station? Oh, and you had sent only two units away?
Dispatcher:	No, I had sent them right away and they were exactly on time, I think
Observer:	Okay, that's good. So at first, you had only one unit allocated to the apartment building?
Dispatcher:	Indeed, that's why it went wrong. I think I was just one period too late. Just like the other times.
Observer:	Yes, yes, yes

Team members evaluate the performance of the past scenario in detail. The observer forces the dispatcher to rethink the way units were allocated in order to determine why the apartment building was not saved. Team members continue to evaluate:

Dispatcher:	I did that to be on time for the factory or the hospital
Observer:	Yes
Dispatcher:	So, maybe, but I am not sure, I don't know how many periods we have
Observer:	Well, three periods should be enough
Dispatcher:	Hmmm, but that depends on how soon you inform me
Observer:	Yes
Dispatcher:	I mean, when it is just in the last three seconds...
Observer:	Of a period
Dispatcher:	Yes, of a period, then...
Observer:	You are not able to respond on time
Dispatcher:	Indeed
Observer:	Okay, now we gonna save a lot of people

The outcome of the evaluation is that the second apartment building can be saved when both units are present one period earlier. The observer transfers knowledge about the number of periods needed to allocate units to the large building. Finally, team members discuss the consequences of their new strategy in terms of the communication needed. This gives the observer very detailed knowledge about the fact that information must be provided as soon as possible within a period ("when it is just in the last three seconds").

Team 17, between novel Scenario 9 and 10. Scenario 9 is the first novel scenario team members perform:

Observer:	That was the same score as before
Dispatcher:	Yes
Observer:	Our score is relatively constant
Dispatcher:	Yes, that's true
Observer:	Well I think we talked everything through
Dispatcher:	Yes, I do too
Observer:	I think we have a half an hour to go
Dispatcher:	So, that means more casualties
Observer:	That's for sure. Because a scenario lasts, what is it? About five minutes? Than we have six scenarios to go
Dispatcher:	Yes, so that will be about 680 casualties
Observer:	Well say 480 to, maybe we will get a disaster scenario, 700 casualties in total, I hope
Dispatcher:	I do too
Observer:	Then I'm happy
Dispatcher:	Me too
Observer:	Yes
Dispatcher:	But also a little sad, because as a feeling person you cannot push it all away
Observer:	Indeed not entirely, even though they are all virtual human beings
Dispatcher:	Virtual human beings are also human beings
Observer:	In a virtual world
Dispatcher:	It's what you want to believe, isn't it?

Surprisingly, team members do not communicate about the fact that the pattern in a series of small buildings was incorrect. Probably the observer found the factory by chance and did not pay further attention to it. The communication is further confined to a brief evaluative statement about the score. Subsequently, team members communicate, less seriously, about the scenarios to go. With respect to the first scenario, no knowledge is transferred or strategies are determined. It seems that team members communicate to fill the spare time.

Team 17, between novel Scenario 10 and 11. Because team members did not pay attention to the novel scenario whatsoever, we analyzed also the protocol from the time between Scenario 10 and 11. Now team members have been confronted for the second time with a novel scenario:

Observer:	With a little more luck we could save the apartment building also
Dispatcher:	Yes, or at least half, but it is still guessing, isn't?
Observer:	Indeed, for me too, because the pattern predicted another sector
Dispatcher:	Hmmm...
Observer:	So I had to search where the large building was
Dispatcher:	Yes
Observer:	I had to watch all the buildings to find out where the building in danger was
Dispatcher:	How do you search?
Observer:	Well, usually you have, for example, a pattern in sector I and then you can predict that it comes in sector IV
Dispatcher:	Yes
Observer:	But now I was clicking on the buildings in sector IV and this time there was no building with a message in danger
Dispatcher:	Hmmm...

This time the team members have discovered that the pattern is incorrect. While evaluating, the observer tells the dispatcher that the fire search is difficult because the pattern does not predict the sector as expected. Meanwhile, the dispatcher is also informed about how the observer performs the fire search.

Hence, information of each other's task is exchanged. Knowledge about the learned pattern is also transferred. Team members continue to communicate about the pattern:

Observer:	So I had to click all the buildings in the map to find the large building in danger
Dispatcher:	Yes
Observer:	Therefore, I was somewhat late with the message
Dispatcher:	But, in general, the pattern is correct?
Observer:	No, the past two times not. I think the scenarios become more difficult now
Dispatcher:	Hmmm..., but the pattern still predicts the expected building type
Observer:	For now, yes. So an apartment building and two houses predicts a factory, such as in the last scenario
Dispatcher:	An apartment building and two houses?
Observer:	First an apartment building, then a house, and then another house
Dispatcher:	Yes
Observer:	And then a factory is on fire

The observer explains why the message of the building in danger was sent too late. Common knowledge is developed about the situation. Both team members are now aware that the pattern in a series of small fires has changed. Subsequently, the dispatcher wants to know exactly what elements of the pattern have changed. The dispatcher is especially interested in whether the pattern still predicts the large building in danger as usual. This is important for the dispatcher's task execution, because this information is needed to decide on the withdrawal of units in Period 7. However, because the focus is on how the pattern predicts the building type, team members have no time to determine how the new pattern predicts the sector.

Team 17, between novel Scenario 15 and 16. The time between Scenario 15 and 16 is the last time that team members communicate unrestrictedly with each other:

Observer:	That's disappointing
Dispatcher:	Only one period too late and then...
Observer:	Did you pull one unit back from that apartment building?
Dispatcher:	Yes
Observer:	That wasn't necessary
Dispatcher:	If it was a hospital, then it was
Observer:	Yes, but I had told you that it was going to be a factory?
Dispatcher:	Yes, but I wanted to react on the developments
Observer:	Yes, yes
Dispatcher:	But when I heard that it was a factory, I put it right back
Observer:	Yeah, great
Dispatcher:	That wasn't of any use, I think
Observer:	No, because it was saved anyway
Dispatcher:	Okay
Observer:	So we saved another ten

First, team members judge their performance and, subsequently, analyze where it went wrong. The way units were allocated is discussed in detail. Knowledge is transferred about the numbers of casualties associated with an apartment building ("we saved another ten"). Team members continue to communicate:

Dispatcher:	Well I expect a bouquet
Observer:	At least
Dispatcher:	So, this was not the last time
Observer:	No, apparently not
Dispatcher:	Maybe, this evaluating conversation is also important
Observer:	Yes, they need that on tape also
Dispatcher:	I don't think we have said anything interesting
Observer:	I don't think so either
Dispatcher:	Well, say something crucial

Observer:	It is going outstanding
Dispatcher:	So his thesis will be more thicker
Observer:	Yes, exactly
Dispatcher:	I can say something Malaysian, so that they have to consult all sorts of dictionaries
Observer:	Okay, go on
Dispatcher:	(...)
Observer:	(...)
Dispatcher:	There comes another round
Observer:	Yes!

Because team members arrive at the last scenario, there is probably nothing more to say or to evaluate. The time left between scenarios is filled with social communication. Team members make jokes and talk about one thing and another.

In conclusion, team members use their opportunity to communicate between scenarios to evaluate and determine strategies. With respect to the communication during scenarios, team members communicate less about the specific periods when events take place and activities have to be performed.

Examples of verbal protocols

We now turn to some selected examples from protocols to illustrate the communication categories.

Information exchange. Team members often inform each other verbally about the status of fires (Team 5, Scenario 1, Period 10):

Observer:	School is free, an apartment building is burned down, and another apartment building is almost extinguished
Dispatcher:	Okay

The dispatcher may inform the observer about the allocation decision (Team 11, Scenario 3, Period 8):

Dispatcher: I sent five units to the hospital

The dispatcher may also inform the observer about the number of units present at the station (Team 1, Scenario 9, Period 10):

Dispatcher: Unfortunately, I have only two units available

Performance monitoring. Performance monitoring is communication about the tasks team members perform during the scenario. It occurs when team members inform each other about what they are doing at particular moments (Team 3, Scenario 15, Period 3):

Observer:	Okay, here is apartment building M
Dispatcher:	Right, I send two units

This type of communication allows team members to watch each other's task performance. For example, when the dispatcher made a wrong decision by sending two units to the apartment building, the observer is now able to verify this. In case of mistakes, the observer can give feedback and tell the dispatcher the right number of units needed to extinguish the fire. In the following example, the observer corrects the dispatcher (Team 9, Scenario 3, Period 5 and 6):

Observer:	Did you send one unit to that house?
Dispatcher:	Yes, I did
Observer:	Well, maybe it is better if you pull back ... because there comes another apartment building in IV
Dispatcher:	Okay, I pull one unit back
Observer:	Otherwise it becomes a mess

By informing each other about the present activities, team members may also determine the best course of action during task performance (Team 5, Scenario 4, Period 8):

Observer:	Let's see
Dispatcher:	we are still able to save two houses
Observer:	Yes, one house is going to need more units
Dispatcher:	Oh
Observer:	We cannot save that one, but house Q maybe, and the apartment buildings, F maybe?

One of the team knowledge elements important in shared mental models is knowledge about the sequence and timing in activities. In the fire-fighting task, it is crucial that information about the building in danger is exchanged before Period 8 finishes so that the dispatcher has enough time to (re)allocate units. During performance monitoring, team members can transfer knowledge about the sequence and timing of actions, which may refine the knowledge of the team members. In the following example, the dispatcher informs the observer about the number of periods that is needed to allocate units in time (Team 5, Scenario 13, Period 8):

Dispatcher:	Units are on their way to the large building in eight, in Period 9 they're present
Observer:	That's one period too late
Dispatcher:	Huh?
Observer:	That's one period too late, because in Period 10 the building starts to burn
Dispatcher:	No, in Period 9 they're present, just in time
Observer:	Yes? Okay.
Dispatcher:	Yes

The observer may also inform the dispatcher about her search for the large fire in danger (Team 3, Scenario 14, Period 7 to 8):

Observer:	I am going to look for the hospital. Well, the pattern is not right. I am always looking in the wrong sector
Dispatcher:	Yes, we are being misled

When the observer informs the dispatcher that the large building in danger cannot be found, this is a sign that the team may be confronted with a novel situation. This is important when team members are going to evaluate their task performance. Based on this situational knowledge, team members can track down that the performance decrease was due to the incorrect pattern in a series of small fires. Another example is (Team 2, Scenario 8, Period 9):

Dispatcher:	Okay, we are in trouble. We are now in Period 9 and there is still no large building
Observer:	Well, then there will be a big thing in a minute
Dispatcher:	Do you think?
Observer:	You can count on it

Here the dispatcher realizes that there is still no large building. By informing the observer, he receives feedback that things must be sped up to be on time. The dispatcher also mentions Period 9, which may refine the knowledge of the observer about the period that information about the large building must be exchanged (i.e., at least in Period 8).

Evaluation. In the during condition, evaluation occurs typically at the beginning of a scenario when the workload in the fire-fighting task is relatively low (Team 5, Scenario 14, Period 1):

Dispatcher:	This one went great. What do you think?
Observer:	yes, indeed
Dispatcher:	Yes
Observer:	Not bad at all
Dispatcher:	I think we must keep going on like this

Observer: Thus, first saving one or two small buildings and then...
Dispatcher: Yes, but the house, wasn't that burned down yet?
Observer: No, I don't think so

This example shows that team members first give a judgement of the past scenario. Subsequently, team members analyze in more detail specific moments of the scenario. Team members also establish the best strategy ("thus, first saving one or two small buildings"). This gives members a common understanding of the strategy. Another example of evaluation is (Team 1, Scenario 2, Period 2 to 3):

Dispatcher: That were a lot of casualties
Observer: Yes, that was because we didn't pay attention to the pattern
Dispatcher: No, that's not the point. I was too late for the factory
Observer: Yes, indeed, but it was my mistake that I was too late with searching the large building. I didn't pay attention to it. Next time, I will
Dispatcher: Yes, that is very important

Here, team members clarify their roles and responsibilities. The conclusion is that the poor performance was due to the observer's fault to be too late with sending the message about the large building in danger that caused the dispatcher to be too late with allocating units. This emphasizes the interdependency of the members and the importance to provide information on time. Hence, team knowledge of each other's informational needs is developed. In the between condition, team members do not have to perform fire-fighting tasks, so they can spend their time solely to evaluate. In the following example, team members tell each other what went wrong in the past scenario (Team 19, between Scenario 1 and 2):

Dispatcher: It's difficult. Well we shall see how we are going to do it
Observer: Yes, this was the just the first one
Dispatcher: Yes
Observer: I had to search for the factory
Dispatcher: Yes
Observer: But I lost the factory
Dispatcher: I didn't recognize a pattern yet
Observer: I had it quickly. However, it took a while to find the factory

When team members evaluate a novel scenario, they can track down that the pattern in a series of small buildings is incorrect (Team 16, between Scenario 10 and 11):

Observer: The sector was different from what you expected
Dispatcher: Oh...
Observer: It was in sector II and not in sector I
Dispatcher: Yes, I cannot see that always
Observer: That's why it went wrong. The pattern wasn't right, so...

This type of communication makes team members aware of the fact that they may have encountered a novel situation. Based on this knowledge, team members can determine the new pattern together.

Determining strategies. Team members may inform each other about the best strategy in general (Team 5, Scenario 2, Period 10):

Dispatcher: We have to take care that we find the pattern as soon as possible so that we can send very quickly units to the large building, because I just have only six units
Observer: Okay

Here, the dispatcher's strategy is to perform the activities as soon as possible, which emphasizes that the large building in danger must be found directly when the pattern is recognized. Based on this knowledge, the observer may be more aware that the fire search must begin as soon as possible. In novel scenarios, it is important that team members determine the new patterns in a series of small buildings. In the following example, team members cooperatively determine the new pattern (Team 6, Scenario 15, Period 6 to 7):

Observer:	Well, there is again a house in sector I. I hope that if another thing is gonna burn in sector I, soon a factory will be in danger in sector III. Otherwise I have to search again all the large buildings on the map
Dispatcher:	Thus, the new pattern is that it is gonna be a fire above or below the sector with the pattern?
Observer:	Yes, I think so
Dispatcher:	Let's hope so
Observer:	Yes
Dispatcher:	Well, it should be a factory in sector III
Observer:	Yes, I found it
Dispatcher:	Great, give it to me quickly

The observer expresses his or her expectation of the sector in which the large building in danger will be on fire. The dispatcher generalizes this such that it can be applied to other scenarios as well. In other words, an alternative pattern is hypothesized that can be tested. Somewhat later, the observer finds the large building in the sector that was expected based on team members' alternative pattern. This confirms team members' hypothesized pattern.

Team knowledge. An important team knowledge element is knowledge of each other's task. In the following example, the observer is informed about the number of periods that the dispatcher needs to allocate units in time (Team 6, Scenario 2, Period 6 to 7):

Observer:	Again a hospital in the tenth period. Meaning that the units must on their way by now
Dispatcher:	No, in the next period
Observer:	No, in this period, because you need three periods before the units are present
Dispatcher:	No, when I send units in Period 8, then they are present in Period 10
Observer:	Are you sure?
Dispatcher:	Yes

The importance of this type of communication is that the observer develops a profound understanding of when tasks of the dispatcher take place. The observer may also develop an understanding of the consequences for his own task execution; to be in time in Period 8, the search after the large building in danger must be finished at least in the middle of Period 8. This way, team members develop detailed procedural knowledge of each other's task sequence. Team members may also inform each other about each other's informational needs (Team 1, Scenario 1, Period 4):

Dispatcher:	On the moment that a large building is burning...
Observer:	Yes
Dispatcher:	Don't give me too much information about apartment buildings, because it gets so unclear
Observer:	Yes, I will

The dispatcher explicitly tells the observer when and what information is not needed to provide. Sometimes dispatchers are more direct (Team 6, Scenario 6, Period 9):

Dispatcher:	That's why I need to know all those things as soon as possible, at least before Period 8

In the following example, the observer takes the initiative to ask the dispatcher in which way the information must be provided (Team 3, Scenario 12, Period 2 to 3):

Observer:	What is better? If I say house A in sector IV or do you want it otherwise?
Dispatcher:	You only have to mention house A, I can see the sector number on my screen
Observer:	Are you sure?
Dispatcher:	Yes
Observer:	What kind of display do you have? Don't you have a map of the city, like me?

Dispatcher: No, I don't have a map
Observer: Thus, I just have to call the building name and that's enough?
Dispatcher: Yes that's enough

Another example in which team members develop a common understanding of the way information must be exchanged is (Team 5, Scenario 1, Period 3):

Observer: I shall try to send only messages when something changes in the city
Dispatcher: Yes please
Observer: Because I think you're gonna get crazy if I send you 10.000 messages
Dispatcher: No, only send me the most important messages
Observer: Even not small houses?
Dispatcher: Yes, but I would like to have the apartment buildings
Observer: Okay

Situation knowledge. Situation knowledge includes the exchange of information concerning the pattern or changes in the pattern of small buildings and predictions of the large building in danger (Team 5, Scenario 2, Period 6):

Observer: Yes, I ... there will be a pattern soon, because there comes a house in sector III
Dispatcher: Apartment building, house, apartment building
Observer: Indeed

Team members may help each other in predicting the sector of the large building in danger (Team 5, Scenario 3, Period 6):

Observer: ...and now we have a new apartment building in sector IV
Dispatcher: Yes, sector IV, apartment building, apartment building
Observer: Yes
Dispatcher: What do we have here?
Observer: A house, or an apartment building, I guess
Dispatcher: In sector I
Observer: An apartment building, a hospital is coming up

In novel situations, team members must reveal that the pattern in a series of small buildings is incorrect (Team 5, Scenario 9, Period 7):

Observer: It is gonna be a factory
Dispatcher: Fortunately
Observer: Oops, I can't find it, I think it is in a different sector, now I have to search
Dispatcher: Maybe it is in sector III, the sector besides the one we normally expect
Observer: Yes, indeed
Dispatcher: Thus, when we have a factory or hospital in sector IV, we have to search in sector III

Here, situation knowledge is transferred about the sector.

4.3.3 Summary and conclusions unrestricted communication

The purpose of the cognitive team task analysis of this section was a) to determine what additional teamwork is introduced when team members have the opportunity to communicate unrestrictedly, b) which knowledge is needed to perform this teamwork successfully, and c) what knowledge is transferred when team members communicate unrestrictedly. In the following paragraphs, these subjects will be discussed separately.

Teamwork

When team members have the opportunity to communicate unrestrictedly, several teamwork tasks are introduced. Based on the literature we determined that team members might use their opportunity to communicate unrestrictedly for performance monitoring, evaluation, and determining strategies. Performance monitoring helps team members to adjust the task execution immediately. Team members watch each other's task execution, provide feedback, and give advice to optimize task performance. Observational studies in the military field have shown that good performing teams engage more often in performance monitoring than poor performing teams (McIntyre & Salas, 1995). Blickensderfer et al. (1997b) assert that communication is beneficial for team self-correction. Two important phases can be distinguished in team-self correction discussions. In the one phase, team members look back and evaluate their past performance. In the other, often subsequent phase, team members look ahead and determine strategies to improve performance for the next time. Although the value of this type of discussions is especially described in terms of improving teamwork (e.g., more implicit coordination, and performing activities in sync) it can be argued that such discussions are also important to develop strategies to handle unexpected problems in novel situations. Stout et al. (1996) theorized that this so-called strategizing is especially important in order to develop commonly hold strategies. In flight simulator studies, Orasanu (1990, 1993) showed that teams committed fewer flight errors when the members used the low workload periods to communicate about task strategies and plans. Taken together, these studies assert that unrestricted communication may have a positive effect on performance.

The qualitative analysis of the verbal protocols shows that performance monitoring, evaluation, and determining strategies can be distinguished in the fire-fighting task. Performance monitoring takes place by informing each other about what one is doing during fire fighting. This allows team members to watch each other's performance. For example, when the dispatcher mentions how many units he or she wants to allocate, the observer can verify whether this is the right amount. Team members may also provide each other with feedback or give advice to improve performance further. Evaluation seems to take place typically during the relatively low workload periods in the fire-fighting task. The performance outcome is judged and team members jointly analyze the causes of the good or poor performance. For example, team members conclude that their poor performance is due to the dispatcher who was too late with allocating units. Further evaluation might reveal that this was caused by the observer being too late with sending the message about the large building in danger. Finally, team members determine strategies together. For example, team members determine that the pattern must be recognized as soon as possible or that a series of fires in small buildings forms a new pattern from which the type and sector of the large building in danger can be predicted. In conclusion, based on the examination of the verbal protocols we believe that team members that have the opportunity to communicate without restrictions use this opportunity to monitor each other's performance and jointly evaluate and determine strategies in the fire-fighting task.

Knowledge

Based on the literature and the verbal protocols we concluded that when teams have the opportunity to communicate unrestrictedly, three additional teamwork tasks (i.e., performance monitoring, evaluation, and determining strategies) are introduced in the fire-fighting task. Now, the question is whether the knowledge that is needed to perform this teamwork in the fire-fighting task is similar to what researchers expect to be important for shared mental models. Just as with the restricted condition, we compared this. The starting point is the four team knowledge elements described by Cannon-Bowers et al. (1993):

1. *Equipment knowledge.* Team members do not need equipment knowledge for performance monitoring, evaluation, or determining strategies.
2. *Task knowledge.* For performance monitoring it is important that team members know the current state of the progress made on the task. Knowledge of the past performance on the task is needed for evaluation. In order to determine strategies, team members must also know the past performance and know that different strategies lead to different performance outcomes. Knowledge of strategies is needed to compare strategies and decide on which one is the best.
3. *Team interaction knowledge.* To determine team strategies, team members need team interaction knowledge that describes which way information exchange can take place. This includes knowledge describing that information exchange can take place each period or only when there are changes in the number of units needed.
4. *Team members' characteristics.* The knowledge we determined for the teamwork that is introduced when team members communicate unrestrictedly in the fire-fighting task does not include knowledge of the characteristics of the team members.

Besides these four knowledge elements, Blickensderfer et al. (2000) also assert that it is important to have common knowledge of the goal. In the fire-fighting task, team members need to know that the goal is to save as many potential casualties as possible. It is also important that team members translate this knowledge in terms of how fire fighting should ideally take place and what optimal performance is. This knowledge is needed to be able to determine whether the present (performance monitoring) or past (evaluation and determining strategies) performance is such that it can be improved. Finally, in the unrestricted condition, it is important that team members have up-to-date situation knowledge. With the help of this knowledge team members are able to evaluate the performance and determine strategies jointly. Team members must, for example, know that there are novel scenarios in which the pattern does not predict the sector and the type of the large building as usual. Based on this knowledge, team members can determine new strategies together.

Knowledge transfer

We hypothesized that unrestricted communication fosters the knowledge team members have in their shared mental models. Based on the literature, we defined several categories in which communication can be classified. The verbal protocol analysis shows that for each of the categories we determined, knowledge is transferred. Unrestricted communication seems to be especially important to refine members' team knowledge into specific procedural rules of how to perform teamwork in the fire-fighting task. For example, instead of knowing that it is important to exchange information in time, team members develop knowledge that it is important to exchange information in one period. Because team members know more specifically when information is important to exchange, they are more able to coordinate implicitly. Unrestricted communication gives team members also the opportunity to develop up-to-date knowledge of the ongoing performance and situational developments. This commonly held knowledge helps team members to engage in performance monitoring, evaluation, and determining strategies.

4.4 Conclusions

The main purpose to perform the cognitive team task analysis was to reveal whether the psychologically important elements of the shared mental model theory are present in the fire-fighting task. If that is the case, we are confident that the fire-fighting task can be used to investigate the shared mental model theory empirically. The cognitive team task analysis shows that the fire-fighting task contains team processes that researchers expect to be important for shared mental models.

The first team process is implicit coordination. In the restricted communication condition, information exchange is needed to accomplish the tasks. The analysis revealed further that this information exchange must take place at certain moments in the scenario and under considerable time pressure. Implicit coordination and, therefore, communicating efficiently and effectively is possible and also expected to be beneficial for team performance. Other team processes are concerned with communication as antecedent of shared mental models. The analysis shows that in the unrestricted condition, team members perform several additional teamwork tasks. Team members monitor each other's performance, evaluate, and determine strategies together. The examples of the verbal protocols give a detailed description of how team members engage in this teamwork and how this fosters the knowledge of team members. Based on the cognitive team task analysis, we conclude that the fire-fighting task contains the psychologically important elements to investigate the shared mental model theory empirically.

Another purpose was to examine whether the knowledge needed to perform teamwork in the fire-fighting task has to be shared among team members. The cognitive team task analysis provides a detailed description of the knowledge needed to perform taskwork as well as teamwork in the fire-fighting task. The knowledge needed to perform the teamwork (i.e., implicit coordination, performance monitoring, evaluation, and determining strategies) in the fire-fighting task is similar to the knowledge that researchers expect to be important for shared mental models. Whether this knowledge must be completely held in common remains a difficult matter. In order to coordinate implicitly, it can be argued that there is a certain overlap in the knowledge of the team members. This especially goes for team interaction knowledge. Knowing when to provide *and* expect certain information seems to be important. However, as far as it is concerned with task knowledge, such as knowledge of each other's tasks and task strategies, this is less clear. It can be argued that to coordinate implicitly it is sufficient when team members know which information must be exchanged when. However, it can also be argued that team members have a better understanding of why information must be exchanged when they have knowledge of each other's task (and thus have several task knowledge elements in common).

For performance monitoring, evaluation, and determining strategies it can also be argued that a certain overlap in team member's knowledge is needed. Commonly held knowledge ensures that team members interpret the teamwork demands and the situation similarly, which ensures that team members provide each other with information, suggestions, or alternative courses of action that are both expected and can be explained by the teammate. Regardless of the knowledge overlap, we conclude that team members need specific knowledge to perform the teamwork effectively.

The verbal protocol analysis shows that communication can be used to foster team member's knowledge in a shared mental model. Within the communication categories we defined, team members communicate about each other's task, their informational dependencies, task strategies, changes in the situation, and other knowledge elements expected to be important for shared mental models. The transcriptions of the verbal communication give a detailed insight of how the process of knowledge fostering takes place.

Finally, the cognitive team task analysis provides a clear picture of the relationships between knowledge in shared mental models, team processes, and performance. A good performance can be obtained only when team members perform accurately on their teamwork tasks. It is essential that team members exchange the necessary information in time and apply the right strategies. The cognitive team task analysis shows that team and situation knowledge is needed to perform this teamwork accurately.

Therefore, we assert that team performance is a good indicator of having knowledge in shared mental models. The higher the performance, the better team members' knowledge in shared mental models.

In chapter 2 to 4, we examined conceptually team processes of teams that perform in complex and dynamic environments. After the theoretical exploration (chapter 2), the description of the experimental team task (chapter 3), and the description of the teamwork and knowledge needed in this task (chapter 4), we now turn to the empirical work of this thesis. In the next chapter, the first two experiments are described in which the effect of cross training on communication and performance is investigated.

5 CROSS TRAINING, COMMUNICATION, AND PERFORMANCE

In this chapter, we describe two experiments that we performed to investigate the effect of cross training on communication and team performance. In both experiments, we compared teams that received a cross training with teams that received no cross training. The hypothesis that cross training has a positive effect on communication and performance is not supported by the results. We explain these results in terms of several shortcomings of the experimental task employed. In addition, we discuss the results in the light of recent cross training experiments performed by other researchers.

5.1 Introduction

This chapter addresses the first question of this thesis: how can communication and performance be improved by fostering the knowledge team members have in their mental models? The first method we employ to foster the knowledge of team members is cross training. Cross training is defined as a strategy "in which each team member is trained on the tasks, duties and responsibilities of his or her fellow team members" (Volpe et al., 1995, p. 87). The purpose of cross training is to develop team knowledge. Cross training must provide team members with an understanding of how the team functions and how team member's tasks and responsibilities relate to those of the teammates. It is expected that cross training fosters the knowledge that team members hold in a mental model of the tasks, roles, and responsibilities of the teammates. This gives team members an understanding of each other's informational needs that enable them to anticipate on each other and provide information without explicit requests (Cannon-Bowers et al., 1998). Based on their team knowledge, team members can coordinate implicitly with a minimal communication requirement (Kleinman & Serfaty, 1989; Volpe et al., 1995). Especially in teams that must exchange large amounts of information under high time pressure, this is expected to be effective.

Cross training can be divided into three types based on the depth of information provided. The assumption that underlies this typology is that the extent of interdependency between team members determines the type of cross training needed (Blickensderfer et al., 1998b; Cannon-Bowers et al., 1998). The three cross training methods described by Blickensderfer et al. (1998b, p. 305) are:

1. *Positional clarification.* The goal of positional clarification is to provide team members with general knowledge of the team structure and each member's general position and associated responsibilities. Positional clarification is an appropriate cross training for low-interdependence teams in which information exchange and coordinated interaction is required occasionally. Training methods include discussion, instruction, and demonstration.
2. *Positional modeling.* The goal of positional modeling is to provide team members with knowledge about team members' duties and an understanding of how these duties are related to, and influence those of the other team members. With respect to positional clarification, the knowledge concerning team member's roles and responsibilities is more detailed. Medium interdependent teams in which team members have moderately distinct functions and where

regularly information exchange and coordination is needed, benefit from positional modeling. Positional modeling involves a cross training in which the duties of team members are discussed, modeled, and observed.

3. *Positional rotation*. The goal of positional rotation is to provide team members with knowledge concerning the tasks of teammates. Team members must gain also an understanding of the interaction between team members and develop different perspectives of the task. Positional rotation is especially suitable for high-interdependent teams that consist of team members with unique functions and in which there is a critical need for information exchange and coordination. Members in such teams require extensive knowledge of the roles and tasks of their teammates so that they can anticipate on each other's informational needs and provide information in advance of requests. Positional rotation involves active participation in each other's tasks allowing team members to obtain "hands-on" experience.

Because of the high interdependency between members in a team, we believe that the most appropriate cross training strategy to be applied is positional rotation.

5.1.1 Experiment 1 and 2

Experiment 1 and 2 addresses the question whether cross training improves implicit coordination and team performance. A comparison is made between teams that receive training on their own tasks only and teams that receive a cross training (i.e., positional rotation). Figure 5.1 represents the dimensions (denoted by the gray boxes) and the relationships (denoted by the uninterrupted lines) that are under investigation in Experiment 1 and 2.

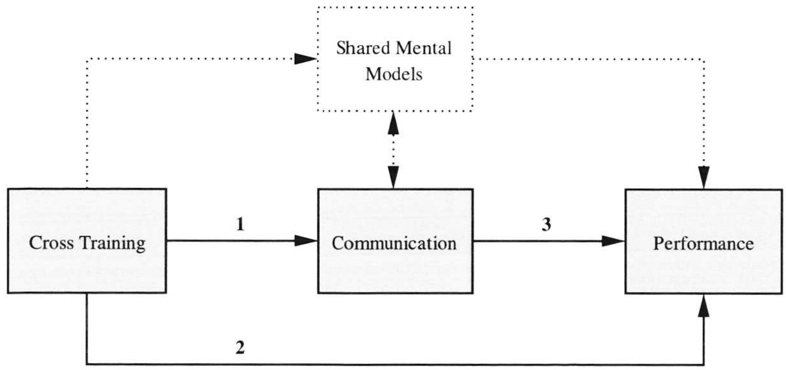

Figure 5.1: Hypothesized relationships under investigation in Experiment 1 and 2 between cross training, implicit coordination, and performance

5.2 Experiment 1

5.2.1 Hypotheses

Given the expected value of cross training on the development of shared mental models containing knowledge of team members' tasks, roles and responsibilities and, in turn, using effective communication and coordination strategies during high workload situations, the following hypotheses are put forward:

1. We expect that the teams that receive a cross training coordinate more implicitly and therefore communicate more efficiently and effectively (i.e., less communication, more necessary information, more necessary information in advance of requests, less requests, answering more requests, more necessary information in time, and answering more requests in a shorter time notice) than the teams that receive no cross training; this communication improvement will be most pronounced in high workload situations
2. We expect that the teams that receive a cross training perform better than the teams that receive no cross training; this performance improvement will be most pronounced in high workload situations
3. We expect that communication is positively correlated with performance

5.2.2 Method

Participants

The data for Experiment 1 were obtained from 44 students of Utrecht University in 22 teams of two participants. The distribution of participants over the two conditions with regard to sex was as follows: two female, two male, and seven mixed teams in the *no* cross training condition and two female, five male, and four mixed teams in the cross training condition. It was attempted to assign participants that were not acquainted to each other in one team (this failed with one team). The participants were paid Dfl. 60, = for their contribution.

Design

Between teams. In order to test the hypotheses, two experimental conditions were designed. In the *no* cross training condition, team members did not receive training in the teammate's task, whereas in the cross training condition team members did receive such a training.

Within teams. The presence of high workload scenarios was a within team manipulation. High and low workload scenarios were equally present (four high and four low workload scenarios) and randomly distributed over the eight experimental scenarios.

Task

In Experiment 1, Version 1 of the fire-fighting task as described in section 3.2.1 was used.

Manipulation

In addition to the three scenarios in which team members were trained in their own task, the cross-trained teams received a training of the teammate's task, which existed of three scenarios. Team members that received no cross training did *not* receive such a training.

Workload was manipulated by the number and type of fires that were present in a scenario. In the high workload scenarios, more large buildings were set on fire than in the low workload scenarios. Moreover, these fires followed each other more rapidly.

Measures

Communication. Team members could only communicate by using the standardized electronic messages. The messages were time-stamped and saved in a computer log file for analysis. In order to determine whether teams coordinated implicitly and therefore communicated efficiently and effectively, nine communication measures were developed. The measures are based on the communication features of implicit coordination in the fire-fighting task that were established with the help of the cognitive team task analysis of chapter 4 (see section 4.2.2, Table 4.7). Table 5.1 gives an overview of the communication features when team members coordinate implicitly and the way these are measured in the fire-fighting task.

Table 5.1: Overview of the communication features when team members coordinate implicitly and the way these are measured in the fire-fighting task

General communication features	**Measures**
Less communication	1. Number of messages
The exchange of relevant information only	2. Percentage necessary messages sent of the total number of messages that was sent (necessary messages for the observer were messages about new fires and changes in the units needed, necessary messages for the dispatcher were messages about the number of units allocated) 3. Percentage necessary messages sent of the total number of necessary messages that could be sent
The exchange of information in advance of requests	4. Number of necessary messages provided without requests
Less requests	5. Number of questions asked
In case of requests, answers will be given	6. Percentage questions answered
The exchange of relevant information in time	7. Percentage necessary messages sent *in one period* of the total number of necessary messages that could be sent 8. Percentage necessary messages sent *in two periods* of the total number of necessary messages that could be sent
In case of requests, answers will be given as soon as possible	9. Time between request and answer

Performance. Performance was measured by the percentage of casualties saved out of the total number of potential casualties that could be saved in a scenario.

Procedure

An experimenter assigned the participants randomly to the role of dispatcher and observer and told them to read the instruction. Participants were placed in separate soundproof rooms and communication between the participants was made possible by sending and receiving the standardized electronic messages. They were told not to speak to each other about the experiment and the experimenter was always present in situations where participants were together in the same space. The instruction first explained the fire-fighting task in general, followed by specific instructions for each role. Participants were allowed to ask questions at any point during reading.

After reading the instruction, there was a training session of three scenarios that consisted of 10 periods of 45 seconds each. During the training, the two members of the team played the same scenarios at the same time. The dispatcher played with a computer program that simulated observer behavior (e.g., sending messages and so forth) and the observer played with a computer program that simulated dispatcher behavior. The programs, or "agents" as they were called, displayed ideal observer and dispatcher behavior. That is, the agents were always in time with the right information. The participants were informed of this. Participants were also informed that in the experimental session they would play with their actual teammate. The choice for this technique was made, to ensure an equal level of expertise at the end of the training by controlling the teammate's behavior.

After the training, the experimental session started. Participants were presented with eight scenarios that consisted of 20 periods of 30 seconds each. Compared with the training scenarios, the experimental scenarios were more difficult because there were more fires and there was less time to perform the activities (30 instead of 45 seconds for each period). In total, an experimental session lasted about four hours.

5.2.3 Results

Communication

In order to test Hypothesis 1, an analysis of variance using repeated measures for each scenario was performed. The repeated measures design consisted of eight scenarios. For low and high workload scenarios, a separate analysis was performed also using repeated measures for each scenario. Exceptions were Measure 6 (percentage of questions answered) and 9 (time between request and answer) for which we performed an analysis of variance without repeated measures. This was done because in several scenarios team members did not provide answers, which resulted in several missing values. The results of the analysis are shown in Table 5.2 to 5.4 in which the means for each scenario for the low workload, high workload, as well as the total number of scenarios can be found.

As can be seen in Table 5.2 to 5.4, the hypothesis that team members would coordinate more explicitly and, therefore, would communicate more efficiently and effectively as a result of cross training did not receive support. For the total number of scenarios, as well for the low and high workload scenarios there are no differences between the conditions on the number, percentages, and timing of messages sent. An exception is the total number of messages in low workload scenarios. Cross-trained teams sent fewer messages than noncross-trained teams. Contrary to our expectations, this was not more pronounced during the high workload scenarios. Another exception is that, especially during high workload scenarios, the cross-trained teams provided more answers than the noncross-trained teams. Nevertheless, the significance levels are low, and given the number of tests and, therefore, the capitalization on chance, these results should be interpreted with great caution.

Table 5.2: Communication results for the total number of scenarios

Communication measure:	No cross training	Cross training	*F*-value
1. Number of messages	58	46	$F(1,20) = 2.50$
2. Percentage necessary messages sent of the total number of messages that was sent	47	51	$F(1,20) < 1$
3. Percentage necessary messages sent of the total number of necessary messages that could be sent	63	60	$F(1,20) < 1$
4. Number of necessary messages provided in advance of requests	23	21	$F(1,20) = 2.41$
5. Number of questions asked	12	9	$F(1,20) < 1$
6. Percentage questions answered	65	82	$F(1,20) = 3.53$*
7. Percentage necessary messages sent *in one period* of the total number of necessary messages that could be sent	53	51	$F(1,20) < 1$
8. Percentage necessary messages sent *in two periods* of the total number of necessary messages that could be sent	61	57	$F(1,20) < 1$
9. Time between request and answer (seconds)	22	17	$F(1,19) = 1.24$

Note. *$p < .10$

Table 5.3: Communication results for the low workload scenarios

Communication measure:	No cross training	Cross training	*F*-value
1. Number of messages	55	42	$F(1,20) = 3.18$*
2. Percentage necessary messages sent of the total number of messages that was sent	46	50	$F(1,20) = 1.19$
3. Percentage necessary messages sent of the total number of necessary messages that could be sent	64	62	$F(1,20) < 1$
4. Number of necessary messages provided in advance of requests	20	18	$F(1,20) = 1.52$
5. Number of questions asked	11	9	$F(1,20) < 1$
6. Percentage questions answered	70	84	$F(1,20) = 2.11$
7. Percentage necessary messages sent *in one period* of the total number of necessary messages that could be sent	54	53	$F(1,20) < 1$
8. Percentage necessary messages sent *in two periods* of the total number of necessary messages that could be sent	61	59	$F(1,20) < 1$
9. Time between request and answer (seconds)	19	19	$F(1,19) < 1$

Note. *$p < .10$

Table 5.4: Communication results for the high workload scenarios

Communication measure:	No cross training	Cross training	*F*-value
1. Number of messages	61	51	$F(1,20) = 1.84$
2. Percentage necessary messages sent of the total number of messages that was sent	49	51	$F(1,20) < 1$
3. Percentage necessary messages sent of the total number of necessary messages that could be sent	62	58	$F(1,20) = 1.24$
4. Number of necessary messages provided in advance of requests	26	23	$F(1,20) = 2.75$
5. Number of questions asked	12	10	$F(1,20) < 1$
6. Percentage questions answered	61	81	$F(1,20) = 4.41$**
7. Percentage necessary messages sent *in one period* of the total number of necessary messages that could be sent	52	49	$F(1,20) < 1$
8. Percentage necessary messages sent *in two periods* of the total number of necessary messages that could be sent	60	56	$F(1,20) = 1.16$
9. Time between request and answer (seconds)	25	14	$F(1,19) = 3.31$*

Note. *$p < .10$, **$p < .05$

Performance

In order to test Hypothesis 2, which states that cross-trained teams perform better than noncross-trained teams, we performed an analysis of variance using repeated measures for each scenario. The repeated measures design consisted of eight scenarios. For low and high workload scenarios, a separate analysis was performed also using repeated measures for each scenario. The results are shown in Figure 5.2.

Hypothesis 2 was not supported. There were no significant differences between the conditions on the total number of scenarios, $F(1,20) < 1$, on the low workload scenarios, $F(1,20) < 1$, or on the high workload scenarios, $F(1,20) < 1$.

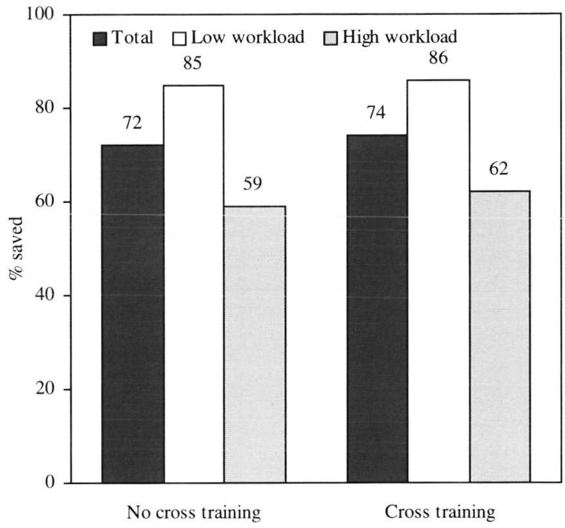

Figure 5.2: Mean percentage of potential casualties saved in the cross-trained and the noncross-trained condition for the total number of scenarios, and the low and high workload scenarios

Communication and performance

Table 5.5 shows the correlations among the communication measures and performance. These correlations indicate little support for Hypothesis 3. With respect to performance, there are only positive correlations with the percentage questions answered, $r = .37$, $p < .10$, and the percentage of necessary messages sent in one period of the total number of necessary messages that could be sent, $r = .38$, $p < .10$. Nevertheless, both significance levels are low. Hence, there is only a small indication that better communication improves performance in teams.

Table 5.5: Correlations between communication (denoted by number 1 to 9) and performance (denoted by number 10)

Measure	*N*	*M*	*SD*	1.	2.	3.	4.	5.	6.	7.	8.	9.
1. Number of messages	22	52.1	18.3									
2. Percentage necessary messages sent of the total number of messages that was sent	22	49.0	11.0	-.87***								
3. Percentage necessary messages sent of the total number of necessary messages that could be sent	22	61.5	9.8	.79***	-.56***							
4. Number of necessary messages provided in advance of requests	22	21.8	3.4	.73***	-.38*	.79***						
5. Number of questions asked	22	10.4	8.0	.44**	-.52**	.58***	.14					
6. Percentage of questions answered	22	73.8	22.9	-.08	.14	.07	.04	-.18				
7. Percentage of necessary messages sent *in one period* of the total number of messages that could be sent	22	52.0	8.4	.77***	-.60***	.92***	.75***	.60***	-.06			
8. Percentage of necessary messages sent *in two periods* of the total number of messages that could be sent	22	59.0	10.1	.83***	-.62***	.98***	.82***	.58***	.02	.95***		
9. Time between request and answer (seconds)	21	19.2	11.7	.05	-.09	.14	.08	.30	-.56***	.20	.16	
10. Percentage of potential casualties saved	22	73.3	9.2	.15	-.21	.23	.11	.33	.37*	.38*	.24	.01

Note. $*p < .10$, $**p < .05$, $***p < .01$

5.2.4 Discussion of Experiment 1

Cross training was not an effective training method to improve implicit coordination and performance for the teams in Experiment 1. In contrast to our hypothesis, team members did not communicate more efficiently and effectively as a result of cross training. In addition, no performance improvements were obtained. Finally, the relationships between communication and performance were lacking or weak. In the following paragraphs, we provide three explanations for the absence of the expected effects.

The first explanation is that the cross training method used was not effective to develop sufficient knowledge. The purpose of positional rotation, as explained in the introduction of this chapter, is to provide team members with team knowledge. Team members must develop a thorough understanding of the tasks, roles, and responsibilities of teammates such that team members know what information must be exchanged when. It is possible that simply giving team members the opportunity to practice in each other's task is insufficient to achieve this goal. Although it is asserted that positional rotation is the best method for high-interdependent teams, Experiment 1 does not confirm this assumption.

The second explanation is concerned with the task. The fire-fighting task has substantial difficult interfaces, which may have limited the impact of cross training. It is possible that team members could have been busier with learning how to interact with the system of their teammate than with developing higher order team knowledge about the interdependency of the tasks and each other's informational needs. According to Cannon-Bowers et al. (1998), cross training influences performance only to the extent that the skills or knowledge it addresses are important for performance. Learning how to use the teammate's interface is not important for teamwork. Learning what information must be exchanged and on what moments, however, is expected to be highly important.

The third explanation is that in the present task (i.e., Version 1 of the fire-fighting task), implicit coordination was not effective. Implicit coordination is expected to be effective when the conditions are such that effective and efficient communication is needed. Several researchers assert that implicit coordination is especially beneficial in high workload situations (Cannon-Bowers et al., 1998; Kleinman & Serfaty, 1989; Volpe et al., 1995). It is possible that the task we used in this experiment did not provide a level of workload high enough (even during the so-called high workload scenarios) that implicit coordination was needed to perform successfully.

5.3 Experiment 2

We performed a second study to test whether cross training improves the performance of the team members through implicit coordination. Compared to Experiment 1, two changes are made in Experiment 2. First, cross training is elaborated with the opportunity for team members to communicate unrestrictedly during the training. The rationale behind this is that team members that have the opportunity to make plans and determine strategies together, develop a better understanding of each other's tasks and informational needs (Orasanu, 1990, 1993; Stout et al., 1996; Stout et al., 1999). Second, with respect to the task, we attempted to adjust the scenarios in such a way that the team members would experience a higher level of workload.

5.3.1 Hypotheses

For Experiment 2, we formulated the same hypotheses as in Experiment 1.

5.3.2 Method

For Experiment 2, we used the same methodology as Experiment 1. Therefore, this section only describes the differences with Experiment 1.

Participants

The data for Experiment 2 were obtained from 32 students of Utrecht University in 16 teams of two participants. The distribution of participants over the two conditions with regard to sex was as follows: two female, two male, and four mixed teams in the *no* cross training condition and two female, three male, and three mixed teams in the cross training condition. It was attempted to assign participants that were not acquainted to each other in one team (this failed with one team). The participants were paid Dfl. 60, = for their contribution.

Design

In Experiment 2 the within teams design was different than in Experiment 1. Again, the presence of high workload scenarios was a within team manipulation and high and low workload scenarios were equally present (four high and four low workload scenarios). This time, instead of distributing the scenarios randomly over the eight experimental scenarios, we balanced the scenarios following a Latin square design. The result was that teams had to perform at most two high workload scenarios in a row. The sequence in which the scenarios were presented was such that there were no scenarios that were preceded or followed by similar scenarios. In addition, each scenario had a unique place in the sequence of scenarios. This way, eight unique sequences were formed for all eight teams in each condition. The cross-trained and the noncross-trained teams both received the identical eight sequences of eight scenarios.

Manipulation

Teams in the no cross training condition were trained during four scenarios in their own task only, whereas teams in the cross training condition were trained for two scenarios in their own task and for two scenarios in the teammate's task. In addition, the team members in the cross training condition could also communicate unrestrictedly with each other during the training.

In order to increase the level of workload compared to Experiment 1, the time between the periods in which the fires started was shortened. This way, each fire was rapidly followed by a new fire. To be able to extinguish as many fires as possible, units had to be withdrawn as soon as they were not needed any more and then reallocated. Therefore, the observer had to watch all fires closely and provide the dispatcher immediately with the information about the changes in the number of units needed. Because there were more fires than that could be saved due to the limited number of units, the dispatcher had to provide the observer with information about the allocation of units. With the help of this information, the observer could limit his or her search and watch only those fires where units were present. Altogether, we expected that this put such an amount of workload on the team, that implicit coordination would be beneficial.

Procedure

The procedure of Experiment 1 differed from Experiment 2 with respect to the training that was provided. First, in both conditions, participants were presented with four scenarios (instead of three scenarios in the no cross training condition and six scenarios in the cross training condition during the first experiment). Because teams were trained in an equal number of scenarios in both conditions, a possible performance improvement of the cross-trained teams could not be ascribed to the fact that they received training in more scenarios. Second, the periods of the training scenarios was shortened from 45 to 30 seconds and the four training scenarios consisted of two scenarios with a low and two with a high level of workload. This made the training scenarios more similar to the experimental scenarios. During the experimental scenarios, communication was only possible by sending and receiving the standardized electronic messages.

5.3.3 Results

Communication

In order to test Hypothesis 1, an analysis of variance using repeated measures for each scenario was performed. The repeated measures design consisted of eight scenarios. For low and high workload scenarios, a separate analysis was performed also using repeated measures for each scenario. The results of the analysis are shown in Table 5.6 to 5.8, in which the means for each scenario for the low workload, high workload, as well as the total number of scenarios can be found.

Hypothesis 1 is not supported by the results. As can be seen in Table 5.6 to 5.8, there are no differences in the communication between teams that were cross trained and teams that were not cross trained.

Table 5.6: Communication results for the total number of scenarios

Communication measure:	No cross training	Cross training	$F(1,14)$
1. Number of messages	53	44	= 1.23
2. Percentage necessary messages sent of the total number of messages that was sent	47	58	= 2.99
3. Percentage necessary messages sent of the total number of necessary messages that could be sent	73	69	< 1
4. Number of necessary messages provided in advance of requests	20	20	< 1
5. Number of questions asked	10	10	< 1
6. Percentage questions answered	81	78	< 1
7. Percentage necessary messages sent *in one period* of the total number of necessary messages that could be sent	51	51	< 1
8. Percentage necessary messages sent *in two periods* of the total number of necessary messages that could be sent	66	63	< 1
9. Time between request and answer (seconds)	13	20	= 1.17

Table 5.7: Communication results for the low workload scenarios

Communication measure	No cross training	Cross training	$F(1,14)$
1. Number of messages	52	44	= 1.32
2. Percentage necessary messages sent of the total number of messages that was sent	44	54	= 2.51
3. Percentage necessary messages sent of the total number of necessary messages that could be sent	74	70	< 1
4. Number of necessary messages provided in advance of requests	19	17	< 1
5. Number of questions asked	10	9	< 1
6. Percentage questions answered	83	79	< 1
7. Percentage necessary messages sent *in one period* of the total number of necessary messages that could be sent	51	51	< 1
8. Percentage necessary messages sent *in two periods* of the total number of necessary messages that could be sent	66	63	< 1
9. Time between request and answer (seconds)	14	25	= 1.31

Table 5.8: Communication results for the high workload scenarios

Communication measure	No cross training	Cross training	$F(1,14)$
1. Number of messages	54	45	= 1.11
2. Percentage necessary messages sent of the total number of messages that was sent	49	62	= 3.34*
3. Percentage necessary messages sent of the total number of necessary messages that could be sent	72	69	< 1
4. Number of necessary messages provided in advance of requests	22	22	< 1
5. Number of questions asked	11	10	< 1
6. Percentage questions answered	80	76	< 1
7. Percentage necessary messages sent *in one period* of the total number of necessary messages that could be sent	51	50	< 1
8. Percentage necessary messages sent *in two periods* of the total number of necessary messages that could be sent	65	62	< 1
9. Time between request and answer (seconds)	13	16	< 1

Note. $*p < .10$

Performance

In order to test Hypothesis 2, we performed an analysis of variance using repeated measures for each scenario. The repeated measures design consisted of eight scenarios. For low and high workload scenarios, a separate analysis was performed also using repeated measures for each scenario. The results are shown in Figure 5.3.

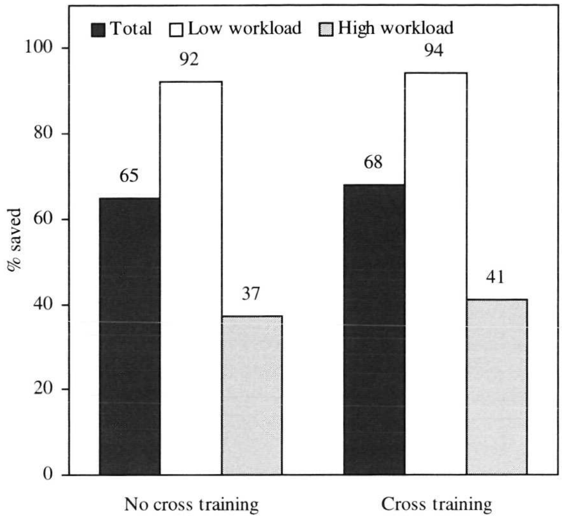

Figure 5.3: Mean percentage of potential casualties saved in the cross-trained and the noncross-trained condition for the total number of scenarios, and the low and high workload scenarios

Hypothesis 2 predicted that cross-trained teams would perform better than noncross-trained teams. This hypothesis is not supported by the results. There were no significant differences between the conditions on the total number of scenarios, $F(1,14) < 1$, on the low workload scenarios, $F(1,14) < 1$, or on the high workload scenarios, $F(1,14) < 1$.

Communication and performance

Table 5.9 shows the correlations among the communication measures and performance. These correlations indicate little support for Hypothesis 3. There is only one positive correlation between the percentage questions answered and performance, $r = .59$, $p < .05$. This indicates that the more requests for information are answered, the better the performance.

Table 5.9: Correlations between communication (denoted by number 1 to 9) and performance (denoted by number 10)

Measure	*N*	*M*	*SD*	1.	2.	3.	4.	5.	6.	7.	8.	9.
1. Number of messages	16	48.3	16.6									
2. Percentage necessary messages sent of the total number of messages that was sent	16	52.4	13.7	-.91***								
3. Percentage necessary messages sent of the total number of necessary messages that could be sent	16	71.3	11.3	.84***	-.73***							
4. Number of necessary messages provided in advance of requests	16	20.0	3.2	.30	-.26	.43*						
5. Number of questions asked	16	9.9	8.2	.38	-.32	.36	-.26					
6. Percentage of questions answered	16	79.8	14.6	.41	-.22	.34	.26	.03				
7. Percentage of necessary messages sent in *one period* of the total number of messages that could be sent	16	50.8	1.7	.75***	-.54*	.89***	.36	.49*	.49*			
8. Percentage of necessary messages sent *in two periods* of the total number of messages that could be sent	16	64.3	12.5	.77***	-.61**	.97***	.50**	.37	.37	.94***		
9. Time between request and answer (seconds)	16	16.6	11.6	-.17	.23	-.16	-.61**	.25	-.47*	-.15	-.19	
10. Percentage of potential casualties saved	16	66.3	6.8	-.21	.33	-.14	.16	-.10	.59**	.16	-.02	-.19

Note. $*p < .10$, $**p < .05$, $***p < .01$

5.3.4 Discussion of Experiment 2

Despite the changes we made with respect to the cross training strategy (i.e., the opportunity to communicate unrestrictedly during the training) and the task (i.e., higher workload), the hypothesis that cross training improves communication and performance was not supported by the results of Experiment 2. In the discussion of Experiment 1, we explained the absence of the expected performance improvements in three ways. First, the applied cross training strategy could have been ineffective to provide team members with sufficient team knowledge. Second, although cross training acquainted team members with each other's system, team knowledge may not have been developed. Third, the workload in the task was too low for implicit coordination to be effective. It is possible that these also explain the lack of effects in Experiment 2. In the general discussion of this chapter, we will explain the results of Experiment 1 and 2 in the light of the cross training research that is recently performed. Here, we describe how the use of dynamically evolving scenarios in an experimental team task may explain the absence of the effect of cross training on performance.

The use of dynamically evolving scenarios enables us to create a situation where team members have to react upon and teamwork is required. This allows us to investigate theoretically important factors such as implicit coordination. Scenarios develop autonomously (buildings are set on fire at predefined periods) and because of the activities of the team (allocated units extinguish fires). A problem associated with dynamically evolving scenarios is that team members are disproportionately penalized when they make a mistake at the beginning of a scenario. When team members are, for example, one period too late with the withdrawal of units, then it is difficult to catch up in the remainder of the scenario. Although team members have performed well during the remainder of the scenario, because of their mistake at the beginning of the scenario this is not expressed in the overall performance. It is possible that minor unsystematic mistakes at the beginning of a scenario could have had such a great impact on performance, that possible differences in team members' performance resulting from cross training were difficult to obtain. In the adjusted versions of the fire-fighting task (Version 2 and 3), scenarios are designed such that minor mistakes ate the beginning of a scenario do not outweigh the results of effective performance in the remainder of the scenario.

5.4 Discussion

The purpose of Experiment 1 and 2 was to test empirically whether cross training improves team performance. We hypothesized that cross training would foster team knowledge that team members hold in a mental model. Based on this knowledge, team members are able to anticipate on each other's informational needs and exchange the necessary information in a coordinated and timely manner. It is expected that this so-called implicit coordination is especially effective in high workload situations (Kleinman & Serfaty, 1989). The hypothesis that cross-trained teams would coordinate more implicitly and, therefore, would communicate more efficiently and effectively and perform better than noncross-trained teams is not supported by the results of Experiment 1 and 2.

Recent studies have shed new light on cross training methods that might give an answer to the question why cross training was unsuccessful in Experiment 1 and 2. The first study to be addressed is performed by Schaafstal and Bots (1997). In an experiment, 24 three-person teams had to perform the TANDEM task (for a brief description of TANDEM, see section 3.1.2). Three different cross training methods were developed to investigate their effect on team performance. The first method was the *read only* method that consisted of a brief written instruction about the teammate's tasks. The second method, which was called the *read and practice* method, consisted of actual hands-on experience in the teammate's task and was provided in addition to the written instruction. In the third method, team members were provided with a written instruction that consisted of explicit information about the overlap and interdependency about each other's tasks. This was called the *explicit instruction* method. It was expected that the teams that received the read and practice method would perform better than the teams that received the read only method, and that the teams that received the explicit instruction method would outperform the teams that received the read only as well as the read and practice method. The expected performance improvements were all ascribed to the expected improvements of the communication and coordination strategies of the team members.

In contrast to their hypothesis, the results of the Schaafstal and Bots (1997) study show no performance improvement for the teams that received the read and practice method compared to the teams that received the read only method. When teams received the explicit instruction method, however, the results show that teams performed better. Team members of these teams communicated also more efficiently by providing each other more often the necessary information in advance of requests. Moreover, for these teams, a positive relationship was established between the provision of information in advance of requests and performance. When comparing these results to the results of Experiment 1 and 2, several parallels can be found. The manipulation of the read and practice method of the Schaafstal and Bots study is similar to the cross training method we used in Experiment 1 and 2. In both studies, cross training took place by positional rotation in which team members performed each other's task. Moreover, in both studies this manipulation did not result in more efficient and effective communication strategies or an improved performance.

Another study that investigated cross training was recently published by McCann et al. (2000). These researchers also used the TANDEM task in which 30 three-person teams participated. Teams in the cross training condition were trained in each of the three team positions, whereas the teams in the noncross-trained condition were trained in their own task only. The results show that during training the performance of the cross-trained teams increased less than the noncross-trained teams. During the experimental session, the performance of the cross-trained teams was unexpectedly worse than the noncross-trained teams. These teams also failed to perform better on any of the process measures including the amount of communication. In other words, the experiments of Schaafstal and Bots (1997) and McCann et al. and the ones in the present chapter show that training in each other's tasks does not lead to better team processes and an improved performance.

How can it be explained that training in each other's task does not result in better team processes and an improved performance? The first explanation is provided by McCann et al. (2000) and states that training in each other's task *does* result in better team knowledge, however, that this is at the expense of team members' task knowledge. Thus, although cross-trained teams may improve their teamwork, the overall performance decreases because team members perform worse on their taskwork. Nevertheless, McCann et al. cannot confirm this explanation given the fact that they did not find any improvements on the efficiency of communication, which was their teamwork measure. We think that another explanation is also possible. Team members may have improved their knowledge of the teammate's task. However, because the teammate's task has a different interface and requires different skills, it might have been that team members developed low level knowledge of the teammate's task. Team members might have been practiced in using the buttons and windows for proceeding the teammate's task. However, higher order knowledge of how this is related to the own task in terms of information dependency and when and what information must be exchanged is not developed. We believe that it is this type of team knowledge that is important for better teamwork and improves performance.

That team interaction knowledge is important for team processes and performance is supported by the results of the Schaafstal and Bots (1997) study. As described previously, teams performed better when team members are explicitly instructed on the interdependencies in the team, including information that explicitly tells what information must be provided when. This way, team members are trained to develop procedural team knowledge. This result gives a clue to the lack of performance improvement when team members are trained in each other's task. Training in each other's task may provide team members with knowledge of each other's tasks, roles, and responsibilities. However, specific procedural knowledge of what information must be exchanged on what moments may not be developed. With respect to the cross training typology we described in the introduction of this chapter, this means that positional rotation does not provide the necessary knowledge needed to perform effectively in high-interdependent teams. Unfortunately, Schaafstal and Bots had no measures of team members' knowledge, so it must be assumed that team members that received the explicit instruction developed better team interaction knowledge than teams that are trained in each other's task. More work is needed to investigate this assumption.

The study of Schaafstal and Bots (1997) suggests that it is better to provide team members with information that explicitly describes each other's tasks and informational needs, instead of training in each other's task. In one study a comparison was made between such training methods: so-called *conceptual* cross training versus *full* cross training (Cooke, Cannon-Bowers, Kiekel, Rivera, Stout, & Salas, 2000a). In the conceptual cross training condition, team members were provided with information of teammates' positions and informational needs, whereas in the full cross training condition, teams had to perform the teammates' tasks in each position. The results show no performance differences between these conditions. Nevertheless, teams in the full cross training condition had better IPK (i.e., interpositional knowledge that includes knowledge of each other's task, roles, responsibilities, and informational needs) than teams in the conceptual cross training condition. In contrast to the Schaafstal and Bots (1997) study, this result suggests that training in each other's tasks is a better method to obtain team knowledge than the provision of team information. However, no measures of team processes were included in this study, and the relationships between IPK and the performance outcome were weak. Therefore, it is not clear how performance and communication is improved by fostering team knowledge through training in each other's tasks.

The previously described experiments and our own experiments show that merely training in each other's task (i.e., positional rotation) does not result in the expected improvements in team member's communication, coordination, and performance. Nevertheless, to complicate things, there is one study where training in each other's task was effective. This study was performed by Cannon-Bowers et al. (1998) also using the TANDEM task in which 40 three-person teams participated. Cross training was manipulated between teams by training team members in each other's tasks. It was expected that teams that received a cross training would perform better, provide more information in advance of requests, and improve the overall quality of teamwork processes (measured by a teamwork rating scale). Furthermore, it was expected that teams would report higher levels of subjective IPK (i.e., the judgement of the team members about their interpositional knowledge). It was further expected that the effects would be most pronounced during high-workload situations, which was manipulated within teams.

The results of the Cannon-Bowers et al. (1998) study supported all hypotheses that were formulated by the authors. Cross training not only resulted in better performance, but also in higher levels of subjective IPK, a higher frequency in the provision of information in advance of requests, and better teamwork. A manipulation check showed that cross-trained team members had higher levels of objective IPK. With respect to the previously described experiments and Experiment 1 and 2 of the present chapter, the question may be raised why positional rotation in one study resulted in better teamwork and performance, whereas in other studies this was not found. One explanation is that the teams of the Cannon-Bowers et al. study were better trained because they were trained in each other's tasks to a certain level of proficiency. It is possible that this provided team members with the knowledge needed to anticipate on team member's informational needs and coordinate implicitly. Because this was not applied in the previously described experiments, merely training in each other's tasks could have been insufficient to achieve that knowledge. One problem with this explanation is that Cannon-Bowers et al. did not find a significant correlation between IPK and all other measures. Only the objective IPK score explained 10% and 16% of the variance in team performance and team process scores respectively. However, objective IPK was not correlated with the provision of information in advance of requests. Thus, although team members had better knowledge of each other's tasks, roles, responsibilities, and informational needs, this did not account for the performance improvement.

In conclusion, Experiment 1 and 2 and the experiments of other researchers show a rather confusing picture with respect to the various cross training methods and their influences on communication and performance in teams. With respect to the cross training typology we described in the introduction of this chapter, the results do not confirm the assumption that positional rotation is needed to train members of high-interdependent teams. Explicit instruction (i.e., positional clarification) that was geared to develop team interaction knowledge also improved communications and performance in teams (Schaafstal & Bots, 1997).

In the next chapter, we continue to investigate the question of how communication and performance can be improved by fostering the knowledge team members have in their mental models. Team members will be presented with *team information* that consists of an explicit instruction about each other's tasks and informational needs. We also investigate the relationships between team information, team knowledge, communication, and performance.

6 TEAM INFORMATION, TEAM KNOWLEDGE, COMMUNICATION, AND PERFORMANCE

In this chapter, we describe an experiment in which the effect of a written instruction containing team information is investigated on members' team knowledge, communication, and performance. The results show that teams that receive team information improve their communication on several points. Less information was exchanged, whereas the percentage of necessary information exchange was higher than in the teams that did not receive team information. The provision of team information resulted also in better team knowledge that was, in turn, positively correlated with communication. Surprisingly, the improved communication did not result in better performance.

6.1 Introduction

As described in chapter 5, the research concerning cross training as a method to improve communication and performance shows conflicting results. In Experiment 1 and 2, and experiments of other researchers (McCann et al., 2000; Schaafstal & Bots, 1997), training in each other's task had no effect upon implicit coordination and performance. In only one experiment, this resulted in better performance (Cannon-Bowers et al., 1998). Team members of these teams had also better team knowledge and provided more information in advance of requests. Nevertheless, there were no correlations between these measures, and the provision of information in advance of requests was not correlated to performance. Hence, the performance improvement in this experiment cannot be explained by the improvement of team member's communication because of having better team knowledge. Referring to the first research question of this thesis, the question remains how communication and performance can be improved by fostering the knowledge in the mental models of team members.

Two studies might give an answer to this question. First, the Schaafstal and Bots (1997) study shows that communication and performance improves when team members are explicitly instructed on the interdependencies in the team. Second, in another study, team members that watched a videotape and received a written instruction with information about each other's tasks, roles, responsibilities, and informational needs, provided more information in advance of requests and performed better (Volpe et al., 1995). Both studies show that the provision of explicit instructions is effective to improve communication and performance in teams. The Schaafstal and Bots study shows that this was even better than training in each other's tasks. In both studies, it was hypothesized that the communication and performance improvement could be ascribed to the development of team knowledge. Nevertheless, because there were no measures of the knowledge of the team members in these studies, this could not be confirmed.

Two other studies show that training methods directly aimed at the development of team knowledge lead to improvements. In one study, a team interaction training resulted in improved coordination behaviors (Minionis et al., 1995). However, the teams that received the team interaction training did not communicate or perform differently than the teams that did not receive such a training. There was also a measure of whether teams developed mental models containing team interaction knowledge. The results show that the extent of similarity in these mental models is positively correlated to coordination and performance. However, there were no correlations between mental model similarity and the number of statements in any of the communication categories. A problem with interpreting these results is the way communication is classified. This classification includes communication categories such as planning, execution, and group regulation. It is not clear how this teamwork is influenced by shared mental models. For example, these types of categories do not reflect implicit coordination. It is therefore possible that a relationship between team interaction training and communication could not be established.

In another study, an experiment is performed in which team members received an instruction of how to interact effectively as a team (Marks et al., 2000). In this experiment, team mental model similarity as well as accuracy was measured. The quality of teamwork was measured by rating the communication in several categories such as assertiveness, decision making, and adaptability. The results show that teams that received a team interaction training had more similar and accurate mental models. Nevertheless, whereas mental model similarity was positively associated with the quality of teamwork, mental model accuracy was not associated with the quality of teamwork at all. The quality of teamwork was positively associated with performance. This study shows that a team interaction training improves team members' mental models with respect to the teammates' tasks and the sequences of activities. However, because this was not measured, no relationships could be established between such a training and implicit coordination or the effectiveness and efficiency of communication.

The above-described studies show that training methods directly aimed at the development of team knowledge are promising for the improvement of communication and performance in teams. These studies have shown that team training improved communication and performance (Schaafstal & Bots, 1997; Volpe et al., 1995) or improved coordination (Minionis et al., 1995) and teamwork in general (Mathieu et al., 2000). In the studies of Mathieu et al. (2000) and Minionis et al. (1995) there is also support that this was mediated by the knowledge team members developed in a mental model. Nevertheless, there have been no studies that investigated the effect of a team training (i.e., a training that is directly aimed at the development of team knowledge) to team knowledge, implicit coordination in terms of effective and efficient communication, and performance.

In the present experiment we operationalize a team training by giving team members a written instruction that contains explicit information about each other's tasks, roles, and responsibilities. We also highlight the informational interdependencies among team members and the timing of each other's activities and when information exchange is necessary. Our reasoning is that team members, when receiving such team information, will gain a detailed understanding of how and when to communicate. Therefore, we expect that teams will communicate more effectively (i.e., more necessary information exchange in time and in advance of requests) and efficiently (i.e., less information exchange in general and a higher proportion of necessary information exchange). In turn, we expect that this has a positive impact on team performance.

In contrast to other studies (Blickensderfer et al., 1997c; Cannon-Bowers et al., 1998; Entin & Serfaty, 1999; Schaafstal & Bots, 1997; Stout et al., 1996; Volpe et al., 1995), implicit coordination in the present experiment is not only measured by the provision of information in advance of requests. In our opinion, this is just one measure of implicit coordination, but not the only one. In chapter 2 (see section 2.3.1, Table 2.1), we described several other communication measurements including the total amount, timeliness, and number of requests that measures implicit coordination more precisely. It is possible that in other studies (Cannon-Bowers et al., 1998; Stout et al., 1996) the relationship between the shared mental model measures and implicit coordination (measured by the provision of information in advance) could not be established because this measure was too limited. For that reason, we measure implicit coordination more precisely in the present experiment.

A measure to assess team members' knowledge is also included in the present experiment. Based on the cognitive team task analyses described in chapter 4, we developed a questionnaire that team members had to answer after the experimental session. Besides a team measure, we included a heterogeneous accuracy measure (see also Cooke et al., 2000b) for the answers that are unique for each team member's role and two similarity measures for the answers that are similar for both team members. One measures similarity regardless of whether it was accurate, the other measures similarity for the accurate answers only. We also defined a priori which answers comprise knowledge of each other's tasks and procedural knowledge about the timing of interaction. This way, we attempt to get a better picture of the knowledge team members need to coordinate implicitly and to what extent this needs to be shared. By our knowledge, there are no studies yet in which knowledge type and heterogeneous measures as well as similarly measures are related to implicit coordination and performance.

6.2 Experiment 3

6.2.1 Hypotheses

The experiment described in this chapter addresses the question whether the provision of team information improves members' team knowledge, communication, and team performance. A comparison is made between teams that receive team information and teams that receive no team information. Figure 6.1 represents the dimensions and the relationships that are under investigation in Experiment 3.

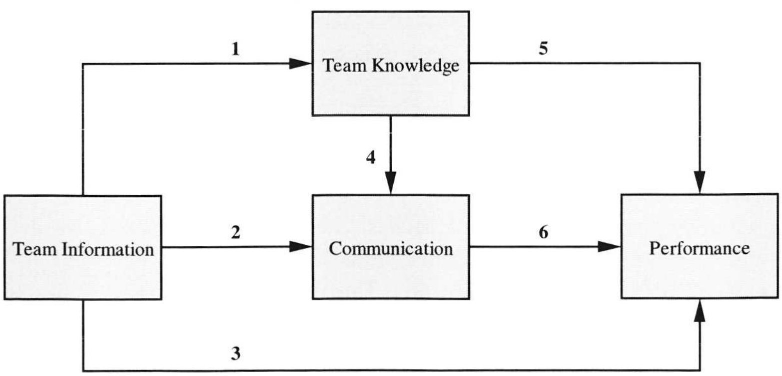

Figure 6.1: Hypothesized relationships between team information, team knowledge, communication, and performance under investigation in Experiment 3

Given the expected value of team information on the development of team knowledge in the mental models of the team members, communication, and performance, the following hypotheses are put forward:

1. We expect that the teams that receive team information develop better team knowledge than the teams that receive no team information

2. We expect that the teams that receive team information coordinate more implicitly and therefore communicate more efficiently and effectively (i.e., less communication, more necessary information, more necessary information in advance of requests, less requests, answering more requests, more necessary information in time, and answering more requests in a shorter time notice) than the teams that receive no team information
3. We expect that the teams that receive team information perform better than the teams that receive no team information
4. We expect that team knowledge is positively correlated with communication
5. We expect that team knowledge is positively correlated with performance
6. We expect that communication is positively correlated with performance

6.2.2 Method

Participants

The data for Experiment 3 were obtained from 80 students of Utrecht University in 40 teams of two participants. The distribution of participants with regard to sex was as follows: 12 female, five male, and three mixed teams. Participants that formed the team were not acquainted to each other. The participants were paid Dfl. 70, = for their contribution.

Design

In order to test the hypotheses, two experimental conditions were designed. In the *team information* condition, team members received a written instruction that contained team information. In the *no team information* condition, team members did not receive team information.

Task

In Experiment 3, Version 3 of the fire-fighting task as described in section 3.3.2 was used.

Manipulation

Team information was manipulated as follows. For the teams that received team information, a separate section in the instructions was included in which important team knowledge in the fire-fighting task was described. Based on the cognitive team task analysis described in chapter 4, we determined what important team knowledge was. All knowledge important to perform teamwork in the restricted condition was explicitly described in the instruction. This included a description of the teammate's task and timing and sequences of the teammate's activities. The instruction also highlighted the necessary interactions between team members. It was not only described what information was necessary to exchange but also in which periods. Team members that did not receive the team information were instructed on their own tasks only. This included information of the tasks and the timing and sequences of activities. In contrast to the team information instruction, this was geared completely to team members' own taskwork. The taskwork description in the instruction was identical in both conditions.

Measurements

Knowledge. To assess the team knowledge of the team members, a 12-item questionnaire was developed. The questionnaire was based on the cognitive team task analysis described in chapter 4. As with the development of the instructions concerning team information, we used the cognitive team task analysis to determine what important team knowledge was in the fire-fighting task. This helped us in developing the items that should be included in the questionnaire. The questions are listed in Table 6.1 (translated from Dutch).

Table 6.1: Knowledge measurement; overview of the questions

Question	Answer observer	Answer dispatcher
1. Which information was necessarily needed by your teammate to accomplish the tasks?	1 Changes in the number of units 2 Large building in danger	1 Changes in the allocation of units 2 Changes in the amount of units present in the station
2. In which period had the units to be withdrawn to be on time?	Period 6	Period 6
3. What is the most important task of your teammate?	Allocation of units	Detecting fires
4. How many periods was a message relevant?	Maximal 2 periods	Maximal 2 periods
5. What are the two most important messages you had to give to your teammate?	1 Changes in the number of units 2 Large building in danger	1 Changes in the allocation of units 2 Changes in the amount of units present in the station
6. In which period had the message of the large building in danger to be sent at least?	Period 7	Period 7
7. Give two of your teammate's tasks that were the most important to perform accurately	1 Allocation of units 2 Providing information about the allocation of units	1 Detecting fires 2 Providing information about the detected fires
8. How many periods were needed to withdraw units, reallocate, and effectively extinguish fires	4 periods	4 periods
9. From which information is your teammate dependent to accomplish the tasks accurately?	1 Allocation of units 2 Providing information about the allocation of units	1 Detecting fires 2 Providing information about the detected fires
10. In which period had units to be allocated to be on time for the large building in danger?	Period 7	Period 7
11. How could your teammate obtain information about the fires in the city?	Messages containing a question mark	Clicking buildings on the map in the city
12. In which period was the building in danger known?	Period 6	Period 6

The odd numbered questions were developed to tap team members' task knowledge about each other's tasks, roles, responsibilities, and informational needs. The even numbered questions were developed to tap team members' procedural knowledge about the timing and sequences of activities. Each question that was accurately answered was scored with one point. For the questions where team members were asked to provide two answers (i.e., Question 1, 5, 7, and 9) one accurate answer was rewarded with half a point and two with one point. In total, each team member could earn 12 points.

Several scores were calculated. The *team score* was the average score of both team members of all accurate answers. The *heterogeneous score* was the score of all accurate answers of both team members that are unique for each team member's role (all accurate answers on the odd questions). Note that the heterogeneous score is concerned with the questions that were developed to tap team members' declarative task knowledge about each other's tasks, roles, responsibilities, and informational needs. The *procedural score* was the score of all accurate answers of both team members on the questions that were developed to tap team members' knowledge of the timing of activities and interaction needed (all accurate answers on the even questions). The *similarity score* was the score of all answers that both team members could have and had similar (all answers on the even questions that were similar). The *similarity and accuracy score* was the score of all answers that both team members could have and had similar, and were accurate (all answers on the even questions that were similar and accurate).

Communication. As with Experiment 1 and 2, team members could only communicate by using the standardized electronic messages. The messages were time-stamped and saved in a computer log file for analysis. The same communication measures of Experiment 1 and 2 were used to determine whether teams coordinated implicitly and therefore communicated efficiently and effectively (see section 5.2.2, Table 5.1). These measures were based on the communication features of implicit coordination in the fire-fighting task that we established with the help of the cognitive team task analysis of chapter 4 (see section 4.2.2, Table 4.7).

We added one communication measure. The percentage of scenarios in which the message of the large building in danger was sent and read in time. In the scenarios that were used in Version 3 of the fire-fighting task, it was highly important that this message is sent and read before Period 7 finishes. If team members are not able to perform this in time, then it is not possible to allocate units to the large building in danger and save a large number of potential casualties. We believe that this is an important measure of implicit coordination. It measures whether team members have provided the necessary information on the time in the teammate's task sequence that this information is needed. Moreover, this measure indicates whether team members have declarative team knowledge of what information is necessary to exchange (i.e., the large building in danger), and procedural knowledge of when this information must be provided (i.e., before Period 7 finishes).

Performance. Performance was measured by the percentage of casualties saved out of the total number of potential casualties that could be saved in a scenario.

Procedure

An experimenter assigned the participants randomly to the role of dispatcher and observer and told them to read the instruction. Participants were placed in separate soundproof rooms and communication between the participants was made possible by sending and receiving the standardized electronic messages. They were told not to speak to each other about the experiment and the experimenter was always present in situations where participants were together in the same space. Participants were allowed to ask questions at any point during reading.

The instruction first explained the fire-fighting task in general, followed by instructions specific for each role. This included a systematic instruction on how to manipulate the interface, accompanied by small tasks that had to be carried out by the participants. Subsequently, there was a training session of five scenarios. After this first training session, participants were asked to continue to read the instruction. In this instruction, it was explained how participants could predict, based on a pattern in a series of small fires, the location, type, and time of a large fire later in the scenario. In addition, the participants in the team information condition had to read the section in which team knowledge was described.

After the training, the experimental session started. Participants were presented with 20 scenarios that consisted of 11 periods of 15 seconds each. Each team was presented with identical scenarios in a fixed order.

In the last part of the experiment, participants answered the questionnaire. The questions were presented one by one on a computer screen. Participants were asked to give the first answer they could think of. Time to answer each question was limited and participants could not go back to a previous question. This way we attempted to avoid that participants reasoned their answers and forced them to give answers that were on top of their heads. In total, an experimental session lasted about four hours.

6.2.3 Results

Knowledge

In order to test Hypothesis 1, a Mann-Whitney *U*-test was performed to find out whether there are differences in the scores on the team knowledge questionnaire. The results of the test are shown in Table 6.2.

Table 6.2: Mean score for each condition on the team knowledge questionnaire

Knowledge score	No team information	Team information	$U =$
1. Team score (maximum 12)	3.2	5.2	38***
2. Heterogeneous/ declarative score (maximum 12)	4.6	6.7	81***
3. Procedural score (maximum 12)	1.9	3.8	55***
4. Similarity score (maximum 6)	4.2	3.5	139*
5. Similarity and accuracy score (maximum 6)	0.0	0.6	100***

Note. *p < .10, ***p < .01

Hypothesis 1 predicted that teams that receive team information have better team knowledge than teams that receive no team information. As can be seen in Table 6.2, this hypothesis is supported by the results. Teams that received team information gave more accurate answers on all questions, and on the declarative and procedural questions than team members that did not receive team interaction information. There are no differences on the similarity score. For the answers that both team members could have and had similar, there is a tendency that the teams that did not receive team information scored higher than the teams that did receive team information. The similarity and accuracy measure shows a floor effect. In both conditions, team members had almost no answers that were accurate and similar for both team members. The procedural score and the similarity and accuracy score were calculated for the same set of questions (i.e., the odd questions). The difference is that the procedural score counted the number of accurate answers for both team members, whereas the similarity scores counted the number of answers that were similar. Therefore, the results indicate that in the team information condition, the teams had better procedural knowledge than in the no team information condition. This knowledge, however, was distributed among team members and not held in common.

Communication

In order to test Hypothesis 2, an analysis of variance using repeated measures for each scenario was performed. The repeated measures design consisted of 20 scenarios. Exceptions were Measure 6 (percentage of questions answered) and 9 (time between request and answer) for which we performed an analysis of variance without repeated measures. This was done because in several scenarios team members did not provide answers, which resulted in several missing values. The results of the analysis are shown in Table 6.3 in which the means for each scenario can be found.

Table 6.3: Communication results for each condition

Communication measure	No team information	Team information	*F*-value
1. Number of messages	27	21	$F(1,38) = 5.67$**
2. Percentage necessary messages sent of the total number of messages that was sent	50	65	$F(1,38) = 11.29$***
3. Percentage necessary messages sent of the total number of necessary messages that could be sent	45	48	$F(1,38) = 2.05$
4. Number of necessary messages provided in advance of requests	11	13	$F(1,38) = 2.62$*
5. Number of questions asked	5	2	$F(1,38) = 4.42$**
6. Percentage questions answered	76	78	$F(1,34) < 1$
7. Percentage necessary messages sent *in one period* of the total number of necessary messages that could be sent	38	41	$F(1,38) < 1$
8. Percentage necessary messages sent *in two periods* of the total number of necessary messages that could be sent	42	46	$F(1,38) = 2.99$*
9. Time between request and answer (seconds)	15	17	$F(1,34) < 1$

Note. *$p < .10$, **$p < .05$, ***$p < .01$

Hypothesis 2, which predicted that teams that receive team information coordinate more implicitly and therefore communicate more efficiently and effectively than teams that receive no team information, is partially supported by the results. As can be seen in Table 6.3, the teams in the team information condition communicated more efficiently than teams in the no team information condition. These teams sent fewer messages, whereas the percentage of necessary messages was higher. However, the teams in the team information condition did not communicate more effectively. There were no differences between the conditions on the percentage of necessary messages of the total number of necessary messages that could be sent.

With respect to the provision of information in advance of requests, there is a tendency that the teams in the team information condition did this more than the teams in the no team information condition. Team members that received team information had fewer questions than team members that did not receive team information. However, the percentage answers did not differ between the conditions. With respect to the timing of the provision of necessary information, there is a tendency that the teams that received team information were more often in time (i.e., more often in two periods) than the teams that did not receive team information. However, there are no differences between the conditions on the time between a request for information and receiving an answer.

The last communication measure was defined as the percentage of scenarios in which the building of the large building in danger was sent and read in time. In each scenario, team members could be either in time or too late (i.e., when the message was not sent at all, this was considered as too late). The scores can be found in Table 6.4.

Table 6.4: Communication measure; total number of scenarios in which team members were in time with sending and reading the message about the large building in danger ($N = 800$)

Condition	Message	
	In time	Too late
No team information	251	149
Team information	277	123

To test the differences between the conditions, a Chi^2 for the two-way table was calculated and tested. It appeared that the teams in the team information condition were more often in time with sending and reading the message about the large building in danger (69%) than teams in the no team information condition (63%), $\chi^2(1, N = 800) = 3.77, p = .05$.

Performance

In order to test Hypothesis 3, which states that teams that receive team information perform better than teams that receive no team information, we performed an analysis of variance using repeated measures for each scenario. The repeated measures design consisted of 20 scenarios. Hypothesis 3 did not receive support. There was no performance difference between the team information condition (45% potential casualties saved) and the no team information condition (40% potential casualties saved), $F(1,38) < 1$.

Team knowledge, communication, and performance

As a final step, the relationships between the knowledge, communication, and performance were examined. The correlations can be found in Table 6.5.

Hypothesis 4 predicted that team knowledge is positively associated with communication. As can be seen in Table 6.5, a moderate positive relationship appeared between the team score and the percentage of necessary messages sent of the total number of messages that was sent, $r = .39$, $p < .05$, the provision of information in advance of requests, $r = .39$, $p < .05$, and the percentage of scenarios in which the building of the large building in danger was sent and read in time, $r = .36$, $p < .05$. We also took different sets of questions of the questionnaire that were created to measure declarative and procedural team knowledge respectively. As can be seen in Table 6.5, there are several moderate positive correlations between the heterogeneous/ declarative score and the communication measures. Positive relationships appeared between the heterogeneous/ declarative score and the percentage of necessary messages sent of the total number of messages was sent, $r = .47$, $p < .01$, the percentage of necessary messages sent of the total number of necessary messages that could be sent, $p = .35$, $p < .05$, the provision of information in advance of requests, $r = .50$, $p < .01$, the percentage of necessary messages sent of the total number of necessary messages that could be sent in two periods, $p = .34$, $p < .05$. With respect to the procedural score, a moderate positive relationship appeared with the percentage of scenarios in which the building of the large building in danger was sent and read in time, $r = .32$, $p < .05$. Finally, with respect to the similarity measure and the similarity and accuracy measure, there are no relationships with exception of a negative relationship between the similarity score and the percentage of scenarios in which the building of the large building in danger was sent and read in time, $r = -.33$, $p < .05$. Note that the similarity score measured the number of answers that both team members had the same, regardless of whether the answers were accurate. This may explain the negative relationship. Similarity in the knowledge that is inaccurate is negatively associated with the timing of communication.

Table 6.5: Correlations between the knowledge (denoted by number 1 to 5), communication (denoted by number 6 to 15), and performance measures (denoted by number 16)

Measure	*N*	*M*	*SD*	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.
1. Team score	40	4.2	1.5															
2. Heterogeneous/ declarative score	40	5.6	2.1	.87***														
3. Procedural score	40	2.8	1.6	.78***	.38**													
4. Similarity score	40	3.9	1.3	-.55***	-.30*	-.68***												
5. Similarity and accuracy score	40	0.3	0.6	.42***	.19	.57***	.21											
6. Number of messages	40	24.1	7.6	-.22	-.21	-.16	-.01	-.17										
7. Percentage necessary messages sent of the total number of messages that was sent	40	57.7	15.2	.39**	.47***	.14	-.13	.04	-.72***									
8. Percentage necessary messages sent of the total number of necessary messages that could be sent	40	46.4	7.8	.24	.35**	.01	-.11	-.04	.43***	.17								
9. Number of necessary messages provided in advance of requests	40	12.5	4.3	.39**	.50***	.13	-.04	.17	-.05	.50***	.51***							
10. Number of questions asked	40	3.4	4.5	-.28*	-.28*	-.17	.08	-.15	.59***	-.63***	-.06	-.50***						
11. Percentage of questions answered	36	77.3	22.5	.27	.25	.17	-.09	.15	-.14	.34**	.23	.50***	-.64***					
12. Percentage of necessary messages sent in *one period* of the total number of messages that could be sent	40	39.3	7.9	.12	.23	-.05	-.16	-.18	.50***	.09	.92***	.49***	-.07	.16				
13. Percentage of necessary messages sent *in two periods* of the total number of messages that could be sent	40	44.0	9.0	.21	.34**	-.02	-.03	.02	.34**	.29*	.90***	.66***	-.15	.26	.87***			
14. Time between request and answer (seconds)	36	16.6	8.0	-.02	.04	-.09	.11	-.07	-.10	-.04	-.13	-.13	.11	-.35**	-.08	-.19		
15. Percentage of scenarios in which the message of the large building in danger was sent and read in time	40	66.0	29.4	.36**	.28*	.32**	-.33**	.11	-.02	.07	-.05	.17	-.40**	.56***	-.04	.01	-.28*	
16. Percentage of potential casualties saved	40	42.4	22.5	.26	.19	.21	-.12	.15	-.08	.04	-.08	.08	-.26*	.46***	-.12	-.01	-.14	.64***

Note. *$p < .10$, **$p < .05$, ***$p < .01$

With respect to Hypothesis 4, it can be concluded that a better score on the team knowledge questionnaire is positively correlated with several communication measures. This indicates that the better the team knowledge, the better the communication. It appears further that the amount of accurate answers on the questions that were developed to tap team members' declarative knowledge of each other's task (i.e., the heterogeneous/ declarative score: different answers for each team member about the teammate's tasks and informational needs) is positively associated with communication. Procedural knowledge is only correlated positively with a communication measure that measures the timing explicitly (i.e., the percentage of scenarios in which the message of the large building is send and read in time). There are no positive correlations found on both similarity measures, indicating that the better communication in this experiment was dependent on the knowledge each team members held individually.

Contrary to Hypothesis 5, which predicted that team knowledge would be positively associated with performance, there are no significant correlations. A theoretical important assumption of the shared mental model construct is that the relationship between knowledge and performance is mediated by communication. To conclude that communication mediated the influence of team knowledge on performance, we must first demonstrate that team knowledge is correlated with performance (Baron & Kenny, 1986). Since there are no correlations between the knowledge scores and performance, we could not confirm mediation.

Hypothesis 6 predicted that communication is positively associated with performance. As can be seen in Table 6.5, a moderate positive relationship appeared between the percentage of answers provided and performance, $r = .46$, $p < .01$. This indicates that the more team members answered each other's requests for information, the better the performance. The percentage of answers accounted for approximately 21% of the variance in the performance. A positive correlation also appeared between the percentage of scenarios in which the message of the large building in danger was sent and read in time and performance, $r = .64$, $p < .01$. This indicates that the more often team members were in time with sending and reading the message about the large building in danger, the better the performance. This accounted for approximately 41% of the variance in the performance.

6.3 Discussion

Our goal in Experiment 3 was to demonstrate that team information, which explicitly describes team member's tasks and informational needs, improves performance as a result of better communication. In contrast to our hypothesis, there was no performance improvement when team information is provided. This is surprising because the teams that received team information improved their communication on several points. The teams communicated less, whereas the percentage of necessary information was higher than the teams that did not receive team information. The teams also requested less information from each other, and the results indicate that they provided more information in advance of requests. Finally, the teams were more often in time with exchanging the necessary information. In short, the teams that received team information were more effective and efficient in their communication. Less communication was needed to exchange the same amount of necessary information in time. Based on these communication improvements, we would expect a performance increase.

An explanation for the lack of performance improvement is that while the provision of team information improved communication, other factors may have weighed more into performance. One of these factors is the individual taskwork of each team member. It is possible that although the teamwork skills were improved, team members' taskwork skills lagged behind. The results provide some evidence for this explanation. Team members in the team information condition provided more often a crucial piece of information. With the help of this information it was possible to obtain a high performance. In other words, the conditions to perform well, as a result of good teamwork, were more often present in the team information condition than in the no team information condition. The fact that performance did not differ between the conditions must have been due to team members failing to perform well on their taskwork. In this case, while having all the information they needed, dispatchers were still too late with allocating units. This echoes the ideas of several researchers that team performance depends on task as well as teamwork factors.

The findings of the present experiment provide support for the hypothesis that team knowledge improves when members receive team information. The knowledge questionnaire shows that team members had better declarative knowledge of each other's tasks and informational needs, and better procedural knowledge about the moments that the necessary information had to be exchanged. In other words, team information consisting of an explicit instruction about team member's tasks and informational needs fosters team knowledge. However, the results must be interpreted with caution. Although there were differences in the scores on the knowledge test depending on whether teams received team information, the scores were relatively low. Even in the condition with the highest scores, only half of the questions were answered accurately. This indicates that in both conditions, team members had not fully developed team knowledge. Although the provision of team information is a good start for developing team knowledge, longer practice or better training methods may be needed to develop full team knowledge. A combination of an explicit team instruction and a systematic training that is geared to the acquisition of efficient and effective communication strategies is a possible candidate for that matter.

Another point of interest is the way knowledge is distributed among team members. One set of questions was created to tap team member's procedural knowledge. Regardless of the role that team members had in the task, the answers on these questions could have been the same. Thus, the number of similar answers of both team members indicates the extent of similarity in their procedural knowledge. When viewing the total number of accurate answers on these questions for each team (i.e., the sum of accurate answers of the observer and the dispatcher), the results show that the teams that received team information had better procedural team knowledge than the teams that did not receive team information. However, there were practically no accurate answers on the procedural questions that were the same for both team members. This leads us to conclude that although the procedural knowledge of the teams in the team information condition was better, this knowledge was distributed among team members, not held in common.

The other set of questions of the knowledge questionnaire was created to tap team member's declarative knowledge. The accurate answers were different depending on the role team members had. It can be argued that, because different knowledge seems to be tapped, this knowledge is also distributed among team members. Given that the provision of team information led to better scores on the declarative questions, it seems that the better team knowledge (procedural and declarative) in the team information condition is totally distributed among the members. Note, however, that if one team member has knowledge of the teammate's task, this might be similar to the knowledge that the teammate has about his or her own task. In this sense, it is possible that there is overlap in the declarative knowledge of each other's task and informational needs. However, we have not measured this overlap.

We hypothesized that communication improvements would be affected by having team knowledge. The correlations between the scores on the knowledge questionnaire and the communication measures give some evidence that supports this hypothesis. Especially declarative knowledge appears to have a positive effect on communication. Knowledge of each other's tasks and informational needs is positively correlated with the percentage of necessary information that was exchanged of the total amount that took place and was possible respectively. There is also a positive correlation with the exchange of information in advance of requests. Finally, procedural knowledge is correlated positively with the percentage of scenarios in which a crucial piece of information was passed and received in time. Taken together these results are consistent with the shared mental model theory; the better the team knowledge, the better the communication.

Whereas teams differed in the amount of communication depending on whether they received team information, there was no correlation with team knowledge. Therefore, the provision of team information directly influenced the amount of communication, independent of having team knowledge.

Several researchers assert that it is the degree of overlap in team member's knowledge that accounts for better communication strategies (Cannon-Bowers et al., 1993; Converse et al., 1991; Kleinman & Serfaty, 1989). Based on the results of Experiment 3, this assertion cannot be confirmed. There are no positive correlations found between the degree of similarity in team member's knowledge and the communication. Moreover, similarity, regardless of the accuracy, was even negatively correlated with one communication measure. For a large part this is due to a floor effect. There were hardly any teams in which this knowledge was accurate and similar among both members. Given the positive relationships we did find with communication, we conclude that knowledge overlap is not necessarily needed for better communication. With respect to the shared mental model theory, this indicates that it is the individual knowledge content that is important, not the similarity.

Although we expected that communication would be positively associated with performance, there were practically no significant correlations. The lack of relationship may be caused by the previously mentioned explanation that the influence of team member's taskwork on performance might have outweighed the influence of teamwork. The most important correlation we did find was the timely exchange of a crucial piece of information. The exchange of this information accounted for 40% in the variance of the performance. This is solid support for the hypothesized relationship between better communication and performance. The timely exchange of necessary information within a teammate's task is basically what effective communication is about. Exchanging this information in advance of requests may be preferable because no additional communication is needed. However, not exchanging this information at all or too late is, with respect to performance, unacceptable. Therefore, we view the obtained relationship between this communication measure and performance as evidence for the hypothesized positive relationship between communication and performance.

7 UNRESTRICTED COMMUNICATION AND PERFORMANCE[1]

In chapter 7, we shift our attention from the potential benefits of limiting the communication to the potential benefits of expanding the communication. We hypothesize that communication is important to develop team and situation knowledge in shared mental models and perform teamwork that consists of performance monitoring, evaluation, and determining strategies. The question when and how communication improves performance is under investigation in the two experiments described in this chapter. The opportunity to communicate unrestrictedly was manipulated systematically. In Experiment 4, teams could either communicate unrestrictedly or not, and in Experiment 5 only between or during task execution. The results show that, compared to communicating restrictedly, unrestricted communication had a positive impact on performance in all cases.

7.1 Introduction

In chapter 5 and 6, we concentrated on the question how communication and performance could be improved by fostering team knowledge in the mental models of team members. By providing cross training and team information, we expected that teams would communicate more efficiently and effectively, which should have had a positive effect on performance. Most studies that investigated communication in relation to shared mental models, examined communication in the same manner. Efficient and effective communication as *a result of* having shared mental models. In chapter 7 to 9, we take another point of view. We are now interested in how team members can use their communication to improve their performance by fostering the knowledge in team members' mental models. In other words, we investigate communication as an *antecedent* of shared mental models. Instead of investigating how performance can be improved by *limiting* the communication (by providing the necessary information on the moments that team members need it), we are now interested in how performance can be improved by *expanding* the communication in teams.

These perspectives are also reflected in the literature. Researchers claim that performance improves when team members limit their communication by coordinating implicitly (Cannon-Bowers et al., 1998). However, researchers also claim that performance is positively affected when teams communicate extensively to develop a shared understanding of the team, task and situation, plan activities, and cooperatively solve problems (Blickensderfer et al., 1997b; Orasanu, 1993; Rochlin et al., 1987; Seifert & Hutchins, 1992; Stout et al., 1996). The goal of the experiments described in chapter 7 to 9 is to shed light on these claims, and to gain a better understanding of the conditions under which communication in teams affects performance.

In chapter 4 (see section 4.3.1), we described, based on the literature and a cognitive team task analysis, which type of communication is important for performance. We presented a model (see Figure 4.8) in which we illustrated the hypothesized relationships between communication, team and situation knowledge in shared mental models, and performance. Summarizing the model, we hypothesize that communication is important to develop and maintain up-to-date team and situation knowledge in a

[1] This chapter is a revised version of Rasker et al. (2000a)

shared mental model. In turn, this knowledge is used a) to coordinate implicitly and exchange timely the information that team members need to complete their tasks successfully, and b) to perform other teamwork that consists of performance monitoring, evaluation, and determining strategies together. We believe that the timely exchange of necessary information is important for performance. In some conditions, additional communication may be needed to perform teamwork and develop team and situation knowledge in mental models. The question is when and how communication improves performance by fostering the knowledge team members have in their mental models, which is the second research question of this thesis.

The verbal protocol analysis described in chapter 4 (see section 4.3.2) gives insight in the answers of this question. First, when team members communicate, knowledge important for shared mental models is transferred. With respect to team knowledge, the analysis shows that team members informed each other about their tasks and informational needs. Moreover, team members communicated in detail about the time that information must be exchanged. We believe that this type of communication fosters team knowledge. With respect to situation knowledge, team members informed each other about the ongoing developments and the changes in the environment. We believe that this type of communication fosters situation knowledge. Second, the analysis shows that team members communicate to perform teamwork that involves performance monitoring, evaluation, and determining strategies, which also foster team and situation knowledge. Altogether, we expect that these communications have a positive effect on performance.

7.1.1 Research on communication in teams

There are only a few experiments that have investigated communication as an antecedent of shared mental models. In one experiment it was investigated whether team self-correction discussions resulted in an overlap in team members' expectations (Blickensderfer et al., 1997c). When team members engage in team self-correction, they communicate to evaluate the past performance and determine how teamwork can be improved for the next time. The results show that teams that were engaged in team self-correction had more overlap in their expectations of team roles, team strategy, and communication manners than teams that did not engage in team self-correction. Although these teams also coordinated more implicitly (measured by the amount of information provided in advance of requests), this resulted not in an improved performance. The results show further that the extent of overlap in expectations was positively correlated to implicit coordination and performance.

In another experiment, the effect of communication on shared mental models and performance was investigated in a similar way (Stout et al., 1999). This time, it was examined how team members use their communication for planning. Planning in this experiment was defined as communication that existed of 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 results show that planning before task execution, allowed teams to use more efficient communication strategies under conditions of high workload during task execution. These teams provided more information in advance of requests and also performed better. Furthermore, these teams had better shared mental models of each other's informational requirements. However, better shared mental models were not associated to the provision of information in advance of requests. Therefore, better planning directly influenced communication and performance, independent of having shared mental models.

Both experiments have investigated the effect of communication before or between task execution on shared mental models and performance. These experiments show that communication during these periods had a positive effect on the overlap in team members' expectations or mental models. However, the mediating role of shared mental models and the relationships with the provision of information in advance of requests and, in turn, performance are not clear. Especially the lack of relationship between shared mental models and the provision of information in advance of requests is of concern. It questions the construct validity of shared mental models. What these two experiments also not have captured is how communication to self-correct or to make plans *during* task execution may improve performance. The interesting point here is that this type of communication, although expected to be beneficial, may conflict with the expected value of coordinating implicitly by communicating as effective and efficient as possible. Finally, these experiments have not investigated communication during versus before (or between) task execution.

That communication during task execution can improve performance can be inferred from the following two studies. In the first study, the communication of cockpit crews during a full-mission simulated flight was observed (Orasanu, 1990, 1993). The author found that effective teams (in terms of fewer flight errors) had more task-oriented communication during the flight. This included the formulation of plans and strategies. The author reasoned that this type of communication is especially beneficial when teams must handle novel or difficult problems. Communication is needed to develop a shared problem model that is necessary to ensure that all members are solving the same problem. Based on this model, team members are able to interpret the communication in the same manner and develop compatible explanations and expectations of the informational needs of the teammates and the strategies needed to deal with novel situations.

In another study, the communication of military teams was observed (McIntyre & Salas, 1995). It appeared that effective teams monitored each other's performance more often than ineffective teams. Performance monitoring consists of communication in which team members give, seek, and receive task-clarifying feedback during a task execution session (see also Cannon-Bowers et al., 1995). Team members monitor the performance of fellow team members, provide constructive feedback regarding errors, and offer advice for improving performance (McIntyre & Salas, 1995). Communication is needed to inform each other about the progress made on the task, the situational changes, and to be able to give feedback. By providing feedback to each other, team members can adjust their task execution immediately when necessary. We believe that performance monitoring is especially important to preserve up-to-date team and situation knowledge of the ongoing developments during task execution. This so-called strategic knowledge is important to ensure that team members keep track of the currently used strategies, team members' progress on the tasks, and the changes in team members informational needs. With respect to the situation, it is important that team members have up-to-date knowledge of the changes in the environment and unexpected problems. Common situation knowledge support team members in evaluating and determining strategies for the same environment or problems faced with.

The final study to be described is a conceptual examination of Stout et al. (1996) that emphasizes the role of communication for the development and maintenance of knowledge specific for a task execution session. According to Stout et al. (1996) team members need three types of knowledge. First, when entering a task execution session, team members need declarative knowledge that comprises knowledge of the mission, task, and members' roles. Second, team members need procedural knowledge about the sequence and timing of activities and information exchange. Third, in changing situations, team members must develop and maintain strategic knowledge that provides them with a common understanding of a) the operational context, b) actions that must be taken when unexpected events occur, and c) the information that should be obtained or exchanged to respond appropriately to the situation. Stout et al. reason that communication is needed to develop this strategic knowledge. This so-called *strategizing* involves communication in which team members clarify, confirm and disseminate information, plans, expectations, roles, procedures, strategies, and future states.

7.1.2 Experiment 4 and 5

The above-described research argues for teams to communicate extensively. However, there are no empirical studies that investigated the effect of communication during task execution on performance or studies that contrasted this with the effect of communication before (or between) task execution. In Experiment 4 and 5, we could treat communication as a factor that is manipulated between teams. We used an experimental team task in which the information needed to accomplish the tasks could be exchanged by standardized electronic messages. On top of that, team members could or could not communicate verbally with each other. This way, we were able to create conditions in which team members could communicate either restrictedly or unrestrictedly. In the restricted condition, team members cannot communicate to develop team or situation knowledge. Therefore, team members must rely on the knowledge that is developed before task execution. We expect that unrestricted communication improves performance because it fosters the development of team members' knowledge concerning the team and the situation in a shared mental model. This knowledge supports team members in a) predicting each other's informational needs and providing each other with the necessary information within the teammate's task sequence when it is needed, and b) performing additional teamwork that consists of performance monitoring, evaluation, and determining strategies together. We expect that these behaviors have a positive impact on performance.

The experiments described in this chapter address the question whether unrestricted communication improves performance. A comparison is made between teams that have the opportunity to communicate unrestrictedly and teams that communicate restrictedly. Figure 7.1 represents the dimensions (denoted by the gray boxes) and the relationship (denoted by the uninterrupted line) that are under investigation in Experiment 4 and 5.

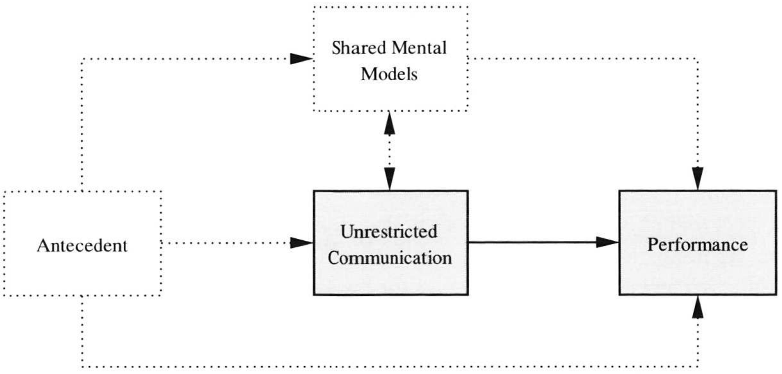

Figure 7.1: Hypothesized relationship between unrestricted communication and performance under investigation in Experiment 4 and 5

7.2 Experiment 4

7.2.1 Hypotheses

We expect that the performance improvement will be influenced by unrestricted communication that fosters members' team knowledge. In turn, this supports team members in predicting each other's informational needs and providing each other with the information needed to perform the tasks within the task sequence when it is most needed. Therefore, we formulated a hypothesis about the necessary information exchange. In the experimental task used, there is one piece of necessary information that must be exchanged by the standardized electronic messages. Even the team members that could communicate verbally had to provide this information by using the electronic message facility. Although they could also exchange the necessary information verbally, they were not able to put this information into their system and use the information to accomplish their tasks. Hence, by measuring the number and timing of this message, we could determine the team's ability to exchange the necessary information within the task sequence of the teammate when it is needed. This is regarded as an important indicator for having team knowledge. Furthermore, the timely exchange of this message shows whether team members are able to adjust their strategies in case of novel situations, which is supported by communicating unrestrictedly. To test whether teams that can communicate unrestrictedly are better in the timely exchange of necessary information than teams that cannot communicate unrestrictedly, the following hypothesis is put forward:

1. We expect that the teams that can communicate unrestrictedly exchange more often the necessary information in time than the teams that cannot communicate unrestrictedly

We also expect that the performance improvement will be influenced by unrestricted communication that fosters the situation knowledge of the team members. Having team and situation knowledge, support team members in performance monitoring, evaluation, and determining strategies together. Especially in novel situations this is expected to be beneficial. To test whether unrestricted communication improves performance, the following hypothesis is put forward:

2. We expect that the teams that can communicate unrestrictedly perform better than the teams that cannot communicate unrestrictedly

7.2.2 Method

Participants

The data for Experiment 5 were obtained from 44 students of Utrecht University in 22 teams of two participants. The distribution of participants over the different conditions with regard to sex was as follows: three female, three male teams and five mixed teams in the restricted condition; five female and six male teams in the unrestricted condition. Participants that formed the team were not acquainted to each other. The participants were paid Dfl. 60, = and were informed that they had a chance of receiving a bonus of Dfl. 40, = for the best performing team.

Design

Between teams. In order to test the hypotheses, two experimental conditions were designed: the *restricted* and the *unrestricted* condition.

Within teams. The presence of novel scenarios was a within team manipulation. Routine and novel scenarios were equally present. Teams were presented with identical scenarios in a fixed order. The first eight scenarios were routine scenarios, followed by eight novel scenarios.

Task

In Experiment 4, Version 2 of the fire-fighting task as described in section 3.3.1 was used.

Manipulation

In the restricted condition, teams could exchange the necessary information by sending and receiving the standardized electronic messages. Team members were placed in separate soundproof rooms and verbal communication was not possible at all. In the unrestricted condition, team members could communicate unrestrictedly in addition to sending and receiving the standardized electronic messages. Unrestricted communication was made possible by giving team members the opportunity to communicate verbally both during and between scenarios. Team members were placed in the same room and verbal communication was made possible face-to-face.

Scenario type was manipulated as follows. In the routine scenarios, the pattern in a series of small fires predicted the large building in danger as learned during the training. For example, team members could predict a fire in a hospital in sector IV when they recognized the pattern of small fires that consisted of "apartment building-house-apartment building" in sector I. In novel scenarios, the large fire was set in another section than team members would expect based on the pattern in a series of small fires they learned in their training. That is, instead of occurring in the diagonally opposite sector, the fire occurred in the sector underneath or above the sector with the pattern. The prediction with regard to the building type (factory or a hospital) remained intact.

Measurements

Communication. The verbal communication was recorded on tape. Two coders analyzed the communication from tape by classifying each statement of the team members into categories. The categories were derived from the model we developed based on the cognitive team task analysis of chapter 4 (see section 4.3.1, Table 4.10). We added one category in which the coders rated the remaining statements that could not be classified because they were not task related or unclear. For each team, each scenario, and the time between the scenarios the communication was rated. Independently from the first coder, the second coder rated the tapes in the same way. The second coder rated the communication of two randomly chosen scenarios for each team (in total 24 scenarios with a total duration of approximately 75 minutes). For these scenarios, an agreement level of the two coders was determined by the percentage of statements that the coders rated in the same category. With respect to the scenarios that both coders rated, the agreement level was 87%. This was considered sufficiently high such that the data obtained from the first coder (the one that scored all scenarios for all teams) were used for further analysis.

The standardized electronic messages were time-stamped and saved in a computer log file for analyses. The messages were used to determine whether there were differences between the conditions with respect to the timely exchange of a crucial piece of information. Note that, regardless of the opportunity to communicate unrestrictedly, team members had to send this message electronically to accomplish the tasks. The measure we were interested was the percentage of scenarios in which the message of the large building in danger was sent and read in time. We believe that this is an important measure for implicit coordination because it measures whether team members have provided the necessary information on the time in the teammate's task sequence that this information is needed. Moreover, this measure indicates whether team members have team knowledge of what (i.e., the large building in danger) and when (i.e., before Period 8 finishes) information must be exchanged. In the scenarios that were used in Version 2 of the fire-fighting task, it was highly important that this message is sent and read before Period 8 finishes.

Performance. In Version 2 of the fire-fighting task, performance was measured by the number of units that were allocated to the large building in danger in Period 10. This measure determined for every team in every scenario, how many units were assigned to the factory or the hospital at the beginning of the fire. Teams could have either sufficient of insufficient units allocated. Sufficient means that for a factory, four units, and a hospital, five units were allocated. With fewer units, a team was not able to achieve the goal and save as many potential casualties as possible.

Procedure

An experimenter assigned the participants randomly to the role of dispatcher and observer and told them to read the instruction. They were told not to speak to each other about the experiment and the experimenter was always present in situations where participants were together in the same space. Participants were allowed to ask questions at any point during reading.

The instruction first explained the fire-fighting task in general, followed by instructions specific for each role. This included a systematic instruction on how to manipulate the interface, accompanied by small tasks that had to be carried out by the participants. Subsequently, there was a training session of 16 scenarios. After this first training session, participants were asked to continue to read the instruction. In this instruction, it was explained how participants could predict, based on a pattern in a series of small fires, the location, type, and time of a large fire later in the scenario. These instructions were followed by another training session of 16 scenarios that contained such a pattern in a series of fires.

During the training, the two members of the team played the same scenarios at the same time. The dispatcher played with a computer program that simulated observer behavior (e.g., sending messages and so forth) and the observer played with a computer program that simulated dispatcher behavior. The programs, or "agents" as they were called, displayed ideal observer and dispatcher behavior. That is, the agents were always in time with the right information. The participants were informed of this. Participants were also informed that in the experimental session they would play with their actual teammate. The choice for this technique was made, to ensure an equal level of expertise at the end of the training by controlling the teammate's behavior.

After the training, the experimental session started. Participants were presented with 16 scenarios that existed of 12 periods of 15 seconds each. In total, an experimental session lasted about four hours.

7.2.3 Results

Communication

The verbal communication that took place in the unrestricted condition was classified into the categories as described in section 4.3.1 (see Table 4.10). The scores can be found in Table 7.1.

Table 7.1: Verbal communication; mean number of statements for each team in the unrestricted condition

Communication category	Unrestricted condition	
	Score	% of total
Information exchange	212	48
Performance monitoring	68	15
Evaluation	54	12
Determining strategies	20	4
Team knowledge	3	1
Situation knowledge	50	13
Remaining Communication	23	6
Total	430	100

As can be seen in Table 7.1, team members used the opportunity to communicate unrestrictedly. Most statements could be classified in one of the categories that reflect teamwork. Team members also exchanged information that is needed to accomplish the tasks. Although team members could exchange this information with the standardized electronic messages, it appears that team members found it necessary to exchange this information verbally as well.

With respect to the standardized electronic messages, Hypothesis 1 predicted that the teams in the unrestricted communication exchange more often the necessary information in time than the teams in the restricted condition. In each scenario, teams could be either in time or too late with sending and receiving the message about the large building in danger (i.e., when the message was not sent at all, this was considered as too late). The scores can be found in Table 7.2.

Table 7.2: Standardized electronic messages; communication result of the total number of scenarios in which team members were in time with sending and reading the message about the large building in danger for each condition and scenario type ($N = 352$)

Condition	Scenario type	Message	
		In time	Too late
Restricted	Routine	28	60
	Novel	11	77
Unrestricted	Routine	74	14
	Novel	51	37

We fitted three log-linear models to the data. The first model included the general mean and the design (i.e., timeliness, condition * scenario type). The second model included the general mean and the design and the main effect of condition (i.e., timeliness, condition * scenario type, condition * timeliness). For both models, Pearson's Chi^2 was calculated. To test the main effect of condition, the Chi^2 of the first model minus the Chi^2 of the second model was tested. The degrees of freedom for this test were the ones of the first model minus the ones of the second model. The third model included the general mean and the design and the main effects of condition as well as scenario type (i.e., timeliness, condition * scenario type, condition * timeliness, scenariotype * timeliness). To test the interaction effect of condition and scenario type, the Chi^2 and the degrees of freedom of this model were tested. To test the differences between conditions on either the routine or novel scenarios, a Chi^2 for each separate two-way table was calculated and tested.

The results show that teams that communicated unrestrictedly were more often in time with sending and reading the message about the large building in danger (71%) than teams that communicated restrictedly (22%), $\chi^2(1, N = 352) = 78.26, p < .01$. These teams were also more often in time in routine scenarios

(84%) than teams in the restricted condition (32%), $\chi^2(1, N = 176) = 49.34$, $p < .01$, and in more novel scenarios (58%) than teams in the restricted condition (13%), $\chi^2(1, N = 176) = 39.84$, $p < .01$. The results support Hypothesis 1. Teams of the unrestricted condition were more often in time with sending and reading a crucial piece of information (i.e., the large building in danger) than the teams of restricted condition. There was no interaction between condition and scenario type, $\chi^2(1, N = 352) < 1$.

Performance

Team members could perform either sufficiently or insufficiently on the performance measure allocation. The scores can be found in Table 7.3.

Table 7.3: Performance measure allocation; total number of scenarios in which team members had allocated a sufficient number of units during Period 10 for each condition and scenario type ($N = 352$)

Condition	Scenario type	Allocation	
		Sufficient	Insufficient
Restricted	Routine	6	82
	Novel	6	82
Unrestricted	Routine	23	65
	Novel	28	60

We fitted three log-linear models to the data. The first model included the general mean and the design (i.e., sufficiency, condition * scenario type). The second model included the general mean and the design and the main effect of condition (i.e., sufficiency, condition * scenario type, condition * sufficiency). For both models, Pearson's Chi^2 was calculated. To test the main effect of condition, the Chi^2 of the first model minus the Chi^2 of the second model was tested. The degrees of freedom for this test were the ones of the first model minus the ones of the second model The third model included the general mean and the design and the main effects of condition as well as scenario type (i.e., sufficiency, condition * scenario type, condition * sufficiency, scenariotype * sufficiency). To test the interaction effect of condition and scenario type, the Chi^2 and the degrees of freedom of this model were tested. To test the differences between conditions on either the routine or novel scenarios, a Chi^2 for each separate two-way table was calculated and tested.

Hypothesis 2, which predicted that teams that can communicate unrestrictedly perform better than teams that cannot communicate unrestrictedly, received support. As can be seen in Figure 7.2, teams that communicated unrestrictedly allocated sufficient units in more scenarios (29%) than teams that communicated restrictedly (7%), $\chi^2(1, N = 352) = 29.29$, $p < .01$. These teams also allocated sufficient units in more routine scenarios (26%) than teams in the restricted condition (7%), $\chi^2(1, N = 176) = 11.93$, $p < .01$, and in more novel scenarios (32%) than teams in the restricted condition (7%), $\chi^2(1, N = 176) = 17.64$, $p < .01$. There was no interaction between condition and scenario type, $\chi^2(1, N = 352) < 1$.

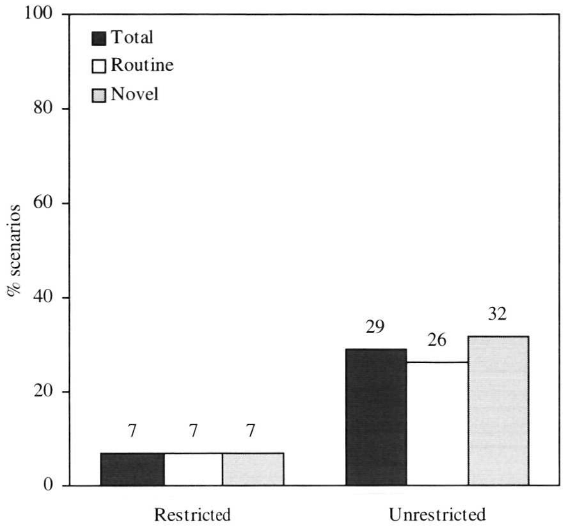

Figure 7.2: Performance measure allocation; percentage of scenarios in which team members had allocated a sufficient number of units during Period 10 for each condition for the total number of scenarios as well as for the routine and novel scenarios separately

7.2.4 Discussion of Experiment 4

Experiment 4 was conducted to investigate the effect of unrestricted communication on performance. The results support our hypothesis that communication without restrictions has a positive effect on performance. We believe that the performance improvement can be ascribed to the development of team members' knowledge concerning the team and the situation. The communication scores show that team members transferred situation and, to a lesser extent, team knowledge. One of the benefits of having this knowledge is that team members are better in predicting each other's informational needs and providing each other with the necessary information within the task sequence of the teammate when it is needed. Our hypothesis that team members of the unrestricted condition would exchange more often the necessary information in time is also supported by the results. This indicates that team members that communicated unrestrictedly developed better knowledge of each other's informational needs.

The verbal protocol analysis described in chapter 4 (see section 4.3.2) shows that team members inform each other in detail what information is needed and when. For example, team members informed each other in which periods information of the large building had to be exchanged. We believe that it is this type of communication that sharpens the knowledge of each other's informational needs. Based on this knowledge, team members can attune their individual taskwork on that of their teammates such that the necessary information is obtained and exchanged in time. In teams, this is essential for a good performance.

Unrestricted communication gives team members also the opportunity to perform teamwork that cannot be performed when communicating restrictedly. The verbal protocol analysis described in chapter 4 shows that performance monitoring, evaluation, and determining strategies can be distinguished. The communication scores shows that teams communicated substantially in the categories that are associated with this teamwork. Team members monitor each other's performance allowing them to inform each other about the progress made on the tasks and give feedback immediately when things go wrong. The result is that they are able to prevent each other from making errors. We believe that performance monitoring also fosters the development of team and situation knowledge. Because information is exchanged concerning the ongoing activities, team members develop an understanding of how they are dependent on each other's information.

Team members that communicate unrestrictedly can also evaluate and determine strategies jointly. Several researchers hypothesized that common knowledge of the team and the situation is important for this type of teamwork (Orasanu, 1990, 1993; Stout et al., 1996). Especially in novel situations it is important that team members keep track of the changes in the situation and, when needed, adjust their strategies. When team members hold common situation knowledge, they are able to provide each other with information, suggestions, alternatives, and expectations that are both explained and expected by the teammates. Given that the teams that communicated unrestrictedly performed also better on the novel situations, it can be concluded that these teams were able to keep up their performance and adjust their strategies successfully. Because the communication scores show that team members evaluated and determined strategies together, we believe that unrestricted communication played an important role herein.

In conclusion, the results of Experiment 4 show that unrestricted communication improves performance. We explained this performance improvement by team members that developed better team and situation knowledge that, in turn, has a positive effect on the timely exchange of necessary information, performance monitoring, evaluation, and determining strategies. The communication measures (electronically as well as verbally) support this explanation.

7.3 Experiment 5

From Experiment 4, we were not able to draw conclusions concerning the relative contributions of communication during task execution or between task execution. In order to investigate this, a second experiment is performed.

7.3.1 Hypotheses

The second experiment is focused on the relative contributions of communication during task execution or in the break between task execution sessions. Based on theoretical grounds, we could not predict which of the two types of communication is more beneficial to improve the performance. Therefore, it is tested whether there is a difference amongst teams depending on the opportunity to communicate unrestrictedly during or between task execution. The conditions of Experiment 5 are also compared with the conditions of Experiment 4. This way, we are able to test directly to what extend unrestricted communication either during or between task execution contributes to performance. To test whether there are differences in the necessary information exchange, the following hypotheses are put forward:

1. We expect that the teams that can communicate unrestrictedly *during* task execution perform differently with respect to the timely exchange of necessary information than the teams that cannot communicate unrestrictedly *between* task execution
2. We expect that the teams that can communicate unrestrictedly *during* task execution exchange more often the necessary information in time than the teams that cannot communicate unrestrictedly

3. We expect that the teams that can communicate unrestrictedly *between* task execution exchange more often the necessary information in time than the teams that cannot communicate unrestrictedly

To test whether the are differences in the performance, the following hypotheses are put forward:

4. We expect that the teams that can communicate unrestrictedly *during* task execution perform differently than the teams that can communicate unrestrictedly *between* task execution
5. We expect that the teams that can communicate unrestrictedly *during* task execution perform better than teams that cannot communicate unrestrictedly
6. We expect that the teams that can communicate unrestrictedly *between* task execution perform better than the teams that cannot communicate unrestrictedly

7.3.2 Method

For Experiment 5, we used the same methodology as for Experiment 4. Therefore, this section only describes the differences with Experiment 4.

Participants

The data for Experiment 5 were obtained from 44 students of Utrecht University in 22 teams of two participants. The distribution of participants over the different conditions with regard to sex was as follows: six female teams and five male teams in the during scenarios condition; five female teams and six male teams in the between scenarios condition. The participants were paid Dfl. 60, = and were informed that they had a chance of receiving a bonus of Dfl. 40, =.

Design

In order to test the hypotheses, two experimental conditions were designed: the *during* and the *between* condition.

Manipulation

In the during condition, team members could communicate verbally without restrictions during the execution of scenarios. In the between condition, team members could communicate verbally without restriction during the break between scenarios. The total time available for unrestricted communication was identical for both conditions (three minutes). In both conditions, teams had also the opportunity to exchange the necessary information by sending and receiving standardized electronic messages. Team members were placed in separate soundproof rooms and verbal communication was made possible via headsets.

7.3.3 Results

Communication

The communication that took place in Experiment 5 was classified into the same categories as in Experiment 4. With respect to the scenarios that both coders scored, the agreement level was 78%. This was considered sufficiently high such that the data obtained from the first coder (the one that scored all scenarios for all teams) were used for further analysis. The scores can be found in Table 7.4.

As can be seen in Table 7.4, team members used the opportunity to communicate unrestrictedly. With respect to percentage of statements of the total amount of communication in each category, we tested post-hoc the differences between the means of the during and the between condition. An analysis of variance, comparing the during and the between condition was used. Because we had no hypothesis, we applied a Bonferroni correction. It appears that the differences for the category *situation knowledge* and *remaining communication* did not reach significance. Teams in the during condition communicated mostly in the categories that are associated with the ongoing task performance (i.e., information exchange and performance monitoring). Teams in the between condition communicated mostly in the categories that are associated with past (evaluation) and future (determining strategies) performance. Teams in the between condition, also communicated more team knowledge than the teams in the during condition.

Table 7.4: Verbal communication; mean number of statements for each team in the during as well as in the between condition

	During condition		Between condition		
Communication category	Score	% of total	Score	% of total	$F(1,20) =$
Information exchange	198	55	32	10	153.83***
Performance monitoring	60	14	6	2	51.58***
Evaluation	39	10	109	35	52.87***
Determining strategies	15	4	55	17	47.24***
Team knowledge	7	2	46	14	40.93***
Situation knowledge	42	12	26	8	5.25**
Remaining Communication	18	5	49	14	7.83**
Total	378	100	322	100	

Note. When applying a Bonferroni correction, the differences between the category *situation knowledge* and *remaining communication* do not reach significance.
Note. $^{**}p < .05$, $^{***}p < .01$

With respect to the standardized electronic messages, Hypothesis 1 predicted differences between the during and the between condition with respect to the exchange of the necessary messages. In each scenario, teams could be either in time or too late with sending and receiving the message about the large building in danger (i.e., when the message was not sent at all, this was considered as too late). The scores of this measure are shown in Table 7.5.

Table 7.5: Standardized electronic messages; communication result of the total number of scenarios in which team members were in time with sending and reading the message about the large building in danger for each condition and scenario type ($N = 352$)

Condition	Scenario type	Message	
		In time	Too late
During	Routine	76	12
	Novel	68	20
Between	Routine	79	9
	Novel	68	20

To test Hypothesis 1 to 3, we fitted the same log linear models on the data and followed the same procedure as for Experiment 4. The results of this analysis show that there are no differences between the teams that communicated unrestrictedly during (82%) and between scenarios (84%), $\chi^2(1, N = 352) < 1$. There were also no differences between the conditions in the routine scenarios (86% for the during and 90% for the between condition), $\chi^2(1, N = 176) < 1$, and the novel scenarios (77% for the during and 77% for the between condition), $\chi^2(1, N = 176) < 1$. There was no interaction between condition and scenario type, $\chi^2(1, N = 352) < 1$. Taken together, these results do not support Hypothesis 1.

Hypothesis 2 predicted that the teams in the during condition are more often in time with the exchange of necessary information than the teams in the restricted condition. With respect to the percentage of scenarios in which the building of the large building in danger was sent and read in time, the results support Hypothesis 2. Teams in the during condition were more often in time (82%) than the teams in the restricted condition (22%), $\chi^2(1, N = 352) = 120.31, p < .01$. These teams were also more often in time in routine scenarios (86%) than the teams in the restricted condition (32%), $\chi^2(1, N = 176) = 54.15$, $p < .01$, and in more novel scenarios (77%) than teams in the restricted condition (13%), $\chi^2(1, N = 176) = 74.62, p < .01$. There was no interaction between condition and scenario type, $\chi^2(1, N = 352) < 1$.

Hypothesis 3 predicted that the teams in the between condition are more often in time with the exchange of necessary information than the teams in the restricted condition. With respect to the percentage of scenarios in which the building of the large building in danger was sent and read in time, the results support Hypothesis 3. Teams in the between condition were more often in time (84%) than the teams in the restricted condition (22%), $\chi^2(1, N = 352) = 126.54, p < .01$. These teams were also more often in time in routine scenarios (90%) than teams in the restricted condition (32%), $\chi^2(1, N = 176) = 62.00, p < .01$, and in more novel scenarios (77%) than teams in the restricted condition (13%), $\chi^2(1, N = 176) = 74.62, p < .01$. There was no interaction between condition and scenario type, $\chi^2(1, N = 352) < 1$.

Performance

Team members could perform either sufficiently or insufficiently on the performance measure allocation. The scores can be found in Table 7.6. We fitted the same log-linear models on the data and followed the same procedure as in Experiment 4 to test the hypotheses.

Table 7.6: Performance measure allocation; total number of scenarios in which team members had allocated a sufficient number of units during Period 10 for each condition and scenario type ($N = 352$)

Condition	Scenario type	Allocation	
		Sufficient	Insufficient
During	Routine	28	60
	Novel	38	50
Between	Routine	12	76
	Novel	18	70

Hypothesis 4, which predicted that teams perform differently depending on whether they could communicate unrestrictedly during or between scenarios, received support. As can be seen in Figure 7.3, teams that communicated unrestrictedly during scenarios allocated sufficient units in more scenarios (38%) than teams that communicated unrestrictedly between scenarios (17%), $\chi^2(1, N = 352) = 18.02, p < .01$. These teams also allocated sufficient units in more routine scenarios (32%) than teams in the restricted condition (14%), $\chi^2(1, N = 176) = 8.28, p < .01$, and in more novel scenarios (43%) than teams in the restricted condition (20%), $\chi^2(1, N = 176) = 10.48, p < .01$. There was no interaction between condition and scenario type, $\chi^2(1, N = 352) < 1$.

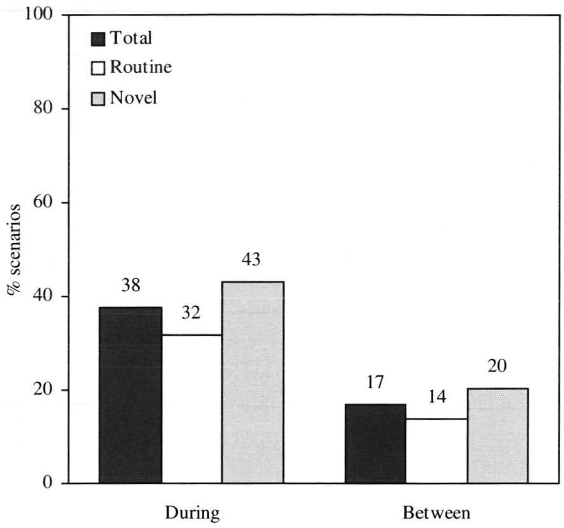

Figure 7.3: Performance measure allocation; percentage of scenarios in which team members had allocated a sufficient number of units during Period 10 for each condition for the total number of scenarios as well as for the routine and novel scenarios separately

Hypothesis 5, which predicted that the teams that communicate unrestrictedly during task execution perform better than the teams that communicate restrictedly, received support. Teams that communicated unrestrictedly during scenarios allocated sufficient units in more scenarios (38%) than teams that communicated restrictedly (7%), $\chi^2(1, N = 352) = 47.85$, $p < .01$. These teams also allocated sufficient units in more routine scenarios (32%) than teams in the restricted condition (7%), $\chi^2(1, N = 176) = 17.64$, $p < .01$, and in more novel scenarios (43%) than teams in the restricted condition (7%), $\chi^2(1, N = 176) = 31.03$, $p < .01$. There was no interaction between condition and scenario type, $\chi^2(1, N = 352) < 1$.

Hypothesis 6, which predicted that the teams that communicate unrestrictedly between task execution perform better than the teams that communicate restrictedly, received support. Teams that communicated unrestrictedly between scenarios allocated sufficient units in more scenarios (17%) than teams that communicated restrictedly (7%), $\chi^2(1, N = 352) = 9.17$, $p < .01$. Surprisingly, these teams did not allocate sufficient units in more routine scenarios (14%) than teams in the restricted condition (7%), $\chi^2(1, N = 176) = 2.23$. In the novel scenarios, however, the teams that communicated unrestrictedly between scenarios performed better (20%) than the teams that communicated restrictedly (7%), $\chi^2(1, N = 176) = 6.95$, $p < .01$. There was no interaction between condition and scenario type, $\chi^2(1, N = 352) < 1$.

7.3.4 Discussion of Experiment 5

In Experiment 5 we were interested in the question whether there are differences in the performance of teams dependent on the opportunity to communicate unrestrictedly during task execution or in the breaks between task execution. The results show that teams that could communicate during task execution performed better than teams that could communicate between task execution. This supports our hypothesis that teams would perform differently dependent on the opportunity to communicate during or between task execution. An explanation for the benefits of unrestricted communication during task execution is that team members developed better team knowledge such that they are better able to provide each other with the necessary information in time. However, the results show no differences in the timely exchange of a crucial piece of information. This indicates that in both conditions, team members had developed team knowledge to the same extent. Regardless of the knowledge that could have been developed, the performance differences cannot be explained by differences in the exchange of necessary information.

We hypothesized that unrestricted communication is also important for teamwork that cannot be performed when team members communicate unrestrictedly. The advantage of communicating unrestrictedly during task execution may be especially important for performance monitoring. When team members can monitor each other's task performance, they are able to prevent each other from making errors. The communication scores show that the teams of the during condition devoted a considerable part of their total communication to performance monitoring. This communication allowed team members to inform each other about the progress that is made on the tasks and give immediate feedback when things go wrong. Because in the between condition performance monitoring cannot take place immediately, potential errors could not be prevented. This may have caused the performance decrease for the teams that communicated only between task execution.

The conditions of Experiment 4 were also compared to the restricted condition of Experiment 5. This way, we are able to test the effect of unrestricted communication between and during task performance. The results show that unrestricted communication during as well as between task execution improves performance when compared to the restricted communication. The effects of unrestricted communication during task execution replicate the results of Experiment 4. Teams that communicated unrestrictedly exchanged more often the necessary information than the teams that could not communicate unrestrictedly. This indicates that better team knowledge was developed. Furthermore, these teams performed better than the teams in the unrestricted condition.

Our findings show that performance improves when teams communicate unrestrictedly between task execution sessions. The communication scores show that the time between task execution sessions is mostly used to look back and evaluate, and to look ahead and determine strategies. This supports the notion that team self-correction discussions between task performance sessions contribute to team performance (Blickensderfer et al., 1997b).

7.4 Discussion

The purpose of Experiment 4 and 5 was to investigate the effect of unrestricted communication on performance. The results show that teams that communicated unrestrictedly between, during, as well as between and during task execution performed better than teams that communicated restrictedly. Our explanation is that unrestricted communication supported team members in developing team and situation knowledge. Team knowledge supports members in predicting each other's informational needs and providing each other with the information needed to perform the tasks within the teammate's task sequence when it is most needed. This line of thinking was supported by the data of the standardized electronic message exchange. Teams that communicated unrestrictedly were more often in time with sending and reading the most important message than the teams that communicated restrictedly. Situation knowledge supports team members in performing teamwork that consists of performance monitoring, evaluation, and determining strategies together. Especially during task execution, team members benefit from having the opportunity to communicate unrestrictedly because it enables them to monitor each other's performance and prevent each other from making errors. For teams performing in complex and dynamic situations, this is important for a good performance.

The findings of Experiment 4 and 5 suggest that the key to better performance is to expand the communication, not to limit the communication. However, before we can firmly draw such a conclusion, two issues have to be taken into consideration. First, the overall performance was relatively low. Even the teams of the best performing conditions had allocated sufficient units in only one third of the scenarios. It is possible that unrestricted communication had such an impact on performance because team members were not fully trained. Unrestricted communication for performance monitoring, evaluation, and determining strategies was simply needed because team members made many mistakes or had inferior strategies. Hence, when team members are better trained, unrestricted communication is not needed for that matter. Second, it is also possible that the effect of unrestricted communication diminishes after time because team and situation knowledge important for shared mental models is transferred especially in the beginning of a team's lifetime. After working for some time, all the knowledge is transferred and unrestricted communication is, therefore, not needed any more. Both issues are under examination in Experiment 6, described in the next chapter.

8 UNRESTRICTED COMMUNICATION, TEAM AND SITUATION KNOWLEDGE, AND PERFORMANCE

In this chapter, we describe an experiment in which the effect of unrestricted communication was investigated in two experimental sessions. This was done to test whether unrestricted communication is still beneficial after time. The need for unrestricted communication may decline after time because knowledge important for shared mental models is transferred among team members. However, unrestricted communication may remain necessary to preserve up-to-date knowledge of the changes in the team and the situation. The results show that in the first session, unrestricted communication improved performance. In a second session, however, unrestricted communication led to worse performance. An explanation for this unexpected result is that too much communication during high workload periods may have distracted team members to perform their individual taskwork accurately.

8.1 Introduction

In this chapter, we focus on the question whether unrestricted communication is still beneficial after time. This question is partially motivated by the results of Experiment 4 and 5. Although it was clear that in these experiments, teams benefited from communicating unrestrictedly, performance was relatively low and could be improved largely (i.e., even the teams in the two best performing conditions had allocated sufficient units in only one third of the scenarios). It can be argued that the effect of unrestricted communication is less strong when team members are better trained. Better-trained teams make fewer errors, which makes the effect of monitoring each other's performance and preventing each other committing errors less strong. Moreover, better-trained teams have better strategies that make it unnecessary to adjust or determine new strategies. For those reasons, it can be argued that unrestricted communication is less necessary when teams work together for a longer period and have had more practice.

The question is also motivated by the idea that the effect of unrestricted communication declines because team members have, after time, transferred all the knowledge important for shared mental models. In other words, unrestricted communication is not needed any more to foster team and situation knowledge in shared mental models. The verbal protocol analyses described in chapter 4 (see section 4.3.2) showed that there were differences in the communication between Scenario 1 and 8. In Scenario 8, the analyzed team transferred less team knowledge than in Scenario 1. For example, team members communicated less about their informational needs. This suggests that unrestricted communication looses its strength after time. It is possible that team members can draw on their previously developed knowledge, which makes it unnecessary to communicate unrestrictedly.

Although unrestricted communication may be less beneficial because of the reasons mentioned, it may be still beneficial to transfer knowledge of the current activities and the ongoing situation. Especially in the rapidly changing environments in which teams perform, this may be of great importance. In that case, unrestricted communication is important to preserve up-to-date shared knowledge of the changes in the team and the situation. In novel situations, unrestricted communication may also be important. A novel situation agrees with a routine situation in the sense that it maintains the primary task objectives, but differs in its physical familiarity, specific performance requirements, and strategic approach (Marks, 1999). Performance in novel situations is more challenging because there is no obvious strategy to handle the situation. In order to keep up the performance, team members must communicate to respond to environmental cues, explain each other why previous strategies do not work in the novel situation, jointly determine new strategies, and predict future states (Orasanu, 1990, 1993). This argues for unrestricted communication, even when teams already have developed team and situation knowledge.

The topic of maintaining up-to-date knowledge "on the fly" is especially interesting because it addresses strategic and situational knowledge in shared mental models. Although several researchers assert that this type of knowledge is important for shared mental models, it has never been investigated empirically. Stout et al. (1996) emphasized this importance and hypothesized that communication is needed to keep up-to-date knowledge of the changes in the team task demands. This so-called *strategizing* consists of communication about the ongoing developments in the team and the situation such as priorities, plans, and strategies. In an observational study, this type of communication differentiated good from poor performing teams (Orasanu, 1990, 1993). The authors reasoned that this type of communication helped the teams to develop a so-called *shared problem model*, which enabled members to give advice, generate alternative solutions, and determine strategies for the same problem.

8.2 Experiment 6

In Experiment 6, we investigate teams in two subsequent experimental sessions and vary systematically the opportunity to communicate unrestrictedly. We have three conditions: unrestricted communication in 1) none of the sessions, 2) Session 1 only, and 3) both sessions (see Table 8.1). This way we attempt to investigate the effect of unrestricted communication on performance over time. With respect to our second research question, this gives us a better picture of the way communication improves performance by fostering the knowledge team members have in their mental models.

Table 8.1: Schematic representation of the conditions

Condition	Session 1	Session 2
1. Restricted condition		
2. Partial restricted condition	■	
3. Unrestricted condition	■	■

■ = unrestricted communication

By allowing team members to communicate unrestrictedly or restrictedly in Session 1 of the experiment, we expect that they either can or cannot develop adequate team and situation knowledge. In turn, the presence of this knowledge will have a direct impact on their task performance. In Session 2, we again manipulate their possibility for communicating. Teams must communicate restrictedly and, therefore, have to depend on their knowledge developed during Session 1. We expect that the teams that can rely on their knowledge developed in Session 1 will perform better than the teams that cannot rely on their knowledge. In the third condition, teams can continue to communicate unrestrictedly during Session 2. Although we expect that they developed team and situation knowledge in Session 1, unrestricted communication in Session 2 will be still beneficial to maintain up-to-date knowledge of the situation.

With respect to Experiment 4 and 5, we made several changes in Experiment 6. First, we developed a brief questionnaire to investigate the team and situation knowledge of the team members. With the help of this questionnaire, we attempted to investigate to what extent team members' knowledge is fostered as a result of unrestricted communication. Second, the training is changed such that team members received practice in their tasks for a longer period. We also employed an improved version of the experimental task, which had a fortunate side effect for training. Because performance was measured more precisely in this version, team members received better feedback about their performance. We believe that both changes contribute to better-trained team members. This is important for the generalisability of the results found in Experiment 4 and 5, because the effect of unrestricted communication may be less when team members are better trained. In general, Experiment 6 is performed to test empirically whether unrestricted communication improves team performance under different conditions, which gives us more insight in the generalisability of the previously obtained results.

8.2.1 Hypotheses

Experiment 6 addresses the question whether unrestricted communication improves performance by fostering team and situation knowledge in team members' mental models. A comparison is made between teams that can communicate unrestrictedly and teams that cannot. Figure 8.1 represents the dimensions (denoted by the gray boxes) and their relationships (denoted by the uninterrupted lines) under investigation in Experiment 6.

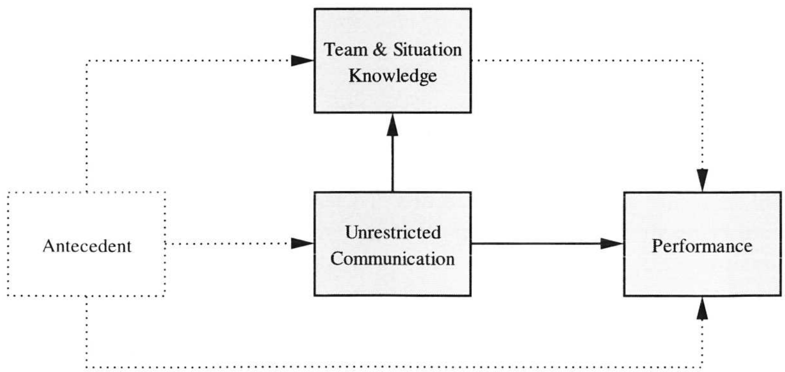

Figure 8.1: Hypothesized relationships between unrestricted communication, team and situation knowledge, and performance under investigation in Experiment 6

Given the expected value of unrestricted communication on the development of team and situation knowledge in the mental models of the team members, the following hypothesis is put forward:

1. We expect that the teams that can communicate unrestrictedly develop better team and situation knowledge than the teams that cannot communicate unrestrictedly

To investigate whether the communication changes after time, we formulated a hypothesis about it. We classified the verbal communication into the same categories as in Experiment 4 and 5. The categories and their definitions can be found in chapter 4 (see section 4.3.1, Table 4.10). We do not expect changes in the communication in the categories: information exchange, performance monitoring, evaluation, determining strategies, and situation knowledge. This communication is concerned with the ongoing task performance and the situation. In the experimental task used for Experiment 6, this is always subject to change. For that reason, team members will communicate in these categories in order to keep things going. However, team knowledge, which can be developed in Session 1, does not change and remains applicable in Session 2 (regardless of the changes in the situation). Therefore, the following hypothesis is put forward:

2. We expect that the teams that can communicate unrestrictedly in Session 1 and 2, communicate less concerning team knowledge in Session 2 than in Session 1

We expect that the performance improvement is a result of unrestricted communication that fosters members' team knowledge. In turn, this supports team members in predicting each other's informational needs and coordinate implicitly. Because the teams in the restricted *and* the partial restricted condition communicate restrictedly in Session 2, we can compare the differences in the way team members communicate with the standardized electronic messages in Session 2. This way, we are able to investigate whether teams that can communicate unrestrictedly in Session 1, coordinate more implicitly in Session 2, than teams that cannot communicate unrestrictedly in Session 1. Therefore, the following hypothesis is put forward:

3. We expect that in Session 2 the teams that can communicate unrestrictedly in Session 1 coordinate more implicitly and therefore communicate more efficiently and effectively (i.e., less messages, more necessary messages, more necessary messages in advance of requests, less requests, answering more requests, more necessary messages in time, and answering more requests in a shorter time notice) than the teams that cannot communicate unrestrictedly in Session 1

One piece of necessary information must always be exchanged by the standardized electronic messages (regardless of the opportunity to communicate unrestrictedly). By measuring the number and timing of this message, we could determine the team's ability to exchange the necessary information within the teammate's task sequence when it is most needed. To test whether the teams that can communicate unrestrictedly are better in the timely exchange of necessary information than the teams that cannot communicate unrestrictedly, the following hypotheses are put forward:

4. We expect that the teams that can communicate unrestrictedly in Session 1 exchange more often the necessary information in time than the teams that cannot communicate unrestrictedly in session 1; this communication improvement will be more pronounced in Session 2
5. We expect that the teams that can continue to communicate unrestrictedly in Session 2 exchange more often the necessary information in time than the teams that can communicate unrestrictedly in Session 1 only; this communication improvement will be more pronounced in Session 2

Because we expect that performance improves because of unrestricted communication, the following hypotheses are put forward:

6. We expect that the teams that communicate unrestrictedly in Session 1 perform better than the teams that cannot communicate unrestrictedly in Session 1; this performance improvement will be most pronounced in Session 2
7. We expect that the teams that can continue to communicate unrestrictedly during Session 2 perform better than the teams that communicate unrestrictedly during Session 1 only; this performance improvement will be most pronounced in Session 2

8.2.2 Method

Participants

The data for Experiment 6 were obtained from 72 students of Utrecht University in 36 teams of two participants. Men and women were equally represented (36 male and 36 female). Each team consisted of two male or two female participants. In each of the three conditions, the task was performed by 12 teams: six male and six female teams. Participants that formed the team were not acquainted to each other. The participants were paid Dfl. 60, = for their contribution.

Design

In order to test the hypotheses, three experimental conditions were designed: the *restricted, partial restricted,* and the *unrestricted* condition.

Task

In Experiment 6, Version 3 of the fire-fighting task as described in section 3.3.2 was used.

Manipulation

In the restricted condition, teams could exchange the necessary information by sending and receiving the standardized electronic messages. Team members were placed in separate soundproof rooms and verbal communication was not possible at all. In the partial restricted condition, team members could communicate unrestrictedly in addition to sending and receiving the standardized electronic messages in Session 1. In the unrestricted condition, team members could communicate unrestrictedly in addition to sending and receiving the standardized electronic messages in Session 1 and 2. Unrestricted communication was made possible by giving team members the opportunity to communicate verbally both during and between scenarios. Team members were placed in separate soundproof rooms and verbal communication was made possible via headsets.

To avoid ceiling effects, scenarios were developed with patterns in a series of fires that changed regularly and differed from the patterns team members learned during the training. There were two experimental sessions of 16 scenarios each. In Session 1, in 11 scenarios the fire was set in the expected section but in an unexpected building, and in five scenarios, the expected building was set on fire, but in an unexpected section. In Session 2, in 11 scenarios the fire was set in an unexpected section as well as an unexpected building, and in five scenarios, the expected building was set on fire, but in an unexpected section. In both sessions, the scenarios were presented in a fixed order and the five scenarios were interchanged with the series of 11 scenarios in the following order: 1, 4, 7, 10, and 13.

Measures

Knowledge. To assess members' team knowledge, a 6-item questionnaire was developed. The questions are listed in Table 8.2 (translated from Dutch).

Table 8.2: Knowledge measurement; overview of the questions

Question	Answer observer	Answer dispatcher
1. What information was the most important to provide your teammate with?	Large building in danger	Changes in the allocation of units
2. When had this information to be provided?	Period 8	Within one period
3. When was the information of the pattern for your teammate available	Period 6	Period 6
4. Was it beneficial to save the small buildings at the beginning of a scenario too?	Yes	Yes
5. Was there always a pattern present?	No	No
6. When had the units to be withdrawn in order to be on time for the large fire?	Period 7	Period 7

Question 1 to 3 were developed to tap members' team knowledge about each other's tasks, roles, responsibilities, and informational needs. Question 4 to 6 were developed to tap team members' situation knowledge. Each question that was accurately answered was scored with one point. In total, each team member could earn six points.

Several scores were calculated. The *team score* was the average score of both team members of all accurate answers. The *team knowledge score* was the score on all accurate answers of both team members on the team knowledge questions (all accurate answers on Question 1 to 3). The *situation knowledge score* was the score on all accurate answers of both team members on the situation knowledge questions (all accurate answers on Question 4 to 6). The *heterogeneous score* was the score of all accurate answers of both team members that are unique for each team member's role (all accurate answers on Question 1 and 2). The *similarity score* was the score of all answers that both team members could have and had similar (all answers on Question 3 to 6 that were similar). The *similarity and accuracy score* was the score of all answers that both team members could have and had similar, and were accurate (all answers on Question 3 to 6 that were similar and accurate).

Communication. The verbal communication was recorded on tape. Two coders analyzed the communication from tape by classifying each statement of the team members into categories. The categories were derived from the model we developed based on the cognitive team task analysis of chapter 4 (see section 4.3.1, Table 4.10). We added one category in which the coders rated the remaining statements that could not be classified because they were not task related or unclear. For each team, each scenario, and the time between the scenarios the communication was rated. Independently from the first coder, the second coder rated the tapes in the same way. For each session, the second coder rated the communication of two randomly chosen scenarios for each team (in total 72 scenarios with a total duration of approximately 216 minutes). For these scenarios, an agreement level of the two coders was determined by the percentage of statements that the coders rated in the same category. With respect to the scenarios that both coders rated, the agreement level was 87%. This was considered sufficiently high such that the data obtained from the first coder (the one that scored all scenarios for all teams) were used for further analysis.

The standardized electronic messages were time-stamped and saved in a computer log file for analyses. The same communication measures of Experiment 1 to 3 (see section 5.2.2, Table 5.1) were used to determine whether the teams in the partial restricted condition coordinated more implicitly and therefore communicated more efficiently and effectively than the teams in the restricted condition in Session 2. These measures were based on the communication features of implicit coordination in the fire-fighting task that we established with the help of the cognitive team task analysis of chapter 4 (see section 4.2.2, Table 4.7).

We also measured the percentage of scenarios in which the message of the large building in danger was sent and read in time. Regardless of the opportunity to communicate unrestrictedly, team members had to send this message electronically to accomplish the tasks. Therefore, we could use this measure to determine whether there are differences between the conditions with respect to the provision of necessary information on the time in the teammate's task sequence that this information is needed. We believe that this is an important measure of implicit coordination, which indicates whether team members have team knowledge.

Performance. Performance was measured by the percentage of casualties saved out of the total number of potential casualties that could be saved in a scenario.

Procedure

An experimenter assigned the participants randomly to the role of dispatcher and observer and told them to read the instruction. Participants were placed in separate soundproof rooms and communication between the participants was made possible by sending and receiving the standardized electronic messages. They were told not to speak to each other about the experiment and the experimenter was always present in situations where participants were together in the same space. Participants were allowed to ask questions at any point during reading.

The instruction first explained the fire-fighting task in general, followed by instructions specific for each role. This included a systematic instruction on how to manipulate the interface, accompanied by small tasks that had to be carried out by the participants. Subsequently, there was a training session of five scenarios. After this first training session, participants were asked to continue to read the instruction. In this instruction, it was explained how participants could predict, based on a pattern in a series of small fires, the location, type, and time of a large fire later in the scenario. These instructions were followed by another training session of 25 scenarios that contained such a pattern in a series of fires. With respect to Experiment 4 and 5 of chapter 7, the training was changed such that participants were less trained in the relatively easy procedural scenarios (e.g., the first five scenarios of the training) and more trained in the more difficult scenarios containing a pattern. At the end of the break after the last training session, the participants were instructed on the experimental condition they were assigned to.

After the training, two experimental sessions of 16 scenarios each started. In each session, participants were presented with 16 scenarios that existed of 11 periods of 15 seconds each. After the two experimental sessions, participants answered the questionnaire. In total, an experimental session lasted about four hours.

8.2.3 Results

Knowledge

In order to test Hypothesis 1, a Mann-Whitney *U*-test was performed to test whether there are differences in the scores on the knowledge questionnaire. The results of the test are shown in Table 8.3.

Hypothesis 1 predicted that the teams that can communicate unrestrictedly have better team and situation knowledge than the teams that cannot communicate unrestrictedly. As can be seen in Table 8.3, this hypothesis is supported by the results. Teams that communicated unrestrictedly gave more accurate answers on all questions of the knowledge questionnaire than teams that communicated restrictedly. The teams that communicated unrestrictedly in Session 1 *and* 2 gave more accurate answers on the team and situation knowledge questions than the teams than communicated restrictedly. For the teams that communicated unrestrictedly in Session 1 only, there is a tendency that they gave more accurate answers on the team and situation knowledge questions than the teams than communicated restrictedly. In both unrestricted communication conditions, the amount of accurate answers was also higher on the questions that were specific for each team member's role (i.e. heterogeneous score). Finally, the teams that communicated unrestrictedly had more similar answers and more answers that were similar *and* accurate than the teams that communicated restrictedly. Taken together, the results on the knowledge questionnaire indicate that team members in the unrestricted condition not only had better team and situation knowledge, but also had more overlap in this knowledge. Post-hoc we tested whether there were differences between the partial restricted and the unrestricted condition to verify whether possible performance differences can be ascribed to differences in the knowledge. As can be seen in Table 8.3, there are no differences between these conditions.

Table 8.3: Mean score for each condition on the team and situation knowledge questionnaire

Knowledge score	Restricted	Partial restricted	Unrestricted	Restricted vs. partial restricted	Restricted vs. unrestricted	Partial restricted vs. unrestricted
1. Team score (maximum 6)	3.3	4.4	4.6	$U = 34$**	$U = 26$***	$U = 66$
2. Team knowledge score (maximum 6)	3.4	4.5	4.8	$U = 41$*	$U = 30$**	$U = 66$
3. Situation knowledge score (maximum 6)	3.3	4.3	4.3	$U = 40$*	$U = 34$**	$U = 71$
4. Heterogeneous score (maximum 4)	2.3	3.3	3.4	$U = 34$**	$U = 28$**	$U = 64$
5. Similarity score (maximum 8)	2.0	2.9	2.8	$U = 36$**	$U = 41$*	$U = 72$
6. Similarity and accuracy score (maximum 8)	1.2	2.3	2.3	$U = 32$**	$U = 30$**	$U = 64$

Note. *$p < .10$, **$p < .05$, ***$p < .01$

Communication

The verbal communication that took place in the unrestricted condition was classified into the categories as described in section 4.3.1 (see Table 4.10). The scores can be found in Table 8.4. With respect to the amount of communication in each category, an analysis of variance was performed to test the differences between Session 1 and 2 of the unrestricted condition, and the partial and the unrestricted condition in Session 1.

Table 8.4: Verbal communication; mean number of statements for each team for Session 1 in the partial restricted and the unrestricted condition as well as for Session 2 in the unrestricted condition

Condition / Communication	Partial restricted Session 1	Unrestricted Session 1	Unrestricted Session 2	Partial restricted vs. unrestricted $F(1,22)$	Unrestricted Session 1 vs. 2 $F(1,22)$
Information Exchange	250	278	282	< 1	< 1
Performance monitoring	90	112	109	= 1.03	< 1
Evaluation	90	119	129	= 2.33	< 1
Determining strategies	19	19	14	< 1	< 1
Team Knowledge	69	83	36	< 1	= 6.81**
Situation knowledge	44	48	25	< 1	= 5.49**
Remaining	40	55	72	= 1.02	< 1
Total	602	715	665	= 1.64	< 1

Note. **$p < .05$

As can be seen in Table 8.4, Hypothesis 2 is supported. Teams in the unrestricted condition communicated less concerning team knowledge in Session 2 than in Session 1. In contrast to our expectations, teams in the unrestricted condition communicated also less in Session 2 concerning situation knowledge than in Session 1. We tested post-hoc the differences between the partial restricted and the unrestricted condition in Session 1, to verify whether possible performance differences can be ascribed to differences in the communication during that session. As can be seen in Table 8.4, there are no differences between these conditions with respect to the communication.

The performance results were not in accordance with Hypothesis 7. One possible post-hoc explanation is that unrestricted communication may have distracted team members in performing their individual activities during high workload periods. Especially during high workload periods, implicit coordination is the mechanism to rely upon. Based on the task analysis of the fire-fighting task (see section 3.3) we determined that in Period 6 to 8, team members had to perform their activities under the highest time pressure when compared to the other periods. Therefore, we expect that the total amount of communication would decrease during these periods. For the teams in the unrestricted communication condition, we tested whether there were differences in the mean number of statements in low versus high workload periods in Session 2. The analysis of variance show that were no differences. Teams communicated as much in low (48 statements) as in high (60 statements) workload periods, $F(1,22) = 1.75$.

With respect to the standardized electronic messages, Hypothesis 3 predicted that in Session 2 teams in the partial condition coordinate more implicitly and therefore communicate more effectively and efficiently than teams in the restricted condition. An analysis of variance using repeated measures for each scenario was performed to test the differences between the conditions in the exchange of the messages in Session 2. The repeated measures design consisted of 16 scenarios. Exceptions were Measure 6 (percentage of questions answered) and 9 (time between request and answer) for which we performed an analysis of variance without repeated measures. This was done because in several scenarios team members did not provide answers, which resulted in several missing values. The results of the analysis are shown in Table 8.5 in which the means for each scenario can be found.

Table 8.5: Standardized electronic messages; communication results for the restricted and the partial restricted condition in Session 2

Communication measure:	Restricted	Partial restricted	*F*-value
1. Number of messages	26	21	$F(1,22) = 2.90$*
2. Percentage necessary messages sent of the total number of messages that was sent	60	75	$F(1,22) = 5.69$**
3. Percentage necessary messages sent of the total number of necessary messages that could be sent	56	55	$F(1,22) < 1$
4. Number of necessary messages provided in advance of requests	14	15	$F(1,22) < 1$
5. Number of questions asked	3	1	$F(1,22) = 3.48$*
6. Percentage questions answered	82	69	$F(1,17) = 1.69$
7. Percentage necessary messages sent *in one period* of the total number of necessary messages that could be sent	48	45	$F(1,22) < 1$
8. Percentage necessary messages sent *in two periods* of the total number of necessary messages that could be sent	49	47	$F(1,22) < 1$
9. Time between request and answer (seconds)	15	14	$F(1,17) < 1$

Note. *$p < .10$, **$p < .05$

Hypothesis 3 is partially supported by the results. As can be seen in Table 8.5, there is a tendency for teams in the partial restricted condition to send fewer messages than the teams in the restricted condition. The percentage of necessary messages was higher in the partial restricted condition. Finally, there is a tendency for teams in the partial restricted condition to ask fewer questions than the teams in the restricted condition. Taken together, the results show that in Session 2, the teams in the partial restricted condition exchanged their messages slightly more effective and efficient than the teams in the restricted condition.

Hypothesis 4 predicted that the teams in the partial restricted condition exchange more often the necessary information in time than the teams in the restricted condition. In each scenario, teams could be either in time or too late with sending and receiving the message about the large building in danger (i.e., when the message was not sent at all, this was considered as too late). The scores can be found in Table 8.6.

Table 8.6: Standardized electronic messages; communication result of the total number of scenarios in which team members were in time with sending and reading the message about the large building in danger for each condition and scenario type (N = 768)

Condition	Session	Message	
		In time	Too late
Restricted	1	90	102
	2	72	120
Partial restricted	1	96	96
	2	104	88

We fitted three log-linear models to the data. The first model included the general mean and the design (i.e., timeliness, condition * scenario type). The second model included the general mean and the design and the main effect of condition (i.e., timeliness, condition * scenario type, condition * timeliness). For both models, Pearson's Chi^2 was calculated. To test the main effect of condition, the Chi^2 of the first model minus the Chi^2 of the second model was tested. The degrees of freedom for this test were the ones of the first model minus the ones of the second model. The third model included the general mean and the design and the main effects of condition as well as scenario type (i.e., timeliness, condition * scenario type, condition * timeliness, scenariotype * timeliness). To test the interaction effect of condition and scenario type, the Chi^2 and the degrees of freedom of this model were tested. To test the differences between conditions on either Session 1 or 2, a Chi^2 for each separate two-way table was calculated and tested.

The results show that teams that communicated unrestrictedly in Session 1, were more often in time with sending and reading the message about the large building in danger (52%) than teams that communicated restrictedly (42%), $\chi^2(1, N = 768) = 7.44, p < .01$. There was a tendency for an interaction between condition and session, $\chi^2(1, N = 768) = 3.58$ $p < .10$. The interaction was as expected. The teams of the partial restricted condition were more often in time in Session 2 (54%) than teams in the restricted condition (38%), $\chi^2(1, N = 384) = 10.47, p < .01$, whereas in Session 1 there were no differences between the teams in the partial condition (50%) and the restricted condition (47%), $\chi^2(1, N = 384) < 1$. Taken together, the results support Hypothesis 4.

Hypothesis 5 predicted that teams in the unrestricted condition exchange more often the necessary information in time than teams in the partial restricted condition. In each scenario, teams could be either in time or too late (i.e., when the message was not sent at all, this was considered as too late). The scores can be found in Table 8.7. We fitted the same log-linear models on the data and followed the same procedure as with Hypothesis 4 to test Hypothesis 5.

Table 8.7: Standardized electronic messages; communication result of the total number of scenarios in which team members were in time with sending and reading the message about the large building in danger for each condition and scenario type ($N = 768$)

Condition	Session	Message	
		In time	Too late
Partial restricted	1	96	96
	2	104	88
Unrestricted	1	80	112
	2	78	114

In contrast to our expectations, the results show that the teams that communicated unrestrictedly in Session 1, were more often in time with sending and reading the message about the large building in danger (52%) than the teams that communicated unrestrictedly in Session 1 and 2 (41%), $\chi^2(1, N = 768) = 9.18$, $p < .01$. This difference became apparent in Session 2. In Session 1, there was no difference between the teams in the partial restricted condition (50%) and the unrestricted condition (42%), $\chi^2(1, N = 384) = 2.69$, whereas in Session 2, the teams in the partial restricted condition were more often in time (54%) than the teams in the unrestricted condition (41%), $\chi^2(1, N = 384) = 7.06$, $p < .01$. There was no interaction between condition and session, $\chi^2(1, N = 768) < 1$. Taken together, Hypothesis 5 is not supported.

Performance

In order to test Hypothesis 6 and 7, an analysis of variance using repeated measures for each scenario was performed. The repeated measure design consisted of two sessions with 16 scenarios each. For Session 1 and 2, a separate analysis was performed using repeated measures for each scenario. Because there were differences in the performance of teams on the training scenarios (the training was identical for all teams), the mean of the performance during the training (the 25 scenarios containing a pattern) was taken into account as covariate. The results are shown in Figure 8.2.

Hypothesis 6 predicted that the teams in the partial condition perform better than the teams in the restricted condition. The results support this hypothesis, $F(1,21) = 4.75$, $p < .05$. When both sessions are taken into account, teams in the partial restricted condition performed better (65%) than the teams in the restricted condition (60%). As expected, the performance improvement was most pronounced in Session 2. There was no difference between the conditions in Session 1, $F(1,21) = 1.85$, whereas in Session 2 there was a tendency for the teams in the partial restricted condition to perform better (69%) than the teams in the restricted condition (61%), $F(1,21) = 3.50$, $p < .10$. There was no significant interaction between condition and session, $F(1,21) < 1$.

Hypothesis 7 predicted that the teams in the unrestricted condition perform better than the teams in the partial restricted condition. The results show that this hypothesis received *no* support. When both sessions are taken into account, the teams in the unrestricted condition performed unexpectedly worse (55%) than teams in the partial restricted condition (65%), $F(1,21) = 5.09$, $p < .05$. There was no difference between the conditions in Session 1, $F(1,21) = 2.22$. There was, however, a significant difference between the conditions in Session 2, $F(1,21) = 6.34$, $p < .05$. As can be seen in Figure 8.2, teams in the unrestricted condition performed worse (57%) than teams in the partial restricted condition (69%). There was no significant interaction between condition and session, $F(1,21) < 1$.

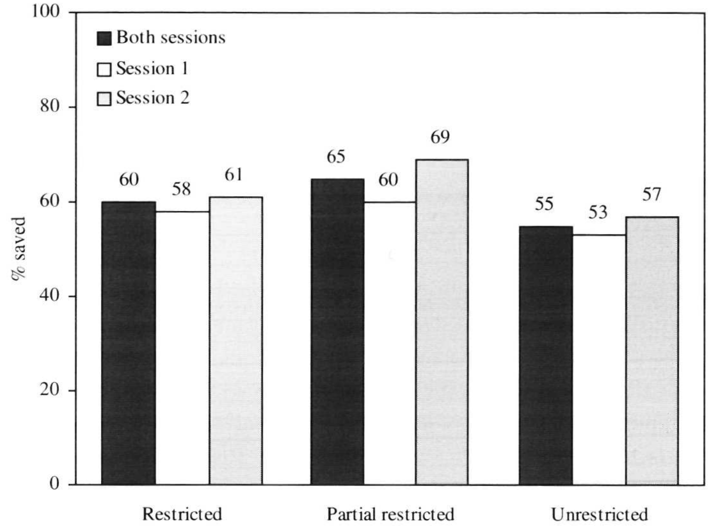

Figure 8.2: Mean percentage of potential casualties saved in the restricted, partial restricted, and the unrestricted condition for both sessions and the first and the second session separately

8.3 Discussion

The purpose of Experiment 6 was to determine whether unrestricted communication in teams is beneficial after a certain amount of time. Toward that end, we investigated teams in two successive sessions. Three conditions were developed in which teams could communicate unrestrictedly in none of the sessions, in Session 1 only, and in Session 1 and 2. The results confirm our hypothesis that teams that can communicate unrestrictedly in Session 1 perform better than teams that cannot communicate unrestrictedly at all. As expected, the difference between the conditions became apparent mainly during Session 2, although the teams in both conditions performed their tasks under identical conditions during that session.

We explain this result by team members using the communication in Session 1 to develop team and situation knowledge, which improves performance in Session 2. The communication scores show that teams indeed used their opportunity to communicate unrestrictedly to perform teamwork and transfer knowledge. Because team members could not communicate unrestrictedly in Session 2, team members had to coordinate implicitly to maintain their performance, indicating that they relied on their knowledge developed in Session 1. The analysis of the standardized messages that had to be exchanged electronically in Session 2, provides additional support for this explanation. Teams that communicated unrestrictedly in Session 1 were able to exchange the necessary information with fewer messages than the teams that communicated restrictedly. Moreover, these teams were more often in time with the provision of a crucial message needed to obtain a high performance. These are typical communication features of teams that coordinate implicitly. The explanation is also supported by the results of the knowledge questionnaire. Teams that communicated unrestrictedly in Session 1 had higher scores on the questionnaire, which indicate that they developed better team and situation knowledge.

We hypothesized further that unrestricted communication would be beneficial to preserve up-to-date knowledge of the changes that occur during task execution, and to perform teamwork that consists of performance monitoring, evaluation, and determining strategies. Therefore, we expected that teams that continue to communicate unrestrictedly in Session 2 would perform better than teams that cannot communicate unrestrictedly in Session 2. Surprisingly, this hypothesis is not supported. Teams that communicated unrestrictedly in Session 1 and 2 performed even *worse* than teams that communicated in Session 1 only. The results show further that the performance decrease became apparent in Session 2 and that teams were more often too late with the exchange of the crucial message in Session 2. In Session 1, there were no differences between the conditions. Performance and the scores of the unrestricted communication categories were similar and teams were equally in time with the exchange of necessary messages in Session 1. Based on this result it can be concluded that the benefit of communicating unrestrictedly is limited. Unrestricted communication does not seem to affect performance after time.

One explanation for this result is that communication does not have benefit once team and situation knowledge is developed. It is possible that the knowledge important for team functioning is already transferred in Session 1, so that unrestricted communication is no longer needed in Session 2. The communication scores show that in Session 1, teams communicated in the same manner. In both conditions, teams communicated in equal amounts in each category and transferred team and situation knowledge. Furthermore, the knowledge questionnaire indicates that in both conditions, team and situation knowledge is developed similarly. The communication scores additionally show that the teams that communicated unrestrictedly in both sessions, devoted less communication to the transfer of team and situation knowledge in Session 2 than in Session 1. Taken together, this indicates that the teams that communicated unrestrictedly in both sessions developed team and situation knowledge in Session 1 such that communication in Session 2 was not needed. However, given that in Session 2 the situation changed constantly and team members needed to inform each other of these changes, it is unlikely that situation knowledge is fully developed. Moreover, even when unrestricted communication was not needed to preserve up-to-date situation knowledge, this does not explain why performance decreased.

Another explanation is that unrestricted communication was not necessary to perform additional teamwork in Session 2. An important difference between the present experiment and Experiment 4 and 5 is that team members were better trained and worked together for a longer period. This may have caused that team members committed fewer errors and had better strategies. It is possible that the effect of unrestricted communication diminished in Session 2 because performance monitoring, evaluation, and determining strategies was not needed. However, because the situation changed constantly in Session 2, team members had to adjust their strategies to keep up their performance. The performance decrease of the teams that communicated unrestrictedly in Session 2 indicates that they were not able to adjust their strategies properly. In other words, whereas the need for unrestricted communication seems to be imperative, it did not help team members to improve their performance. A problem with this explanation is that it also does not explain why unrestricted communication even led to worse performance in Session 2.

An alternative explanation is that too much communication in periods with high workload distracted team members from executing their activities. Given that there are no differences between the conditions in Session 1 in the communication and performance, and that in both conditions knowledge was developed similarly, unrestricted communication is the only factor that influenced performance. The possibility that communication can be inefficient and disrupt the workflow during high workload periods or after critical, rare events, was also acknowledged by Johnston and Briggs (1968), Hutchins

(1992), and Hollenbeck et al. (1995). Partial support for this explanation was obtained in a post-hoc analysis of the communication data. This analysis showed that team members did not decrease their communication during the high workload periods in Session 2. Hence, team members did not adapt to the high workload periods and continued to communicate as if it were low workload periods. Whether the amount of communication was actually too high such that it distracted team members from their work in high workload periods, could not be determined based on the data of Experiment 6.

A problem with the interpretation of the results is the way the scenarios were presented during the experimental sessions. We presented teams with scenarios for which members needed different strategies than the ones learned during the training. Within each session, the scenarios were mixed such that team members received 11 scenarios of one type and five of another type. This way, team members were confronted with situations that were not strictly routine or novel. Moreover, because the scenarios changed constantly, it was difficult to determine the commonalties among the scenarios of one type and determine the best strategy for that type of scenarios. This situational uncertainty may have caused teams to engage in constant overt deliberation, which may actually have degraded performance during high workload periods.

Experiment 6 pointed to the potential costs of unrestricted communication. However, the lack of effect of unrestricted communication on performance in Session 2, should not overshadow the effect that did appear. Unrestricted communication fostered the development of members' team and situational knowledge, and performance improved for the teams that were forced to communicate unrestrictedly in Session 2. Based on the results of Experiment 6, we conclude that unrestricted communication is beneficial for the development of team and situation knowledge. Once this knowledge is developed, no additional effect of unrestricted communication could be obtained. This leads us to conclude that unrestricted communication is especially important at the beginning of a team's lifetime. After time, when team members are attuned to each other, unrestricted communication may not be needed. Instead, team members should minimize their communication and coordinate implicitly.

One exception may be if teams are confronted with novel situations. In that case, unrestricted communication is needed to preserve up-to-date knowledge of the changes in the situation. Unfortunately, due to the mixture of scenarios that were not strictly novel or routine, we were not able to investigate this in Experiment 6. Therefore, we performed a final experiment in which we separated the routine from the novel scenarios more clearly. In addition, we equipped team members with a team knowledge schema that describe each other's tasks and informational needs. Hence, we expected that team knowledge does not have to be developed and unrestricted communication would be especially, if not only, beneficial in novel situations. This way we attempted to investigate more decisively the effect of unrestricted communication on performance in novel situations. This experiment is described in the next chapter.

9 UNRESTRICTED COMMUNICATION AND PERFORMANCE IN ROUTINE VERSUS NOVEL SITUATIONS[2]

The final experiment of this thesis is described in this chapter. In this experiment, we continue to investigate the effect of unrestricted communication on performance. This time, we investigate whether unrestricted communication is needed when teams encounter novel situations. To investigate this question, we separated clearly routine from novel situations. We also equipped team members with a team knowledge schema that consisted of a brief description and graphical representation of each other's tasks, informational needs, and the times when information had to be exchanged. We expected that unrestricted communication would be especially beneficial in novel situations. Because all teams were equipped with the team knowledge schema, unrestricted communication was not needed to develop team knowledge in routine situations. The results support these expectations. Unrestricted communication improved performance in novel situations. In routine situations, however, unrestricted communication had no additional benefits for performance.

9.1 Introduction

The results of Experiment 6 show that, after communicating unrestrictedly in one session, unrestricted communication had a negative impact on performance in a following session. Performance, however, improved for the teams that were forced to communicate restrictedly and coordinate implicitly. An explanation for this result is that too much communication during high workload periods may have distracted team members to perform their individual taskwork accurately. We expected, however, that unrestricted communication would be beneficial because team members were confronted with a constantly changing situation. Unrestricted communication was expected to be needed to maintain up-to-date situation knowledge that supports team members in performing teamwork consisting of performance monitoring, evaluation, and determining strategies. One problem in interpreting the results of Experiment 6 was that the scenarios were mixed, in that they were neither strictly routine nor completely novel. Although we deliberately inserted novel scenarios in between the routine scenarios, the routine scenarios dominated. This may explain why we did not find a positive effect of communication. Thus, in order to examine the effect of unrestricted communication on performance in novel situations, we need to separate the routine from the novel scenarios more clearly. This is the objective of Experiment 7.

In Experiment 7, we also introduced a direct method to ensure that team members have team knowledge. We equipped team members with a *team knowledge schema* that we created based on the task analysis as described in chapter 3 (see section 3.3). The schema consisted of an A4 paper format with a simplified TOSD (see Figure 3.9 for an example). This represented team members' tasks, the information that had to be exchanged, and the exact periods in which tasks had to be performed and information had to be exchanged. Thus, the schema represented important team knowledge in detail. Team members' tasks and informational needs within the task sequence when this information was

[2] The research described in this chapter was supported by Thales Nederland (formerly known as Hollandse Signaalapparaten B.V., Contract No. 961125)

needed. We expected that, with the help of this schema, unrestricted communication would improve team performance especially when team members encounter novel situations. The reason is that communication is not needed to the same extent to develop team knowledge (as this knowledge could be obtained from the schema). However, in novel situations, communication is needed to maintain up-to-date situation knowledge (and the schema provided no guidance in this respect).

By clearly separating routine from novel situations and equipping team members with a team knowledge schema, we attempt to investigate the effect of unrestricted communication on performance in novel situations. Teams must perform the experimental task in two sessions: one with routine and the other with novel scenarios. The effect of unrestricted communication is investigated by comparing teams that had or had no opportunity to communicate unrestrictedly. The attended reader might notice that the present experimental design is similar to the one of Experiment 4 (see chapter 7). However, there are three important differences. First, in contrast to Experiment 4, teams are equipped with a team knowledge schema in Experiment 7. This way we attempted to ensure that in both conditions team knowledge is equally present, so that the effect of unrestricted communication must be ascribed to the maintenance of up-to-date situation knowledge and determining strategies jointly. Second, we used the same experimental task as in Experiment 6, in which the performance feedback and, therefore the training, was improved as compared to Experiment 4. Third, teams work together for a longer period (i.e., two sessions of 16 scenarios in contrast to one session of 16 scenarios). Altogether, we attempted to design Experiment 7 such that we could investigate the effect of unrestricted communication on performance in novel situations. Turning back to the second research question of this thesis, this should give more insight under which conditions unrestricted communication is beneficial for performance.

9.2 Experiment 7

9.2.1 Hypotheses

Experiment 7 addresses the question whether unrestricted communication improves performance when teams encounter novel situations. A comparison is made between teams that can communicate unrestrictedly and teams that cannot. Figure 9.1 represents the dimensions (denoted by the gray boxes) and the relationship (denoted by the uninterrupted line) under investigation in Experiment 7.

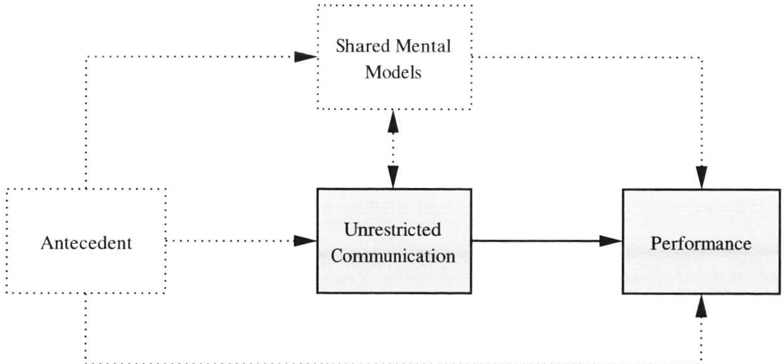

Figure 9.1: Hypothesized relationship between unrestricted communication and performance under investigation in Experiment 7

We attribute the expected performance improvement in novel situations to unrestricted communication that supports the development of situation knowledge and, in turn, how team members determine strategies. Therefore, we expect that teams in the unrestricted condition will transfer more situation knowledge and determine more strategies in novel than in routine situations. We classified the verbal communication into the same categories as in Experiment 4 to 6. The categories and their definitions can be found in chapter 4 (see section 4.3.1, Table 4.10). We do not expect changes in the communication in the categories: information exchange, performance monitoring, evaluation, and team knowledge. With respect to the category team knowledge, this knowledge remains applicable in routine as well as novel situations. With respect to the other categories, we expect no differences because the novelty of scenarios has no influence upon team members' taskwork, the number of tasks, or potential errors team members might commit in their taskwork. Given that the situation is different in novel situations than in routine situations, and that team members must adjust their strategies to cope with these situations, we do expect that unrestricted communication in the categories *situation knowledge* and *determining strategies* is more needed in novel than in routine situations. Therefore, the following hypotheses are put forward:

1. We expect that the teams that can communicate unrestrictedly communicate more concerning situation knowledge in novel situations than in routine situations
2. We expect that the teams that can communicate unrestrictedly communicate more concerning determining strategies in novel situations than in routine situations

One piece of necessary information must always be exchanged by the standardized electronic messages (regardless of the opportunity to communicate unrestrictedly). By measuring the number and timing of this message, we could determine the team's ability to exchange the necessary information within the teammate's task sequence when it is needed. The exchange of this message depends largely on the strategies team members have developed. If team members are able to develop accurate situation knowledge of the novel situation and to determine the right strategy, then team members are able to send this message in time. The team knowledge schema, provided to the teams in *both* conditions, describe explicitly when this message must be send. Thus, in routine as well in novel situations, this schema describes explicitly what information must be exchanged when (i.e., team knowledge). In novel situations, however, other strategies than the ones learned during training are needed to obtain this information (before being exchanged among members). In other words, sending this message in time in novel situations depends on team members' strategies. The better the strategies, the more team members are able to send this message in time. To test whether teams that can communicate unrestrictedly are better in the timely exchange of necessary information than teams that cannot communicate unrestrictedly, the following hypothesis is put forward:

3. We expect that the teams that can communicate unrestrictedly exchange more often the necessary information in time than the teams that cannot communicate unrestrictedly; this communication improvement will be more pronounced in novel scenarios

Because we expect that performance improves because of unrestricted communication, the following hypothesis is put forward:

4. We expect that the teams in the unrestricted condition perform better than the teams in the restricted condition; this performance improvement will be more pronounced in novel scenarios

9.2.2 Method

Participants

The data for Experiment 7 were obtained from 80 students of Utrecht University in 40 teams of two participants. Men and women were equally represented (40 male and 40 female). Each team consisted of two male or two female participants. In each of the two conditions, 10 male and 10 female teams performed the task. Participants that formed the team were not acquainted to each other. The participants were paid Dfl. 60, = for their contribution.

Design

Between teams. In order to test the hypotheses, two experimental conditions were designed: the *restricted* and the *unrestricted* condition.

Within teams. The presence of novel situations was a within teams manipulation. In both conditions, 10 teams started with a session of 16 routine scenarios and ended with a session of 16 novel scenarios, while 10 teams started with a session of 16 novel scenarios and ended with a session of 16 routine scenarios. The reason for using this balanced design is that when teams start with routine scenarios, a possible effect during novel scenarios could be diminished as a result of learning.

Task

In Experiment 7, Version 3 of the fire-fighting task as described in section 3.3.2 was used.

Manipulation

In the restricted condition, teams could exchange the necessary information by sending and receiving the standardized electronic messages. Team members were placed in separate soundproof rooms and verbal communication was not possible at all. In the unrestricted condition, team members could communicate unrestrictedly in addition to sending and receiving the standardized electronic messages. Unrestricted communication was made possible by giving team members the opportunity to communicate verbally both during and between scenarios. Team members were placed in separate soundproof rooms and verbal communication was made possible via headsets.

Scenario type was manipulated as follows. In the routine scenarios, the pattern in a series of small fires predicted the large building in danger as learned during the training. For example, team members could predict a fire in a hospital in sector IV when they recognized the pattern of small fires that consisted of "apartment building-house-apartment building" in sector I. In novel scenarios, the large fire was set on fire in another section and building than team members would expect based on the pattern in a series of small fires they learned in their training. If, for instance, a hospital was expected in the diagonally opposite section, a factory would be in danger above or beneath the section in which there were three sequential fires.

Measures

Communication. The verbal communication was recorded on tape. Two coders analyzed the communication from tape by classifying each statement of the team members into categories. The categories were derived from the model we developed based on the cognitive team task analysis of chapter 4 (see section 4.3.1, Table 4.10). We added one category in which the coders rated the remaining statements that could not be classified because they were not task related or unclear. For each team, each scenario, and the time between the scenarios the communication was rated. Independently from the first coder, the second coder rated the tapes in the same way. For each session, the second coder rated the communication of two randomly chosen scenarios for each team (in total 80 scenarios with a total duration of approximately 240 minutes). For these scenarios, an agreement level of the two coders was determined by the percentage of statements that the coders rated in the same category. With respect to the scenarios that both coders rated, the agreement level was 79%. This was considered sufficiently high such that the data obtained from the first coder (the one that scored all scenarios for all teams) were used for further analysis.

The standardized electronic messages were time-stamped and saved in a computer log file for analyses. We measured the percentage of scenarios in which the message of the large building in danger was sent and read in time. Regardless of the opportunity to communicate unrestrictedly, team members had to send this message electronically to accomplish the tasks. Therefore, we could use this measure to determine whether there are differences between the conditions with respect to the provision of necessary information on the time in the teammate's task sequence that this information is needed. Besides that this is an important measure of implicit coordination, which indicates whether team members have team knowledge, this measures also whether teams have developed the appropriate strategies.

Performance. Performance was measured by the percentage of casualties saved out of the total number of potential casualties that could be saved in a scenario.

Procedure

An experimenter assigned the participants randomly to the role of dispatcher and observer and told them to read the instruction. Participants were placed in separate soundproof rooms and communication between the participants was made possible by sending and receiving the standardized electronic messages. They were told not to speak to each other about the experiment and the experimenter was always present in situations where participants were together in the same space. Participants were allowed to ask questions at any point during reading.

The instruction first explained the fire-fighting task in general, followed by instructions specific for each role. This included a systematic instruction on how to manipulate the interface, accompanied by small tasks that had to be carried out by the participants. Subsequently, there was a training session of five scenarios. After this first training session, participants were asked to continue to read the instruction. In this instruction, it was explained how participants could predict, based on a pattern in a series of small fires, the location, type, and time of a large fire later in the scenario. These instructions were followed by another training session of five scenarios that contained such a pattern in a series of fires. In this session, participants had the team knowledge schema at their disposal.

After the training, two experimental sessions of 16 scenarios each started. In each session, participants were presented with 16 scenarios that existed of 11 periods of 15 seconds each. In total, an experimental session lasted about four hours.

9.2.3 Results

Communication

The verbal communication that took place in the unrestricted condition was classified into the categories as described in section 4.3.1 (see Table 4.10). The scores can be found in Table 9.1. With respect to the amount of communication in each category, an analysis of variance was used to test the differences between the routine and novel session in the unrestricted condition.

Table 9.1: Verbal communication; mean number of statements for each team for the routine and the novel session in the unrestricted condition

Communication	Routine Session	Novel Session	$F(1,38)$
Information Exchange	212	185	= 1.09
Performance monitoring	92	80	= 1.19
Evaluation	40	37	< 1
Determining strategies	16	28	= 4.79**
Team Knowledge	26	26	< 1
Situation knowledge	26	39	= 5.25**
Remaining	18	19	< 1
Total	430	413	< 1

Note. $^{**}p < .05$

Hypothesis 1 and 2 predicted that team members in the unrestricted condition would communicate more concerning situation knowledge and determining strategies in the novel than in the routine session. As can be seen in Table 9.1 both hypotheses are supported.

With respect to the standardized electronic messages, Hypothesis 3 predicted that the teams in the unrestricted communication exchange more often the necessary information in time than the teams in the restricted condition. In each scenario, teams could be either in time or too late with sending and receiving the message about the large building in danger (i.e., when the message was not sent at all, this was considered as too late). The scores can be found in Table 9.2.

Table 9.2: Standardized electronic messages; communication result of the total number of scenarios in which team members were in time with sending and reading the message about the large building in danger for each condition and scenario type (N = 1280)

Condition	Scenario type	Message	
		In time	Too late
Restricted	Routine	282	38
	Novel	117	203
Unrestricted	Routine	294	26
	Novel	168	152

We fitted three log-linear models to the data. The first model included the general mean and the design (i.e., timeliness, condition * scenario type). The second model included the general mean and the design and the main effect of condition (i.e., timeliness, condition * scenario type, condition * timeliness). For both models, Pearson's Chi^2 was calculated. To test the main effect of condition, the Chi^2 of the first model minus the Chi^2 of the second model was tested. The degrees of freedom for this test were the ones of the first model minus the ones of the second model. The third model included the general mean and the design and the main effects of condition as well as scenario type (i.e., timeliness, condition * scenario type, condition * timeliness, scenariotype * timeliness). To test the interaction effect of condition and scenario type, the Chi^2 and the degrees of freedom of this model were tested. To test the differences between conditions on either the routine or novel scenarios, a Chi^2 for each separate two-way table was calculated and tested.

The results support Hypothesis 3. Teams that communicated unrestrictedly were more often in time with sending and reading the message about the large building in danger (72%) than the teams that communicated restrictedly (62%), $\chi^2(1, N = 1280) = 15.12, p < .01$. In the routine scenarios there was no difference between the unrestricted (92%) and the restricted condition (88%), $\chi^2(1, N = 640) = 2.50$. In the novel scenarios, however, teams of the unrestricted condition were more often in time (53%) than teams in the restricted condition (37%), $\chi^2(1, N = 640) = 16.45$, $p < 01$. There was no interaction between condition and scenario type, $\chi^2(1, N = 1280) < 1$.

Performance

In order to test Hypothesis 4, an analysis of variance using repeated measures for each scenario was performed. The repeated measure design consisted of two sessions with 16 scenarios each. For the routine and the novel sessions, a separate analysis was performed using repeated measures for each scenario. Because there were differences in the performance of teams on the training scenarios (the training was identical for all teams), the mean of the performance during the training (the five scenarios containing a pattern) was taken into account as covariate. The results are shown in Figure 9.2.

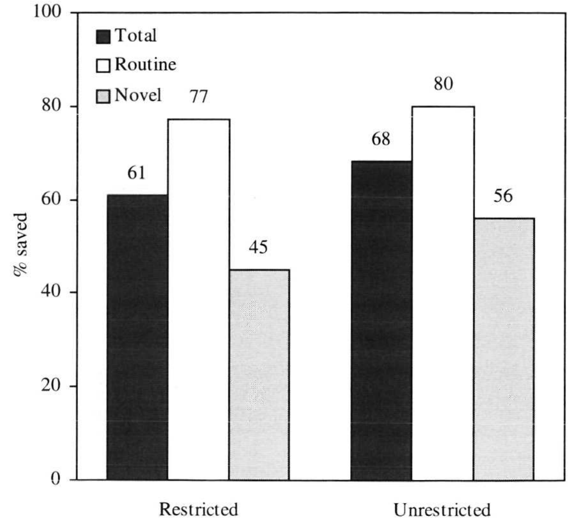

Figure 9.2: Mean percentage of potential casualties saved in the restricted and the unrestricted condition for both sessions and the routine and novel session separately

Hypothesis 4 predicted that teams in the unrestricted condition perform better than teams in the partial restricted condition. The results support this hypothesis, $F(1,37) = 4.75$, $p < .05$. When both sessions are taken into account, teams in the unrestricted condition performed better (68%) than the teams in the restricted condition (61%). As expected, the performance improvement was most pronounced in the novel session. There was no difference between the conditions in the routine session, $F(1,37) < 1$, whereas in the novel session the teams in the unrestricted restricted condition performed better (56%) than the teams in the restricted condition (45%), $F(1,37) = 6.08$, $p < .05$. There was no significant interaction between condition and session, $F(1,37) < 1$.

9.3 Discussion

Experiment 7 was performed to investigate whether unrestricted communication improves performance when teams encounter novel situations. Therefore, we compared teams that could communicate unrestrictedly with teams that could not. In both conditions, teams were presented with routine as well as novel situations and we equipped teams with a team knowledge schema. The team knowledge schema was provided to ensure that in both conditions team knowledge was equally present. For that reason, we expected that unrestricted communication was not needed to develop team knowledge. We expected also that, in routine situations, unrestricted communication was not needed to maintain up-to-date situation knowledge and determine strategies together. In routine situations, team members could apply their strategies as learned in the training. In novel situations, however, we expected that unrestricted communication would improve performance because it helps to maintain up-to-date shared situation knowledge that, in turn, supports team members in performance monitoring, evaluation, and determining strategies jointly.

The results supported the hypothesis that teams that communicated unrestrictedly perform better than teams that did not communicate unrestrictedly. As expected this performance increase became apparent in novel situations, whereas in routine situations unrestricted communication had no additional value. The communication scores additionally show that teams in the unrestricted condition transferred more situation knowledge in novel situations than in routine situations. This indicates that team members maintain up-to-date knowledge concerning the situation. Based on this knowledge team members could determine strategies together by making suggestions, providing alternative explanations, employing their expertise, generating and testing hypothesis, and offering information relevant for that situation. The communication scores also show that teams did this more often in novel than in routine situations. Finally, with respect to the standardized electronic message exchange, the results show that the teams in the unrestricted condition were more often in time with sending the crucial message than the teams in the unrestricted condition. This indicates that the teams that communicated unrestrictedly indeed developed better strategies than the teams that did not communicate unrestrictedly.

In Experiment 6, a negative effect of unrestricted communication was found, whereas in Experiment 7, unrestricted communication had no negative effect on performance. As mentioned in the discussion of Experiment 6, these apparently discrepant results can be reconciled by noting that the scenarios in Experiment 6 consisted of a mix of routine and novel situations. In that case, there was too much of a good thing. Team members communicated too much about the changing situation, particularly during the most hectic periods in their task performance. In Experiment 7, the routine scenarios evolved as expected from the training sessions, and there was no need to communicate unrestrictedly. Therefore, there was no interference with task performance, and teams performed no better and no worse than those teams that were unable to communicate unrestrictedly.

In constantly changing situations, such as on aircraft carriers (Rochlin et al., 1987), constant overt communication may be required to keep team members up-to-date. This corroborates our results on the value of unrestricted communication in novel situations in Experiment 7. Nevertheless, when teams are confronted with a mixture of routine and novel situations such as in Experiment 6, communication may have a negative impact on team performance. This situational uncertainty causes teams to engage in constant overt deliberation, which may actually degrade performance during high workload periods. One important teamwork skill is therefore, knowing when to communicate.

10 CONCLUSIONS AND DISCUSSION

In this final chapter, we summarize the results of this thesis and draw several conclusions. Subsequently, we discuss the theoretical implications, which includes a brief discussion about the shared mental model construct. This is followed by the limitations as well as the strengths of the research described in this thesis. The chapter finishes with several practical implications of our work.

10.1 Summary and conclusions

In teams that have to perform in time-pressured situations, communication can be problematic because there is too little time to communicate or it distracts members from performing their taskwork. Therefore, researchers assert that performance improves when teams *limit* their communication (Cannon-Bowers et al., 1998; Kleinman & Serfaty, 1989; Stout et al., 1999). However, communication in teams may be necessary to develop team and situation knowledge in shared mental models. In turn, this supports team members in coordinating implicitly, and performing additional teamwork such as performance monitoring, evaluation, and determining strategies together. Especially in rapidly changing or novel situations, communication may be needed to develop common knowledge that is up-to-date with the changes in the situation. Therefore, researchers assert that performance improves when teams *expand* their communication (Blickensderfer et al., 1997b; Orasanu, 1993; Rochlin et al., 1987; Seifert & Hutchins, 1992; Stout et al., 1999). To determine what effective communication is, how it can be facilitated, and whether teams must limit or expand their communication, the main objective of this thesis was to investigate the relationship among communication and performance in teams.

The first research question of this thesis was: how can communication and performance be improved by fostering the knowledge team members have in their mental models? Toward that end, we employed two methods: cross training and the provision of team information. In Experiment 1 and 2 (see chapter 5), we provided teams with a cross training method in which members were trained in each other's tasks (i.e., positional rotation). In Experiment 3 (see chapter 6), we provided team members with information that contained explicit information about each other's tasks, the informational interdependencies among members, and the moments that information exchange is necessary. The purpose of these methods was to foster members' team knowledge that includes knowledge of each other's tasks and informational needs. We expected that this would support teams in coordinating implicitly, and therefore communicating efficiently and effectively by exchanging the necessary information only, in advance of requests, and on the moment in a teammate's task sequence when this is needed. In turn, we expected that these improved communications would result in better performance.

The second research question of this thesis was: how and when does communication improve performance by fostering the knowledge team members have in their mental models? In contrast to Experiment 1 to 3, we shifted our attention from the potential benefits of *limiting* the communication to the potential benefits of *expanding* the communication in Experiment 4 to 7. The experimental task we employed gave us the unique opportunity to manipulate communication between team members.

Because the necessary information could be exchanged by sending standardized electronic messages, we were able to create conditions in which teams communicated either restrictedly or unrestrictedly. In the restricted communication conditions, team members could exchange the necessary information by sending messages electronically. For one part, this forces team members to coordinate implicitly because it is not possible to communicate extensively about "who does what" or "which information must be exchanged when." Furthermore, it is also is not possible to transfer team or situation knowledge and to determine strategies together. For another part, teams could coordinate more implicitly by sending more often the necessary messages only, in advance of requests, and on the moment in the teammate's task sequence when this is needed. We expected that the better the team and situation knowledge in team members' mental models, the better teams could coordinate implicitly by sending the necessary messages in time.

In the unrestricted conditions, team members could communicate verbally, on top of the electronic message exchange. By giving teams the opportunity to communicate verbally or not, we could switch the communication literally "on" or "off." Because unrestricted communication enables teams to transfer team and situation knowledge and to perform teamwork that consists of performance monitoring, evaluation, and determining strategies, we expected that unrestricted communication would improve performance. In Experiment 4 and 5 (see chapter 7), we investigated whether performance improves when teams communicate unrestrictedly either during task execution, between task execution, or both. In Experiment 6 (see chapter 8), we investigated the effect of unrestricted communication over time. Although we expected that unrestricted communication would be beneficial for the reasons mentioned, it can be argued that the effect of unrestricted communication diminishes because team members have transferred, after time, all the knowledge important for shared mental models. Therefore we investigated the effect of unrestricted communication in two subsequent sessions in which teams could communicate unrestrictedly in 1) none of the sessions, 2) Session 1 only, or 3) both sessions. In Experiment 7 (see chapter 9), we investigated the effect of unrestricted communication in novel versus routine situations.

With respect to the first research question; training in each other's tasks or (i.e., positional rotation) did *not* improve communication or performance in Experiment 1 and 2. A plethora of explanations exists varying from methodological ones to explanations that question the assumed effectiveness of positional rotation. Most important is that positional rotation is *not* an effective method to provide team members with the knowledge needed to develop an understanding of what information must be exchanged at what moments. Although positional rotation may acquaint team members with each other's tasks and system, thorough team knowledge may not be developed. Therefore, an effect of cross training on communication and performance could not be obtained.

In Experiment 3, the results for the provision of team information were more promising. Teams that received team information needed less communication to exchange the same amount of necessary information than teams that did not receive team information. The results also show that the provision of team information fostered members' team knowledge. The scores on the questionnaire that measured this knowledge were also positively correlated to several communication measures. This indicates that the better the team knowledge, the better the communication. Despite these encouraging results, the provision of team information had no impact on performance. An explanation for this result is that another factor may have weighed more into performance: individual taskwork. Although team members improved their teamwork and communicated more efficiently and effectively, they failed to perform well on their taskwork. Therefore, the effectiveness of the provision of team information might be further improved when team members are fully skilled in their taskwork.

Taken Experiment 1 to 3 together, we conclude that we did not find the ideal method to improve communication *and* performance in teams. Given the sparse support for the assumed effect of training in each other's tasks, from our experiments as well as from the experiments of other researchers, we conclude that the effectiveness of this type of cross training method is questionable. Better results were obtained with training methods that are directly aimed at the development of team knowledge. In Experiment 3, this resulted in more efficient and effective communication, but not, surprisingly, better performance. Better results may be obtained when training methods are elaborated with hands-on practice. Not only a written instruction, but practice in a dynamic task environment with systematic feedback on members' teamwork. More work is needed to explore the impact of these types of training methods on communication and performance. For now, we demonstrated that the provision of team information is an effective method to improve communication and possibly performance given adequate taskwork.

With respect to the second research question, the results of Experiment 4 to 7 show that unrestricted communication improves performance, however, not in all conditions. In Experiment 4 and 5, unrestricted communication did improve performance. The communication analysis shows that team members transferred team and situation knowledge and performed teamwork that consisted of performance monitoring, evaluation, and determining strategies. Moreover, the teams that communicated unrestrictedly were more often in time with the provision of a crucial message than the teams that communicated restrictedly. This indicates that they had developed better team knowledge. They knew when in a teammate's task sequence necessary information had to be provided. The results show further that communicating unrestrictedly was more effective *during* than *between* task execution. We explained this by unrestricted communication during task execution allowing team members to monitor each other's performance, which enabled them to prevent each other from making errors.

That unrestricted communication can also have negative consequences for performance was shown in Experiment 6. In this experiment, team members were trained for a longer time, and investigated in two subsequent sessions. On the positive side, the knowledge questionnaire showed that members' team and situation knowledge was, as expected, better for the unrestricted than the restricted communicating teams. This indicates that unrestricted communication fosters team and situation knowledge. Furthermore, when team members communicated unrestrictedly in Session 1, performance increased, especially in Session 2 (when team members could not communicate unrestrictedly). Nevertheless, when teams could continue to communicate in Session 2, performance decreased. We think that too much communication in periods with high workload distracted team members from executing their activities. A post-hoc analysis of the verbal communication data showed that team members indeed did not adapt to high workload periods. They communicated as much in high as in low workload periods.

Taken together, Experiment 6 shows that, after communicating unrestrictedly in one session, unrestricted communication had a negative impact on performance in a following session, whereas performance improved for the teams that were forced to communicate restrictedly and coordinate implicitly. Based on this result we conclude that the effect of communicating unrestrictedly decreases after time. When teams have worked and practiced together for some time, team and situation knowledge is transferred that support members to act in sync. Because team members have developed team and situation knowledge, necessary information can be exchanged in time and without explicit communication.

A problem in interpreting the results of Experiment 6 was that the teams were presented with a mix of scenarios, in that they were neither strictly routine nor completely novel. This situational uncertainty may have caused teams to communicate extensively, which may have actually degraded the performance. Because team members could not perceive the commonalities among the various scenario types (because these were not present in the mix of scenarios), an optimal strategy could not be determined. To investigate whether unrestricted communication is beneficial in novel scenarios to preserve up-to-date situation knowledge, we separated clearly the routine from the novel situations in Experiment 7. We equipped team members also with a team knowledge schema to ensure that team knowledge was equally present. The results show that unrestricted communication improved performance during the novel scenarios, however, not during the routine scenarios. Based on this result, we conclude that when teams have developed sufficient team knowledge, unrestricted communication is needed in novel, however, not in routine situations.

Turning back to the second research question of this thesis, what can we conclude about the benefits of communication for performance? Based on Experiment 4 to 7, we conclude that communication is especially important in the beginning of a team's lifetime. Communication is beneficial to transfer team knowledge. It refines member's general team knowledge into specific procedural rules of what to communicate and when. Transferring situation knowledge is important to develop a compatible understanding of the situation. Based on this knowledge team members can effectively determine strategies together. In mature teams, where members have fully developed team and situation knowledge, teams should limit their communication as much as possible. In that case, performance can be maintained when team members exchange the necessary information on the moment in a teammate's task sequence when this information is needed.

This being said, however, we have seen that communication also has a positive impact on performance because it facilitates additional teamwork such as performance monitoring or determining strategies. For teams that perform in routine situations and are fully trained, communication is less important than for teams that are *not* fully trained or encounter novel situations. Hence, the answer to the question whether teams should communicate or not, cannot be easily answered with a simple yes or no. In general, we conclude that teams should limit their communication with respect to the fixed elements in team functioning. More precise, teams should a) not transfer team and situation knowledge in routine situations, b) not coordinate explicitly and communicate about "who does what" and "who needs what information and when," and c) not continuously request each other for information. Limiting this type of communication would leave team members free to perform their own tasks as well as they can. At the same time, this would leave as much spare communication capacity available for that type of communication that is important for performance. That is, for performance monitoring, evaluation, and determining strategies together and, only in changing or novel situations, to transfer situation knowledge.

The following list summarizes our conclusions:

1. Training in each other's tasks is not an effective method to improve communication and performance in teams (Experiment 1 and 2).
2. The provision of team information that consists of explicit information about each other's tasks, the informational interdependencies among members, and the moments that information exchange is necessary, is an effective method to improve communication in teams (Experiment 3).
3. Communication improves performance because it supports team members in developing team and situation knowledge and it facilitates teamwork that consists of performance monitoring, evaluation, and developing strategies (Experiment 4 and 5).
4. When teams have practiced for a longer time and have developed team and situation knowledge, communication has no positive impact on performance (Experiment 6).

5. Too much communication has a negative impact on performance because it distracts team members in performing their taskwork (Experiment 6).
6. When team members have team knowledge, unrestricted communication does not contribute to performance in routine situations. However, in novel situations, communication is needed to preserve up-to-date situation knowledge and to determine strategies together (Experiment 7).
7. Communication is especially important for teams that are in the beginning of their lifetime because it fosters the development of team and situation knowledge (Experiment 4 to 7).
8. Teams should limit their communication as much as possible. If there is spare room to communicate, communication should *not* be used to coordinate explicitly, but for performance monitoring, evaluation, and determining strategies together and, *only* in changing or novel situations, to transfer situation knowledge (Experiment 1 to 7).

10.2 Theoretical implications

10.2.1 Results of this thesis

In chapter 2 (see section 2.3.3), we presented a model in which we illustrated the relationships among the antecedents, shared mental models, team processes, and performance. To position our own work in the context of the other research in this field, we determined for each relationship to what extent we found empirical support in the experiments of this thesis. Figure 10.1 shows the model of chapter 2 again, elaborated with the dimensions we manipulated and measured in the experiments described in this thesis (denoted by italics). The relationships that are illustrated by the uninterrupted lines are supported by our results.

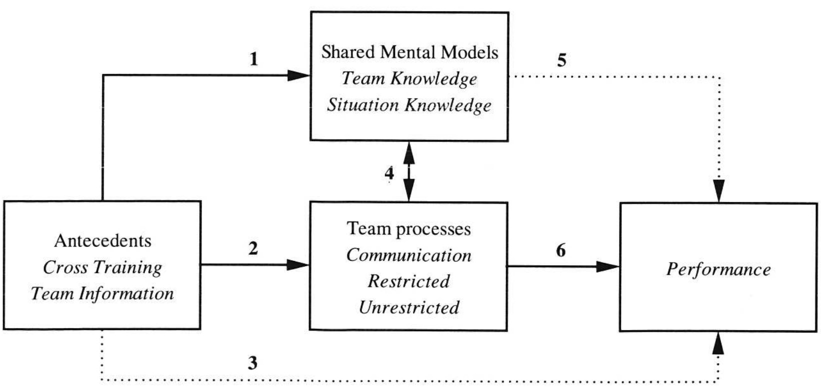

Figure 10.1: Shared mental model dimensions that were under investigation in this thesis (denoted by italics)

The results of Experiment 1 and 2 did not support the hypothesized positive relationships between cross training and communication (Relationship 2), or performance (Relationship 3). Because there was no measure of team member's knowledge or shared mental models in Experiment 1 and 2, no support can be given for the hypothesized positive relationship of cross training on team member's knowledge or shared mental models (Relationship 1). In Experiment 3, we did find support for Relationship 1 and 2. The provision of team information resulted in better team knowledge and more efficient and effective communication. However, Relationship 3 was not supported by the results of Experiment 5.

Performance was not influenced by the provision of team information. In sum, for one antecedent, namely the provision of team information, we found support for the hypothesized relationship between this particular antecedent, team knowledge, and team processes.

Relationship 4 to 6 are important with respect to the construct validity of shared mental models. Recall that the shared mental model theory states that the relationship among shared mental models and performance (Relationship 5) is mediated by team processes. In Experiment 5, we found support for Relationship 4. The better the team knowledge the more efficient and effective the communication. We also found support for the relationship between communication and performance. Exchanging the necessary information in time was positively associated with performance. Both results are in line with the shared mental model theory. However, we were not able to demonstrate statistically that the positive relationship between team knowledge and performance was mediated by communication.

The results of Experiment 4 to 7 show that the relationship among unrestricted communication and performance (Relationship 6) depends on the conditions in which teams perform. There is a positive relationship when teams are immature or perform in novel situations. In routine situations, unrestricted communication has no positive impact on performance. The results of Experiment 6 indicate that unrestricted communication may even lead to worse performance. Finally, as demonstrated qualitatively with the help of the verbal protocols in chapter 4 (see section 4.3.2), the results of Experiment 6 show that unrestricted communication resulted in better team and situation knowledge. Thus, our results provide support for Relationship 4, which states that unrestricted communication fosters team member's knowledge in mental models.

10.2.2 Shared mental model support

Placing our results in the bigger picture of the shared mental model research, several points can be made. With respect to Relationship 1 and 2, we conclude that the empirical support for this relationship is conflicting and limited. We already outlined the conflicting results with respect to cross training as antecedent of shared mental models. Furthermore, the experience of the members in the team as antecedent of shared mental models shows also conflicting results (Blickensderfer, 2000; Mathieu et al., 2000; Rentsch et al., 1994). Other antecedents such as team interaction training (Marks et al., 2000; Minionis et al., 1995), team planning (Stout et al., 1999), leader briefings (Marks et al., 2000) were positively associated with shared mental models. However, the shared mental model measurements vary highly across these studies. Taken together, it seems that researchers (ourselves included) do not yet exactly know how shared mental models can be manipulated.

When looking across the body of research that investigated Relationship 4 to 6, we conclude that the empirical support is again limited and conflicting. The effect of shared mental models on teamwork was established in two studies (Marks et al., 2000; Mathieu et al., 2000), however, not in another study (Cannon-Bowers et al., 1998). Conflicting is also the hypothesized positive effect of shared mental models on communication and implicit coordination. Although our study and that of Blickensderfer et al. (1997c) found support for this hypothesis, in the study of Cannon-Bowers et al. (1998) and Stout et al. (1999) this hypothesis was not supported. Moreover, so far, only one study has demonstrated that the relationship between shared mental models (concerning team knowledge) and performance is mediated by team processes (Mathieu et al., 2000).

Taken together, the shared mental model construct is a powerful construct to explain processes and performance in teams that work in time-pressured and dynamic situations. In this thesis, it explains when and how communication can be limited, and when and how communication must be expanded to obtain a good performance. By utilizing the shared mental model construct and therefore trying to open the "black box," researchers develop a better understanding of why antecedents such as particular training methods affect team processes, and, in turn, performance. Nevertheless, the current body of research does not allow one to reach closure on how shared mental models can be manipulated or measured, and how they operate. Researchers have employed such different interpretations and measurements of the construct, that we are not at all sure if any two authors mean the same thing when they use it. This is problematic. If we do not reach consensus on how to define the construct, and how to manipulate and measure shared mental models, the construct becomes meaningless and loses its explaining and predictive power. Despite its explaining and predictive power, we conclude that the empirical research so far yields no indisputable evidence for the existence and working of shared mental models.

Recent research does not seem to reconcile these problems. In the broader field of *shared cognition*, Cannon-Bowers and Salas (2001) also conclude that shared mental model-like constructs become meaningless if researchers will not become more consistent and exact in defining and measuring these constructs. Recently published work on shared mental model-like constructs, have addressed the interesting topic whether team members' mental models are more (or less) similar as result of various antecedents. These antecedents comprise experience and military rank (Smith-Jentsch, Campbell, Milanovich, & Reynolds, 2001), team composition, acquisition mode, and size (Rentsch & Klimoski, 2001), and team experience in a software development project (Levesque, Wilson, & Wholey, 2001). Although these studies partially address the sharedness issue (see below), this line of research does not provide new insights in how shared mental models influence team processes, and, in turn performance. Team processes were even not measured. Given that shared mental models were initially originated to explain and predict team processes and, in turn, performance, we believe that future research should concentrate more on these relationships.

A final issue we would like to discuss is whether *shared* means that knowledge is similar or distributed among team members. Based on the cognitive team task analysis described in chapter 4, we already concluded that this remains a difficult matter. It can be argued that commonly held knowledge of each other's tasks is important to understand why information must be exchanged and when. Similarly, it can be argued that commonly held team interaction knowledge is important to know when to provide *and* expect necessary information. Nevertheless, it can also be argued that it is sufficient when individual team members know simply what information must be exchanged and when. The results of Experiment 5 point to this latter argument. Communication improvements were obtained whereas the scores on the knowledge questionnaire show that this knowledge was distributed. For situation knowledge, the theory states that team members must have similar situation knowledge so that team members are allowed to determine strategies in a compatible manner. The cognitive team task analysis as well as the results of Experiment 6 support this view.

Keeping in mind the theoretical principle of parsimony, the question arises whether we need a multidimensional construct such as shared mental models to explain team processes. The shared mental model construct implies that team members not only have knowledge, but also that it is *shared* among team members and *organized* in a mental model. It can be argued that team processes can be explained more directly by knowledge that team members individually have about the team and the situation. With respect to the *sharedness* of knowledge, our results suggest that for a positive effect on communication, there is no need for members to have common team knowledge, whereas it is important that team members have common situation knowledge to determine strategies together. With respect to the *organization* of knowledge, our results do not lend themselves to draw conclusions. We had no measures that examined the possible organization of knowledge in mental models. Most studies in this field, however, assert that it is the organization of knowledge that counts (see, for example, Mathieu et al., 2000, p. 280) followed by content and the accuracy of team members' knowledge.

10.2.3 Directions for future research

Given what is said, where do we go from here with the shared mental model research? First, researchers might take a step back and examine the value of a mental model construct. The important question to answer is whether we need this construct to explain human behavior, or whether we can explain this simpler in terms of having specific knowledge. Second, researchers must develop a shared understanding of what is meant by shared mental models. There is much to be gained when researchers a) employ similar definitions of the knowledge content, b) measure the construct similarly, and c) have similar descriptions of how it operates. In that, researchers have to be very specific. Researchers not only have to be very clear in what knowledge is important, but also in what knowledge must be similar or distributed. Furthermore, researchers have to be more specific about the effect of shared mental models on team processes. Simply stating that shared mental models have a positive effect on teamwork is not very informative. What types of teamwork and how it is affected by shared mental models must be described more precisely. On the same token, researchers must be exact in what is measured. This goes for the shared mental model construct itself as well as the team processes.

For future experiments designed to investigate shared mental models, we recommend that these be preceded by a thorough cognitive team task analysis. Such an analysis helps to describe the interdependencies in a team, the teamwork, and the knowledge needed to perform effectively. Moreover, it describes conceptually whether knowledge is shared or distributed among members. This gives not only insight in how knowledge affects teamwork, but also what knowledge and teamwork should be measured. Subsequently, specific knowledge elements can be linked to the general knowledge elements that are expected to be important for shared mental models. To investigate which knowledge elements are the most important for team performance, various knowledge elements can be investigated one-by-one in relation to teamwork. Antecedents such as specific training methods or support aids can be used to foster different knowledge elements. To investigate the effect of common versus distributed knowledge one can attempt to provide team members with different knowledge than their teammates versus similar knowledge elements across members. Knowledge measurements should measure all aspects of shared mental models. That is, the content, extent of similarity, accuracy, and organization of knowledge. Questionnaires can be used for the knowledge content, whereas team interaction concept maps (Marks et al., 2000) can be used for the knowledge organization. Finally, teamwork should be described and measured explicitly. Thorough analysis and ratings of the communication provide a rich source for investigating teamwork.

Taken together, more work is needed to ensure that the shared mental model construct becomes a meaningful construct. We recommend that more empirical studies be conducted in which the sharedness, organization, content, and type of knowledge is systematically varied and examined in relation to communication and other teamwork behaviors. The recently developed measurements of shared mental models (Cooke et al., 2000b; Mohammed et al., 2000) and team processes must be refined and further incorporated. In doing that, researchers might think of those experiments that are designed not to find support, but to refute the shared mental model theory (Popper, 1963). If researchers fail to refute, we can be more confident that shared mental models are a valid construct. Up to now, the construct validity and usefulness of shared mental models remains questionable.

10.3 Limitations and strengths

The research reported in this thesis has several limitations. A first limitation is concerned with the theoretical framework of shared mental models. Although we rely heavily on the shared mental model theory in explaining most of our results, we inferred the existence of shared mental models mostly from team processes (communication) and output measures (performance). To put it even more bluntly: it can be stated that we did not capture shared mental models adequately. In that, the research described in this thesis reflects the developments of the research in the field of shared mental models. The research is in its formative stage and adequate measures of shared mental models are just beginning to come into use (see Mohammed et al., 2000). In the nineties, most research in the field of shared mental models was concerned with the conceptual development of the construct, defining teamwork competencies, and exploring how these competencies are affected by shared mental models. One of the first challenges for the empirical research in this area was to develop an adequate experimental task for teams. Developing networked simulations in order to create a complex and dynamic team task environment, which was needed to capture all dimensions of the shared mental model theory, was no sinecure (Weaver et al., 1995). Looking back, there is no doubt in saying that we made progress on several of these points. However, measuring shared mental models was not one of them.

Because we had no adequate measures of shared mental models, we cannot draw conclusions with respect to the way knowledge might have been organized. Nevertheless, we believe that our results do provide insight in team members' knowledge content. First, with the help of the cognitive team task analysis we examined conceptually what knowledge is needed to perform teamwork. Second, the existence of team and situation knowledge can be inferred from the communication and performance measures. Third, in two experiments we had questionnaires to measure team members' knowledge as part of their shared mental models. These three points partially reconcile the inadequacy of our shared mental model measures.

A second limitation is concerned with the mediating role of particular communication categories in the relationship among the communication conditions and performance in Experiment 4 to 7. We were not able to demonstrate that the theoretically relevant communication categories such as *performance monitoring* or *determining strategies* mediated more than the irrelevant communication category *remaining communication*. For Experiment 4 to 7, we correlated the number of statements in each category and the performance measure (i.e., percentage of casualties saved) for each condition, each experiment, and all experiments. We encountered two problems in interpreting these correlations. First, with respect to the correlations taken from several conditions (i.e., the ones for each experiment and all experiments together) the differences in the conditions interfered with a sound interpretation of these correlations. Second, with respect to the correlations taken from each condition the number of correlated items were small (i.e., varying from 11 to 20 pairs of items per condition). Naturally, these problems came into mind because the overall picture of correlations was rather puzzling. Many of the correlations were not significant and in some conditions certain communication categories were positively correlated with performance, whereas in other conditions these were negatively correlated. Taken together, we conclude that there is no linear relationship between (unrestricted) communication and performance. Rather, what seems to be more important than the volume of communication is the communication content. It can even be argued that the best teams are able to transfer knowledge and perform additional teamwork with a minimum of communication effort.

We can also think of several strengths with respect to the research described in this thesis. First, we experimentally investigated team processes in complex and dynamic conditions, rather than to perform observational studies in the field. Admittedly, we used a contrived team task, but this enabled us to control a lot of error variance, and to be able to investigate the effects of theoretically relevant variables. In our experimental approach, we also measured team processes directly by rating all communication into categories, whereas the majority of team research relies on self-reports, peer reviews, or questionnaires taken a posteriori. Together with the verbal protocols, this gives a better and more objective picture of the communication in teams. In general, the experimental approach and the direct communication measures supported us to gain a good insight in the causal relationships among the antecedents, shared mental models, team processes, and performance.

The second strength of the research reported here is that we explicitly described the knowledge, team processes, performance, and their relationships. While on the contrary most studies provide rather general descriptions of shared mental models and teamwork, we attempted to be very specific about that. Especially how shared mental models influence teamwork remains often unclear. Instead, we defined the knowledge important for shared mental models in chapter 2 (see section 2.3.1) which was linked to the knowledge needed to perform the teamwork in the experimental task in chapter 4. This was also linked to team processes that comprise the communication features of implicit coordination (see section 4.2.2, Table 4.7) as well as additional teamwork illustrated in a model in chapter 4 (see section 4.3.1, Figure 4.8). This way, we attempted to translate abstract concepts as shared mental models and teamwork into concrete descriptions and apply these to an actual team task.

The final strength we would like to point out is the integration of the research areas that are concerned with human factors and performance on the one hand and organizational behavior on the other hand. The human factors research is traditionally concerned with topics comprising individual processes such as man machine interface, decision making, workload, or human computer interaction. The majority of the studies use cognitive theory and modeling techniques to explain and predict performance with respect to individual taskwork. Conversely, the research from the field of organizational behavior is typically concerned with processes and performance of work groups in organizations. Major themes in this research are leadership, cohesion, group polarization, organizational culture, and so forth. Whereas in the one research field the unit of analysis is the individual, in the other field this is the team or the group. In the research described in this thesis, we attempted to integrate this by applying cognitive theory and models to processes measured on a team level. We believe that explaining team processes from a cognitive perspective is promising for future research.

10.4 Practical implications

The results of this thesis also have practical implications. We organized these around three themes: team design, team training, and team support.

10.4.1 Team design

Employing cognitive team task analysis

The first practical spin-off of our research is the development of a method for cognitive team task analysis that can be used for team design. Recent overviews in the areas of cognitive task analysis (Schraagen, Chipman, & Shalin, 2000) and team design (Schraagen, 2001) have pointed out the lack of methods for cognitive team tasks analysis and psychologically motivated principles for team design. The approach to cognitive team task analysis we employed in chapter 4 worked well and can be applied to more complex tasks. Given the potential costs of communication, our results would suggest designing for minimal communication interdependency among team members. Our approach to team task analysis helps to provide insight in this interdependency. The functional decomposition as described in chapter 3 not only involves the tasks, but also the information dependency between tasks. By assigning tasks to team member roles and present them sequentially in a TOSD, it can be easily determined on what moments and how often interaction is needed. Hence, the consequences of assigning tasks to team members in terms of interdependency become clear. With the help of TOSDs various task assignments can be compared, and the one with the lowest communication interdependency can be selected. The cognitive part of the analysis gives insight in the knowledge team members need for their taskwork and teamwork. This description guides the determination of what should be trained to perform effectively.

Future military naval command and control centers

Our results may also have implications for a major theme in future military naval command and control centers, which is the downsizing of the personnel (i.e., often mentioned figures for downsizing are from about 20 to five persons). In current command and control centers, tasks are often assigned such that there are members that perform tasks and others that supervise and monitor the task performance. Our results indicate that a team is more robust for errors when members can communicate freely to monitor each other's performance; members can provide feedback and correct each other's errors. Possible consequences of downsizing may be that there are no members left responsible for performance monitoring, or that the workload is too high to communicate at all. If downsizing of the personnel means that there are fewer opportunities for performance monitoring, then this may result in a performance decrease, particularly in novel situations. When assigning tasks to team members during team design, it must be taken into account that team members have the means and the time to monitor each other's performance.

One way to achieve that downsized teams have the same performance as their larger counter parts is to create a flexible team organization. With such an organization, teams are able to adapt to high workload periods by reassigning tasks from team members with high workload to team members with low workload. By backing up for each other's tasks, team members are able to keep the workload at acceptable levels for each team member. The consequence is, however, that member's team knowledge concerning "who does what and when" is not applicable any more. Our results suggest that, because the team organization changes and tasks are reassigned, communication is needed to preserve up-to-date team knowledge. In case of designing a flexible team organization, it must be taken into account that teams members need the time and opportunity to communicate freely.

10.4.2 Team training

Training taskwork and teamwork

In many areas such as the military, crisis management, fire fighting, and so forth, training is often geared to team member's individual taskwork. This may result in a team of experts, however, *not* in an expert team. The results of this thesis echo the research of many other studies; the success of teams depends on both taskwork *and* teamwork. For that reason, we recommend that if people must work in a team, training also includes teamwork. Team members must be learned how to communicate, coordinate, monitor each other's performance, and back each other up. A candidate for such a training is the Team Dimensional Training method developed by Smith-Jentsch et al., (1998b). This method is centered on the four ATOM teamwork behaviors (Smith-Jentsch et al., 1998a) that involves information exchange, communication, supportive behavior, and team leadership. A procedure is included that helps instructors not only to train teams, but also to diagnose their teamwork performance. By giving meaningful and exact feedback, using scoring schemas, individuals learn how to act as a team member.

Cross training

In the discussion of the main results of this thesis at the beginning of this chapter, we mentioned briefly some implications for team training. Given the sparse and conflicting empirical support for training in each other's tasks as a cross training method to foster team knowledge and improve communication, we do not recommend to train team members by means of positional rotation. An additional reason to refrain from this type of training is that in the real world, training in each other's tasks is long lasting and costly, especially for highly specialized functions. Our results indicate that a more fruitful training method is to explain team members directly a) what information must be exchanged, b) at what moments, c) and for what reason. To ensure that team members translate this from a conceptual notion into applicable procedural rules, additional practice might be needed. Based on our results, we believe that good results can be obtained when team members practice in a dynamic task environment with systematic and meaningful feedback about the way they exchange information.

10.4.3 Team support

Support systems

Communication can be limited when support systems are designed such that the necessary information is available to the team members who need it. Morrison, Kelly, Moore, and Hutchins (1998) evaluated a support system for naval command and control. They found that support systems that provide basic data and tactical information about tracks (such as location, status, kinematics, identity, and relative position) reduced the teams' need to request and provide this data verbally. Given the results of Experiment 6 (see chapter 7) that too much communication in periods with high workload may have distracted team members from executing their tasks, this might be highly beneficial. Moreover, when team members communicate less concerning the necessary data, more time is left for communication that can be used to preserve up-to-date situation knowledge. The study of Morrison et al. (1998) indicates that although team members communicated less concerning basic track data, they communicated proportionally more about critical contacts. This type of situation information may be important to share among team members to ensure that team members have a compatible approach in determining strategies.

An important means for team members to preserve up-to-date situation knowledge is to provide each other regularly with situation reports. In practice, however, these reports are often unstructured, incomplete, too long or too short, unclear or not given at all. It often depends on the individual capabilities of team members whether a situation report is successful or not. Because our results show that having up-to-date situation knowledge is important, a support system may be equipped with means to exchange important situation information among team members. For example, a team support system may be equipped with a window containing relevant and up-to-date situation information in a logical and structured order (see also Lenox, Hahn, Lewis, & Roth, 1999). The utilization of large screen displays in which relevant and up-to-date situation information is presented is another possibility for support.

Work-agreements

Besides support systems, teams can also be supported by using adequate procedures or making work-agreements. To prevent team members from communicating extensively about "who is responsible for what task" or "who needs what information and when," team members can make work-agreements before task execution (Rasker & Willeboordse, 2001). Teams can be guided in making work-agreements by providing a list of items that members can agree upon. Rasker and Willeboordse (2001) provide an example of such a list for naval command centers teams. This list includes items such as: what information must be passed and when, who is responsible for contacts on airways, who takes the small and who takes the large radar range, and so forth. We expect that work-agreements made before task execution result in less communication *during* task execution.

10.5 Concluding remarks

The research described in this thesis reveals and illustrates the benefits and costs of communication in teams that perform in time-pressured and dynamic situations. The results lead us to conclude that communication must be limited as much as possible. If teams have spare room left to communicate, teams should use this room for developing team and situation knowledge and performing additional teamwork consisting of performance monitoring, evaluation, and determining strategies. Developing team knowledge is especially important for immature teams. Once teams are experienced and have developed team knowledge, they should communicate only when encountering novel or rapidly changing situations. In that case, communication is important to preserve up-to-date shared knowledge of the changes in the situation.

We explained communication from a cognitive perspective in terms of shared mental models comprising team and situation knowledge. On that account, we have not investigated one-sidedly either team or cognitive processes but rather attempted to bring this together. We did not succeed totally. Based on the currently developed insight, we now acknowledge that our measurements of (shared) mental models could have been more adequate. Nevertheless, we managed to develop an experimental team task that contained the important psychological elements needed to investigate communication in teams as well as the theory of interest. In addition, we had direct measures of communication and performance. Finally, the cognitive team task analysis illustrates comprehensively how concepts operate in an actual team environment. Altogether, this gives a profound insight in cognitive and team processes, performance, and their relationships.

We advocate strongly that future research continue to relate team processes to cognitive theories and models. We expect that this approach will reveal theoretically new insights that account for team processes yet unexplained. Moreover, a good understanding in the cognitive functioning of team members supports researchers to develop adequate team training methods, design better team tasks, and adapt automation to team settings. This thesis offers results, methods, and insights that contribute to the present research and also provide a ground for future research investigating teams from a cognitive point of view. Altogether, these efforts support the continuous search of researchers to the factors that make a team successful.

REFERENCES

Adams, M. B. (1995). Functional analysis/ decomposition of closed-loop, real time work processes. *Proceedings of the AGARD mission system panel*, 1-10.

Annett, J. (1996). Recent developments in hierarchical task analysis. In S. A. Robertson (Ed.), *Contemporary Ergonomics* (pp. 262-268). London: Taylor & Francis.

Baker, D. P., & Salas, E. (1992). Principles for measuring teamwork skills. *Human Factors, 34*, 469-475.

Baker, D. P., Salas, E., & Cannon-Bowers, J. A. (1998). Team task analysis: Lost but hopefully not forgotten. *The industrial-organizational psychologist, 35*, 79-83.

Baron, R. M., & Kenny, D. A. (1986). The moderator-mediator variable distinction in social psychological research: Conceptual, strategic, and statistical considerations. *Journal of Personality and Social Psychology, 51*(6), 1173-1182.

Beevis, D., Bost, R., Döring, B., Nordø, E., Oberman, F., Papin, J. P., Schuffel, H., & Streets, D. (1992). *Analysis techniques for man-machine system design* (AC/ 243[Panel-8]TR/ 7). Brussels: NATO Defense Research Group.

Blickensderfer, E. L. (2000). *Role of experience and team knowledge in team processes and performance*. Unpublished doctoral dissertation, University of Central Florida, Florida.

Blickensderfer, E. L., Cannon-Bowers, J. A., & Salas, E. (1997a). Does overlap in team member knowledge predict team performance? Paper presented at the 41st Annual Meeting of the Human Factors and Ergonomics Society, Albuquerque, NM.

Blickensderfer, E. L., Cannon-Bowers, J. A., & Salas, E. (1997b). Fostering shared mental models through team self-correction: Theoretical bases and propositions. In M. M. Beyerlein, D. A. Johnson, & S. Beyerlein (Eds.), *Advances in interdisciplinary studies of work teams* (Vol. 4, pp. 249-279). Greenwich, CT: JAI.

Blickensderfer, E. L., Cannon-Bowers, J. A., & Salas, E. (1997c*). Training teams to self-correct: An empirical investigation*. Paper presented at the 12th Annual Meeting of the Society of Industrial and Organizational Psychology, St. Louis, MO.

Blickensderfer, E. L., Cannon-Bowers, J. A., & Salas, E. (1998a*). Assessing team shared knowledge: A field test and implications for team training*. Paper presented at the 42nd Annual Meeting of the Human Factors and Ergonomics Society, Chicago, IL.

Blickensderfer, E. L., Cannon-Bowers, J. A., & Salas, E. (1998b). Cross training and team performance. In J. A. Cannon-Bowers & E. Salas (Eds.), *Making decisions under stress: Implications for individual and team training* (pp. 299-311). Washington, DC: American Psychology Association.

Blickensderfer, E. L., Cannon-Bowers, J. A., Salas, E., & Baker, D. P. (2000). Analyzing knowledge requirements in team tasks. In J. M. C. Schraagen, S. F. Chipman, & V. L. Shalin (Eds.), *Cognitive task analysis* (pp. 431-447). Mahwah, NJ: Lawrence Erlbaum Associates.

Bonham, G. M., Shapiro, M. J., & Heradstveit, D. (1988). Group cognition: Using an oil policy game to validate a computer simulation. Simulation and games, 19, 379-407.

Bougon, M. G., Weick, K. E., & Binkhorst, D. (1977). Cognition in organizations: An analysis of the Utrecht Jazz Orchestra. *Administrative Science Quarterly, 26*, 606-639.

Bowers, C. A., Salas, E., Prince, C., & Brannick, M. T. (1992). Games teams play: A method for investigating team coordination and performance. *Behavior Research Methods, Instruments & Computers, 24*(4), 503-506.

Brannick, M. T., Prince, A., Prince, N., & Salas, E. (1995). The measurement of team process. *Human Factors, 37*, 641-651.

Brannick, M. T., Salas, E., & Prince, C. (1997). *Team performance assessment and measurement: Theories, Methods, and Applications*. Mahwah, NJ: Lawrence Erlbaum Associates.

Brehmer, B. (1992). Dynamic decision making: Human control of complex systems. *Acta Psychologica, 81*, 211-241.

Briggs, G. E., & Johnston, W. A. (1967). *Team training* (Tech. rep. 1327-4). Orlando, FL: Naval Training Device Center.

Briggs, G. E., & Naylor, J. C. (1965). Team versus individual training, training task fidelity, and task organization effects on transfer performance by three-man teams. *Journal of Applied Psychology, 49*(6), 387-392.

Brooks, A. (1994). Power and the production of knowledge: Collective team learning in work organizations. *Human Resource Development Quarterly, 5*, 213-235.

Burke, E. (1997). Psychological research and development in the London fire brigade. In R. Flin, E. Salas, M. Strub, & L. Martin (Eds.), *Decision making under stress: Emerging themes and applications* (pp. 116-125). Aldershot, UK: Asgate Publishing Company.

Cannon-Bowers, J. A., & Salas, E. (2001). Reflections on shared cognitions. *Journal of Organizational Behavior, 22*, 195-202.

Cannon-Bowers, J. A., Salas, E., Blickensderfer, E. L., & Bowers, C. A. (1998). The impact of cross training and workload on team functioning: A replication and extension of initial findings. *Human Factors, 40*(1), 92-101.

Cannon-Bowers, J. A., Salas, E., & Converse, S. A. (1993). Shared mental models in expert team decision making. In N. J. Castellan, Jr. (Ed.), *Individual and group decision making: Current issues* (pp. 221-246). Hillsdale, NJ: Lawrence Erlbaum Associates.

Cannon-Bowers, J. A., Tannenbaum, S. I., Salas, E., & Volpe, C. E. (1995). Defining competencies and establishing team training requirements. In R. A. Guzzo & E. Salas (Eds.), *Team effectiveness and decision making in organizations* (pp. 333-380). San Francisco: Jossey-Bass.

Converse, S. A., Cannon-Bowers, J. A., & Salas, E. (1991). Team member shared mental models: A theory and some methodological issues. *Proceedings of the Human Factors and Ergonomics Society 35th Annual Meeting*, 1417-1421.

Converse, S. A., & Kahler, S. E. (1992). *Knowledge acquisition and the measurement of shared mental models* (Unpublished manuscript). Orlando, FL: Naval Training System Center.

Cooke, N. J., Cannon-Bowers, J. A., Kiekel, P. A., Rivera, K., Stout, R. J., & Salas, E. (2000a). Improving teams' interpositional knowledge through cross training. Proceedings of the IEA 2000/ HFES 2000 Congress, 2/ 390-392/ 393.

Cooke, N. J., Salas, E., Cannon-Bowers, J. A., & Stout, R. J. (2000b). Measuring team knowledge. *Human Factors, 42*(1), 151-173.

Dickinson, T. L., & McIntyre, R. M. (1997). A conceptual framework for teamwork measurement. In M. T. Brannick & E. Salas & C. Prince (Eds.), *Team performance assessment and measurement: Theory, methods, and applications* (pp. 19-43). Mahwah, NJ: Lawrence Erlbaum Associates.

Driskell, J. E., & Salas, E. (1992a). Can you study real teams in contrived settings? The value of small group research: Toward an understanding of teams. In E. Salas & W. Swezey (Eds.), *Teams: Their training and performance* (pp. 101-123). Norwood, NJ: Ablex.

Driskell, J. E., & Salas, E. (1992b). Collective behavior and team performance. *Human Factors, 34*, 277-288.

Duffy, L. T. (1993). Team decision making and technology. In N. J. Castellan, Jr. (Ed.), *Individual and group decision making: Current issues* (pp. 247-266). Hillsdale, NJ: Lawrence Erlbaum Associates.

Dyer, J. L. (1984). Team research and team training: A state of the art review. In F. A. Muckler (Ed.), *Human Factors Review* (pp. 285-323). Santa Monica: The Human Factors Society.

Endsley, M. R. (1995). Toward a theory of situation awareness in dynamic systems. *Human Factors: Special issue on situation awareness, 1*, 32-64.

Entin, E. E., & Serfaty, D. (1999). Adaptive team coordination. *Human Factors, 41*(2), 312-325.

Essens, P. J. M. D., Post, W. M., & Rasker, P. C. (2000). Modeling a command center. In J. M. C. Schraagen, S. F. Chipman, & V. L. Shalin (Eds.), *Cognitive task analysis* (pp. 385-399). Mahwah, NJ: Lawrence Erlbaum Associates.

Fleishman, E. A., & Zaccaro, S. J. (1993). Toward a taxonomy of team performance functions. In W. Swezey & E. Salas (Eds.), *Teams: Their training and performance* (pp. 31-56). Norwood, NJ: Ablex.

Flin, R., Slaven, G., & Stewart, K. (1996). Emergency decision making in the offshore oil and gas industry. *Human Factors, 38*(2), 262-277.

Gladstein, D. (1987). Groups in a context: A model of task group effectiveness. *Administrative Science Quarterly, 29*, 499-517.

Guzzo, R. A. (1995). At the intersection of team effectiveness and decision making. In R. A. Guzzo & E. Salas (Eds.), *Team effectiveness and decision making in organizations* (pp. 1-8). San Francisco: Jossey-Bass.

Hackman, J. R. (1987). The design of work teams. In J. W. Lorsch (Ed.), *Handbook of organizational behavior* (pp. 315-342). Englewood Cliffs, NJ: Prentice-Hall.

Hackman, J. R., Brousseau, K. R., & Weiss, J. A. (1976). The interaction of task design and group performance strategies in determining group effectiveness. *Organizational Behavior and Human Performance, 16*, 350-365.

Heath, C., & Luff, P. (1992). Collaboration and control: crisis management and multimedia technology in London underground line control rooms. *Computer Supportive Cooperative Work (CSCW), 1*, 96-94.

Helmreich, R. L., & Foushee, H. C. (1993). Why crew resource management? Empirical and theoretical bases of human factors training in aviation. In E. L. Wiener, B. G. Kanki, & R. L. Helmreich (Eds.), *Cockpit Resource Management* (pp. 3-45). San Diego, SA: Academic.

Hollenbeck, J. R., Ilgen, D. R., Tuttle, D. B., & Sego, D. J. (1995). Team performance on monitoring tasks: An examination of decision errors in contexts requiring sustained attention. *Journal of Applied Psychology, 80*, 685-696.

Hollenbeck, J. R., Sego, D. J., Ilgen, D. R., Major, D. A., Hedlund, J., & Phillips, J. (1991). Team interactive decision exercise of teams incorporating distributed expertise (TIDE2): A program and paradigm for team research (Tech. Rep. RA 014-91-1). Arlington, VA: Office of Naval Research.

Howard, S. K., Gaba, D. M., Fish, K. J., Yang, G., & Sarnquist, H. (1992). Anesthesia crisis resource management training: Teaching anesthesiologists to handle critical incidents. *Aviation, Space, and Environmental Medicine, 1*, 763-770.

Hutchins, E. L. (1992). The technology of team navigation. In J. Galegher, R. E. Kraut, & C. Egido (Eds.), *Intellectual teamwork: Social and technological foundations of cooperative work* (pp. 191-220). Hillsdale, NJ: Lawrence Erlbaum Associates.

Jackson, S. E., May, K. E., & Whitney, K. (1995). Understanding the dynamics of diversity in decision-making teams. In R. A. Guzzo & E. Salas (Eds.), *Team effectiveness and decision making in organizations* (pp. 204-261). San Francisco: Jossey-Bass.

Johnson-Laird, P. (1987). *Mental models*. Cambridge, MA: Harvard University.

Johnston, W. A., & Briggs, G. E. (1968). Team performance as a function of team arrangement and workload. *Journal of Applied Psychology, 52*(2), 89-94.

Kanki, B. G., Greaud, V. A., & Irwin, C. M. (1991). Communication variations and aircrew performance. *International Journal of Aviation Psychology, 1*(2), 149-162.

Kerstholt, J. H. (1996). *Dynamic decision making*. Wageningen NL: Ponsen & Looijen.

Klein, G. A. (2000). Cognitive task analysis for teams. In J. M. C. Schraagen, S. F. Chipman, & V. L. Shalin (Eds.), *Cognitive task analysis* (pp. 417-429). Mahwah, NJ: Lawrence Erlbaum Associates.

Kleinman, D. L., & Serfaty, D. (1989). Team performance assessment in distributed decision making. In R. Gibson, J. P. Kincaid, & B. Goldiez (Eds.), *Proceedings of the Interactive Networked Simulation for Training Conference* (pp. 22-27). Orlando, FL: Naval Training System Center.

Klimoski, R. J., & Jones, R. G. (1995). Staffing for effective group decision making: Key issues in matching people and teams. In R. A. Guzzo & E. Salas (Eds.), *Team effectiveness and decision making in organizations* (pp. 291-332). San Francisco: Jossey-Bass.

Klimoski, R. J., & Mohammed, S. (1994). Team mental model: Construct or metaphor? *Journal of Management, 20*(2), 403-437.

Kohn, C., Kleinman, D. L., & Serfaty, D. (1987). Distributed resource allocation in a team. *Proceedings JDL symposium on Command and Control research*, 221-233.

Kozlowski, S. W. J. (1998). Developing adaptive teams. In J. A. Cannon-Bowers & E. Salas (Eds.), *Making decisions under stress: Implications for individual and team training* (pp. 115-153). Washington, DC: American Psychology Association.

Langan-Fox, J., Code, S., & Langfield-Smith, K. (2000). Team mental models: Techniques, methods, and analytic approaches. *Human Factors, 42*(2), 242-271.

Lanzetta, J. T., & Roby, T. B. (1960). The relationship between certain group process variables and group problem-solving efficiency. *The journal of social psychology, 52*, 135-148.

Lenox, T., Hahn, S., Lewis, M., & Roth, E. M. (1999). Improving performance: Should we support individuals or teams? *Proceedings of the Human Factors and Ergonomics Society 43rd Annual Meeting*, 223-227.

Levesque, L. L., Wilson, J. M., & Wholey, D. R. (2001). Cognitive divergence and shared mental models in software development project teams. *Journal of Organizational Behavior, 22*, 135-144.

Locke, E. A., & Latham, G. P. (1990). *A theory of goalsetting and task performance*. Englewood Cliffs, NJ: Prentice-Hall.

Marks, M. A. (1999). A test of the impact of collective efficacy in routine and novel performance environments. *Human Performance, 12*(3/ 4), 259-309.

Marks, M. A., Zaccaro, S. J., & Mathieu, J. E. (2000). Performance implications of leader briefings and team interaction training for team adaptation to novel environments. *Journal of Applied Psychology, 85*(6), 971-986.

Mathieu, J. E., Goodwin, G. F., Heffner, T. S., Salas, E., & Cannon-Bowers, J. A. (2000). The influence of shared mental models on team process and performance. *Journal of Applied Psychology, 85*(2), 273-283.

McCann, C., Baranski, J. V., Thompson, M. M., & Pigeau, R. A. (2000). On the utility of experiential cross training for team decision making under time stress. *Ergonomics special issue on teamwork, 43*(8), 1095-1110.

McIntyre, R. M., & Salas, E. (1995). Measuring and managing for team performance: Emerging principles from complex environments. In R. A. Guzzo & E. Salas (Eds.), *Team effectiveness and decision making in organizations* (pp. 9-45). San Francisco: Jossey-Bass.

Millitello, L. G., Kyne, M. M., Klein, G. A., Getchell, K., & Thordsen, M. (1999). A synthesized model of team performance. *International Journal of Cognitive Ergonomics, 3*(2), 131-158.

Minionis, D. P., Zaccaro, S. J., & Perez, R. (1995). *Shared mental models, team coordination, and team performance*. Paper presented at the 10th annual conference of the Society for Industrial and Organizational Psychology, Orlando, FL.

Mohammed, S. (1997). *Toward an understanding of the antecedents and consequences of shared frames in a decision-making context.* Paper presented at the Fifty-seventh Annual conference of the Academy of Management Meetings, Boston, MA.

Mohammed, S., & Dumville, B. C. (2001). Team mental models in a team knowledge framework: Expanding theory and measurement across disciplinary boundaries. *Journal of Organizational Behavior, 22*(2), 89-106.

Mohammed, S., Klimoski, R. J., & Rentsch, J. R. (2000). The measurement of team mental models: We have no shared schema. *Organizational research methods, 3*(2), 123-165.

Morgan, B. B., Jr., & Bowers, C. A. (1995). Teamwork stress: Implications for team decision making. In R. A. Guzzo & E. Salas (Eds.), *Team effectiveness and decision making in organizations* (pp. 262-290). San Francisco: Jossey-Bass.

Morrison, J. G., Kelly, R. T., Moore, R. A., & Hutchins, S. G. (1998). Implications of decision-making research for decision support and displays. In J. A. Cannon-Bowers & E. Salas (Eds.), *Making decisions under stress: Implications for individual and team training* (pp. 375-406). Washington, DC: American Psychology Association.

Nieva, V. F., Fleishman, E. A., & Reick, A. (1978). *Team dimensions: Their identity, their measurement, and their relationships.* Washington, DC: Response Analysis Corporation.

Norman, D. A. (1981). Some observations on mental models. In D. Gentner & A. L. Stevens (Eds.), *Mental models* (pp. 7-14). Hillsdale, NJ: Lawrence Erlbaum Associates.

Oliver, L. W., Harman, J., Hoover, E., Hayes, S. M., & Phandi, N. A. (1999). A quantitative integration of the military cohesion literature. *Military Psychology, 11*(1), 55-83.

Orasanu, J. (1990). *Shared mental models and crew decision making* (Tech. Rep. 46). Princeton, NJ: Princeton University, Cognitive Science.

Orasanu, J. (1993). Decision making in the cockpit. In E. L. Wiener, B. G. Kanki, & R. L. Helmreich (Eds.), *Cockpit Resource Management* (pp. 132-172). San Diego, SA: Academic.

Orasanu, J., & Connolly, T. (1993). The reinvention of decision making. In G. A. Klein, J. Orasanu, R. Calderwood, & C. A. Zsambok (Eds.), *Decision making in action: Models and methods* (pp. 3-20). Norwood, NJ: Ablex.

Orasanu, J., & Salas, E. (1993). Team decision making in complex environments. In G. A. Klein, J. Orasanu, R. Calderwood, & C. A. Zsambok (Eds.), *Decision making in action: Models and methods* (pp. 327-345). Norwood, NJ: Ablex.

Passenier, P. O., & Van Delft, J. H. (1997). The combat information center: The interface between warfare officers and sensor and weapon systems. *Proceedings of the 11th Ship's Control Systems symposium*, 237-249.

Popper, K. R. (1963). *Conjectures and refutations.* London: Routledge and Kegan Paul.

Post, W. M., Rasker, P. C., & Schraagen, J. M. C. (1997). *The role of communication and coordination in team decision making in a command & control task* (Report TM-97-B004). Soesterberg: TNO Human Factors.

Potter, S. S., Roth, E. M., Woods, D. D., & Elm, W. C. (2000). Bootstrapping multiple converging cognitive task analysis: Techniques for system design. In J. M. C. Schraagen, S. F. Chipman, & V. L. Shalin (Eds.), *Cognitive task analysis* (pp. 317-340). Mahwah, NJ: Lawrence Erlbaum Associates.

Rasker, P. C., Post, W. M., & Schraagen, J. M. C. (2000a). The effects of two types of intra-team feedback on developing a shared mental model in command and control teams. *Ergonomics special issue on teamwork, 43*(8), 1167-1189.

Rasker, P. C., Schraagen, J. M. C., & Stroomer, S. M. (2000b). *The effects of intra-team feedback on team performance after developing a shared mental model* (Report TM-00-B010). Soesterberg: TNO Human Factors.

Rasker, P. C., Schraagen, J. M. C., & Van der Kleij, R. (2000c). The effects of intra-team feedback on team performance during routine versus novel situations in command and control teams (Report TM-00-C021). Soesterberg: TNO Human Factors.

Rasker, P. C., & Willeboordse, E. J. (2001). *Werkafspraken in de commandocentrale [Work arrangements in the command center]* (Report TM-01-A002). Soesterberg: TNO Human Factors.

Rentsch, J. R., & Hall, R. J. (1994). Members of great teams think alike: A model of team effectiveness and schema similarity among team members. In M. M. Beyerlein & D. A. Johnson (Eds.), *Advances in interdisciplinary studies of work teams: Theories of self-managing work teams* (Vol. 1, pp. 223-262). Greenwich, CT: JAI.

Rentsch, J. R., Heffner, T. S., & Duffy, L. T. (1994). What you know is what you get from experience: Team experience related to teamwork schemas. *Group and Organization Management, 19*, 485-509.

Rentsch, J. R., & Klimoski, R. J. (2001). Why do "great minds" think alike?: Antecedents of team member schema agreement. *Journal of Organizational Behavior, 22*, 107-120.

Rochlin, G. I., LaPorte, T. R., & Roberts, K. H. (1987). The self-designing high reliability organization: Aircraft carrier flight operators at sea. *Naval War College Review*, 76-90.

Rouse, W. B., Cannon-Bowers, J. A., & Salas, E. (1992). The role of mental models in team performance in complex systems. *IEEE Transactions on Systems, Man, and Cybernetics, 22*(6), 1296-1308.

Rouse, W. B., & Morris, N. M. (1986). On looking into the black box: Prospects and limits in the search for mental models. *Psychological Bulletin, 100*(3), 349-363.

Salas, E., Bowers, C. A., & Cannon-Bowers, J. A. (1995). Military team research: Ten years of progress. *Military Psychology, 7*, 55-75.

Salas, E., Dickinson, T. L., Converse, S. A., & Tannenbaum, S. I. (1992). Toward an understanding of team performance and training. In W. Swezey & E. Salas (Eds.), *Teams: Their training and performance* (pp. 3-29). Norwood, NJ: Ablex.

Salas, E., Prince, C., Baker, D. P., & Shrestha, L. (1995). Situation awareness in team performance: Implications for measurement and training. *Human Factors: Special issue on situation awareness, 1*, 123-136.

Schaafstal, A. M., & Bots, M. J. (1997). Het effect van drie verschillende methoden van cross training op het presteren van teams [The effects of various methods for cross training] (Report TM-97-B001). Soesterberg: TNO Human Factors.

Schaafstal, A. M., & Van Berlo, M. P. W. (2000). Cognitieve modellering van de Luchtverdedigingsofficier [cognitive modeling of the Air Defense Officer] (Report TM-00-A060). Soesterberg: TNO Human Factors.

Schraagen, J. M. C. (1995). Besluitvorming in teams: een onderzoeksparadigma [Team decision making: A research paradigm] (Report TNO-TM 1995 B-1). Soesterberg: TNO Human Factors.

Schraagen, J. M. C. (2001). Team design for Command & Control: A review of the literature and hypothetical theoretical framework (Report TM-01-B006). Soesterberg: TNO Human Factors.

Schraagen, J. M. C., Chipman, S. F., & Shalin, V. L. (2000). *Cognitive task analysis*. Mahwah, NJ: Lawrence Erlbaum Associates.

Schraagen, J. M. C., & Rasker, P. C. (1995). Gemeenschappelijke mentale modellen en teambesluitvorming [Shared mental models and team decision making] (Report TNO-TM 1995 B-17). Soesterberg: TNO Human Factors.

Schraagen, J. M. C., & Rasker, P. C. (1996). De invloed van training in elkaars taken op de besluitvorming in teams [The impact of cross training on team decision making] (Report TM-96-B013). Soesterberg: TNO Human Factors.

Schvaneveldt, R. W. (1990). Proximities, networks, and schemata. In R. W. Schvaneveldt (Ed.), *Pathfinder associative networks: Studies in knowledge organization* (pp. 135-148). Norwood, NJ: Ablex.

Seifert, C. M., & Hutchins, E. L. (1992). Error as opportunity: Learning in a cooperative task. *Human Computer Interaction, 7*, 409-435.

Serfaty, D., Entin, E. E., & Johnston, J. H. (1998). Team coordination training. In J. A. Cannon-Bowers & E. Salas (Eds.), *Making decisions under stress: Implications for individual and team training* (pp. 221-270). Washington, DC: American Psychology Association.

Shea, G. P., & Guzzo, R. A. (1987). Groups as human resources. In K. M. Rowland & G. R. Ferris (Eds.), *Research in Personnel and Human Resources Management* (Vol. 5, pp. 323-356). Greenwich, CT: JAI.

Smith-Jentsch, K. A., Campbell, G. E., Milanovich, D. M., & Reynolds, A. M. (2001). Measuring teamwork mental models to support training needs assessment, development, and evaluation: Two empirical studies. *Journal of Organizational Behavior, 22*, 179-194.

Smith-Jentsch, K. A., Johnston, J. H., & Payne, S. C. (1998a). Measuring team-related expertise in complex environments. In J. A. Cannon-Bowers & E. Salas (Eds.), *Making decisions under stress: Implications for individual and team training* (pp. 61-87). Washington, DC: American Psychology Association.

Smith-Jentsch, K. A., Zeisig, R. L., Acton, B., & McPerson, J. A. (1998b). Team dimensional training: A strategy for guided team self-correction. In J. A. Cannon-Bowers & E. Salas (Eds.), *Making decisions under stress: Implications for individual and team training* (pp. 271-297). Washington, DC: American Psychology Association.

Stasser, G., & Titus, W. (1985). Pooling of unshared information in group decision making: Biased information sampling during discussion. *Journal of Personality and Social Psychology, 48*, 1467-1478.

Stout, R. J., Cannon-Bowers, J. A., & Salas, E. (1996). The role of shared mental models in developing team situational awareness: Implications for team training. *Training Research Journal, 2*, 85-116.

Stout, R. J., Cannon-Bowers, J. A., Salas, E., & Milanovich, D. M. (1999). Planning, shared mental models, and coordinated performance: An empirical link is established. *Human Factors, 41*(1), 61-71.

Tannenbaum, S. I., Beard, R. L., & Salas, E. (1992). Team building and its influence on team effectiveness: An examination of conceptual and empirical developments. In K. Kelley (Ed.), *Issues, Theory, and Research in Industrial/ Organizational Psychology* (pp. 117-153). New York: Elsevier Science.

Tannenbaum, S. I., Smith-Jentsch, K. A., & Behson, S. J. (1998). Training team leaders to facilitate team learning and performance. In J. A. Cannon-Bowers & E. Salas (Eds.), *Making decisions under stress: Implications for individual and team training* (pp. 247-269). Washington, DC: American Psychology Association.

Urban, J. M., Bowers, C. A., Monday, S. D., & Morgan, B. B., Jr. (1995). Workload, team structure, and communication in team performance. Military Psychology, 7(2), 123-139.

Van Berlo, M. P. W. (1998). Richtlijnen ten behoeve van het analyseren van teamtaken [Guidelines supporting the analysis of team tasks] (Report TM-98-B015). Soesterberg: TNO Human Factors.

Van Duin, M. J., & Rosenthal, U. (1996). *De Hercules Ramp: Individuen, organisaties en systemen [Disaster of the Hercules: Individuals, organizations, and systems]*. Leiden: Rijks Universiteit Leiden/ Erasmus Universiteit Rotterdam: Crisis Onderzoeks Team.

Volpe, C. E., Cannon-Bowers, J. A., Salas, E., & Spector, P. E. (1995). The impact of cross training on team functioning. *Human Factors, 38*, 87-100.

Weaver, J. L., Bowers, C. A., Salas, E., & Cannon-Bowers, J. A. (1995). Networked simulations: New paradigms for team performance research. Behavior Research Methods, Instruments & Computers, 27, 12-24.

Wegner, D. M. (1987). Transactive memory: A contemporary analysis of the group mind. In B. Mullen & G. R. Goethals (Eds.), *Theories of group behavior* (pp. 185-205). New York: Springer.

Weick, K. E., & Bougon, M. G. (1993). Collective mind in organizations: Heedful interrelating on flight decks. *Administrative Science Quarterly, 38*, 357-381.

Wellens, A. R., & Ergener, D. (1988). The C.I.T.I.E.S. game: A computer-based situation assessment task for studying distributed decision making. *Simulation and games, 19*, 304-327.

West, M. A., Borrill, C. S., & Unsworth, K. L. (1998). Team effectiveness in organizations. In C. L. Cooper & I. T. Robertson (Eds.), *International Review of Industrial and Organizational Psychology* (Vol. 13, pp. 1-48). New York: John Wiley & Sons.

Wilson, J. R., & Rutherford, R. (1989). Mental models: Theory and application in human factors. *Human Factors, 31*(6), 617-634.

Zsambok, C. A. (1997). Naturalistic decision-making research and improving team decision making. In C. A. Zsambok & G. A. Klein (Eds.), *Naturalistic Decision Making* (pp. 111-120). Mahwah, NJ: Lawrence Erlbaum Associates.

SAMENVATTING

Achtergrond

Communicatie tussen teamleden bepaalt voor een belangrijk deel de prestatie van een team. Vooral wanneer teams werken onder omstandigheden die worden gekenmerkt door hoge tijdsdruk en snel veranderende situaties is communicatie belangrijk. Dergelijke omstandigheden zijn te vinden bij teams die werken in militaire commandocentrales, vliegtuigcockpits of bij crisismanagement. Voor zulke teams is communicatie lastig. Communicatie is noodzakelijk omdat teamleden afhankelijk zijn van elkaars informatie. Ook is het zinvol voor het bespreken en verbeteren van de taakuitvoering, het gezamenlijk bepalen van strategieën en het elkaar op de hoogte houden van de veranderingen in de situatie. Desondanks kan communicatie ook problemen geven omdat er te weinig tijd voor is, of omdat het de eigen taakuitvoering verstoort.

Vooral onder hoge tijdsdruk kan communicatie problemen geven. Er is geen tijd om uitgebreid te praten over "wie doet wat" of "wie heeft welke informatie wanneer nodig." Bovendien kan men te laat zijn met het uitwisselen van de noodzakelijke informatie. In goede teams lijken teamleden zich aan te passen door elkaar tijdig de noodzakelijke informatie te geven voordat teamgenoten daarom vragen. Teamleden anticiperen dus op elkaars informatiebehoefte. Er zijn geen uitgebreide discussies om te coördineren en er wordt niet onnodig om informatie gevraagd. Dit wordt *impliciete coördinatie* genoemd. Een voorbeeld daarvan is de blinde pass van een voetballer die zijn ploeggenoot bespeelt zonder expliciete aanwijzingen en zonder te kijken.

Communicatie heeft dus voor- en nadelen en goede teams zijn in staat hun communicatie aan de omstandigheden aan te passen. Teams moeten zo min mogelijk communiceren en alleen communiceren wanneer het noodzakelijk is, of wanneer het bijdraagt aan de prestatie. De vraag is hoe teams dit kunnen bereiken. Ofwel, hoe kunnen teams hun communicatie verminderen en wanneer is communicatie nodig?

In het recente teamonderzoek is het concept *gemeenschappelijk mentaal model* geïntroduceerd om teamprocessen, waaronder communicatie, en prestatie in teams te verklaren. Een gemeenschappelijk mentaal model is de georganiseerde kennis van teamleden die zij gebruiken bij het beschrijven, verklaren en het voorspellen van het teamwerk. Het bevat *teamkennis* waaronder kennis van de taken, verantwoordelijkheden en de informatiebehoefte van de teamleden en *situatiekennis* waaronder kennis van de ontwikkelingen in de situatie buiten het team. De verklaringen en de voorspellingen die teamleden kunnen doen op basis van hun gemeenschappelijke mentale modellen, geven teamleden de gelegenheid om te anticiperen op elkaars taakgerelateerde behoeften door het tijdig geven van informatie, middelen of andere ondersteuning.

Wat betreft de communicatie geven gemeenschappelijke mentale modellen teamleden de gelegenheid om elkaars informatiebehoefte te verklaren en te voorspellen. Daardoor kan communicatie efficiënt en effectief plaatsvinden. Efficiënt, omdat het niet nodig is om uitgebreid te communiceren over "wie doet wat" of "wie heeft welke informatie wanneer nodig." Ook hoeft men elkaar niet voortdurend om informatie te vragen. Effectief, omdat teamleden in staat zijn a) elkaar de informatie te geven die nodig is om taken succesvol uit te voeren, b) zonder daar expliciet over te communiceren en c) op het moment in de taakvolgorde van de teamgenoot wanneer deze informatie nodig is. Met andere woorden, gemeenschappelijke mentale modellen geven teams de gelegenheid om impliciet te coördineren. Het gevolg is een goede afstemming tussen teamleden die precies weten wanneer ze moeten praten en wat ze moeten zeggen.

Hoewel gemeenschappelijke mentale modellen helpen om efficiënt en effectief te communiceren, is communicatie ook nodig voor het ontwikkelen en het onderhouden van gemeenschappelijke mentale modellen. Communicatie tijdens de taakuitvoering helpt bij het afstemmen van gemeenschappelijke mentale modellen op de context waarin wordt gewerkt. Teamleden kunnen bijvoorbeeld precies vertellen welke informatie ze van elkaar nodig hebben. Verder is communicatie nodig om de gemeenschappelijke mentale modellen actueel te houden. Vooral in snel veranderende of onbekende situaties is communicatie belangrijk. Zowel voor het behouden van een actueel gemeenschappelijk mentaal model als voor het gezamenlijk bepalen van nieuwe strategieën om de situatie aan te kunnen. Vanuit een gemeenschappelijk mentaal model kunnen teamleden elkaar suggesties geven, met alternatieven komen en hypotheses verzinnen en toetsen die bruikbaar zijn voor het bepalen van een strategie in de specifieke situatie. In tegenstelling tot impliciete coördinatie, dat uitgaat van "stille" teams, ligt hier de nadruk op communicatie om te komen tot een gezamenlijke interpretatie van de situatie en om strategieën te bepalen die de situatie het hoofd kunnen bieden.

Huidige onderzoek

Het gemeenschappelijke mentaal model verklaart dus hoe communicatie in teams kan worden verminderd. Aan de hand van hun mentale modellen kunnen teamleden elkaar tijdig de noodzakelijke informatie geven voordat daarom wordt gevraagd. Het verklaart ook waarom communicatie nodig is: voor het ontwikkelen *en* actueel houden van gemeenschappelijke mentale modellen. Deze ideeën hebben ons geïnspireerd tot het uitvoeren van het onderzoek dat staat beschreven in dit proefschrift. Het belangrijkste doel was om de relatie tussen communicatie en de prestatie in teams empirisch te onderzoeken. Dit hebben wij gedaan vanuit twee verschillende perspectieven.

Vanuit het eerste perspectief waren we geïnteresseerd in hoe communicatie kon worden verminderd door zo efficiënt en effectief mogelijk te communiceren. De verwachting was dat de communicatie en prestatie van teams kan verbeteren door de kennis in de mentale modellen van de leden te stimuleren. De onderzoeksvraag voor dit eerste perspectief was: *hoe kan de communicatie en prestatie worden verbeterd door het stimuleren van de kennis die teamleden hebben in hun mentale modellen?*

Om deze vraag te beantwoorden voerden we drie experimenten uit. In experiment 1 en 2 (zie hoofdstuk 5) gebruikten wij een trainingsmethode waarbij teamleden tijdens de training oefenden in elkaars taken. In experiment 3 gaven wij teaminformatie met een expliciete beschrijving van elkaars taken en van welke informatie wanneer moest worden uitgewisseld (zie hoofdstuk 6). Voor beide methodes was de verwachting dat de leden teamkennis zouden ontwikkelen van elkaars taken, verantwoordelijkheden en informatiebehoefte. Op basis hiervan kunnen teamleden anticiperen op elkaars informatiebehoefte door tijdig de nodige informatie uit te wisselen.

Om deze methodes te onderzoeken gebruikten wij een experimentele teamtaak voor twee leden (zie hoofdstuk 3). Deze taak was speciaal ontwikkeld om teamprocessen te onderzoeken van teams die werken onder hoge tijdsdruk en in situaties die snel veranderen. Een cognitieve teamtaak analyse heeft aangetoond dat de taak geschikt was om teamprocessen in relatie tot gemeenschappelijke mentale modellen te onderzoeken (zie hoofdstuk 4). Deze taak is (in verschillende, verbeterde versies) ook gebruikt voor de experimenten die zijn gedaan vanuit het tweede perspectief.

Vanuit het tweede perspectief waren we geïnteresseerd op welke manier communicatie de prestatie in teams kan verbeteren. In tegenstelling tot het eerste perspectief, waarin we onderzochten hoe communicatie verminderd kon worden, waren we nu geïnteresseerd in hoe de prestatie verbeterd kon worden door het *uitbreiden* van de communicatie. Hier was de verwachting dat de prestatie van teams kan verbeteren doordat communicatie de ontwikkeling en het actueel houden van de kennis in de mentale modellen van de leden stimuleert. De onderzoeksvraag voor dit tweede perspectief was: *hoe en wanneer kan de communicatie de prestatie verbeteren door het stimuleren van de kennis die teamleden hebben in hun mentale modellen?*

Om deze vraag te beantwoorden gebruikten wij een mogelijkheid van de experimentele teamtaak om de communicatie te manipuleren. De teamtaak was zó ontworpen dat teamleden de noodzakelijke informatie konden uitwisselen met behulp van gestandaardiseerde elektronische berichten. Door daarnaast al dan niet de mogelijkheid te geven om verbaal te communiceren, konden wij condities creëren waarin teamleden beperkt of *on*beperkt konden communiceren. In de onbeperkte communicatie condities konden leden team- en situatiekennis uitwisselen en teamwerk uitvoeren zoals het volgen en verbeteren van elkaars prestatie, evalueren, en het gezamenlijk bepalen van strategieën. Daarom verwachtten wij dat de prestatie zou verbeteren wanneer teamleden onbeperkt zouden communiceren.

Experiment 4 en 5 waren de eerste experimenten waarin we het effect van onbeperkte communicatie op de prestatie onderzochten (zie hoofdstuk 7). Hoewel onbeperkte communicatie de prestatie positief kan beïnvloeden is het mogelijk dat het effect na verloop van tijd minder wordt. Alle team- en situatiekennis is dan uitgewisseld en mogelijk zijn teams beter getraind. Communicatie voor kennisuitwisseling, evaluatie en het bepalen van strategieën is dan niet meer nodig. Daarom hebben we in experiment 6 het effect van communicatie op de prestatie onderzocht in twee opeenvolgende sessies (zie hoofdstuk 8). Tot slot hebben we in experiment 7 het effect van onbeperkte communicatie op de prestatie onderzocht in routine versus onbekende situaties (zie hoofdstuk 9).

Resultaten en conclusies

Wat betreft de eerste onderzoeksvraag blijkt dat training in elkaars taken *niet* leidde tot betere communicatie of prestatie in experiment 1 en 2. Training in elkaars taken helpt niet bij het ontwikkelen van de teamkennis die nodig is om te begrijpen welke informatie wanneer moet worden uitgewisseld. Gegeven de magere resultaten voor training in elkaars taken, van zowel onze eigen experimenten als die van andere onderzoekers, concluderen wij dat de effectiviteit van dit type trainingen twijfelachtig is.

Betere resultaten worden behaald wanneer een training direct is gericht op het ontwikkelen van teamkennis, zoals bij het geven van teaminformatie. In experiment 3 leidde dit tot betere communicatie en teamkennis. De scores op de vragenlijst die deze kennis mat, waren bovendien positief gecorreleerd met een aantal communicatiematen. Dit geeft aan dat hoe beter de teamkennis is, hoe beter de communicatie. Tot onze verbazing leidde de verbeterde communicatie niet tot een verbeterde prestatie. Dit kan worden verklaard door de individuele taakprestatie van de teamleden. Het effect van de verbeterde communicatie werd tenietgedaan doordat teamleden fouten maakten bij het uitvoeren van hun individuele taken. De verwachting is dat de effectiviteit van het geven van teaminformatie groter zal zijn naarmate teamleden vaardiger zijn op hun individuele taken.

Kortom, meer onderzoek is nodig om te achterhalen wat de beste methode is om communicatie en prestatie in teams te verbeteren. Vooralsnog hebben wij aangetoond dat het geven van teaminformatie de communicatie in teams verbetert. Wanneer teamleden hun individuele taken adequaat uitvoeren zal dit naar verwachting ook de prestatie verbeteren.

Wat betreft de tweede onderzoeksvraag blijkt dat communicatie de prestatie van teams verbetert, echter niet altijd. In experiment 4 en 5 presteerden teams beter wanneer zij onbeperkt konden communiceren. De communicatie is geanalyseerd met behulp van verbale protocollen en gescoord aan de hand van een schema dat was opgesteld op basis van de literatuur (zie hoofdstuk 4). Hieruit blijkt dat teams zowel team- als situatiekennis uitwisselden. Bovendien werd er gecommuniceerd om extra teamwerk uit te voeren. Zo hielden teamleden elkaar op de hoogte van de eigen taakuitvoering, werd de prestatie geëvalueerd en werden strategieën bepaald. Dit ondersteunt onze verklaring dat de teamprestatie verbeterde omdat communicatie hielp bij het ontwikkelen en onderhouden van actuele team- en situatiekennis en teamwerk faciliteerde.

De resultaten van experiment 6 ondersteunen deze verklaring verder. Teams die onbeperkt communiceerden hadden hogere scores op de kennisvragenlijst dan teams die beperkt communiceerden. Dit duidt erop dat onbeperkte communicatie team- en situatiekennis stimuleert. In dit experiment bleek ook dat teams na één sessie onbeperkt communiceren beter presteerden in een volgende sessie toen zij weer beperkt communiceerden. Dankzij de kennis die was opgebouwd door onbeperkte communicatie in sessie 1 konden zij, ondanks de beperkte communicatie in sessie 2, de prestatie verbeteren. De team- en situatiekennis die was opgebouwd in sessie 1, hielp de teams om de noodzakelijke informatie uit te wisselen met een beperkt aantal berichten.

Het ging echter mis met de teams die in sessie 2 doorgingen met onbeperkt communiceren. Ten opzichte van de teams die beperkt gingen communiceren, verslechterde hun prestatie in sessie 2. Dit terwijl we verwachtten dat onbeperkte communicatie nodig was voor het actueel houden van de situatiekennis (de situatie veranderde continu). Een verklaring voor de prestatieverslechtering is dat communicatie in de periodes met hoge werkbelasting verstorend werkte bij de individuele taakuitvoering. Een post-hoc analyse van de communicatie toont aan dat teamleden zich inderdaad *niet* aanpasten aan de periodes met hoge werkdruk. Zij communiceerden evenveel in hoge als in lage werkdrukperiodes.

Experiment 6 toont aan dat het effect van onbeperkte communicatie na verloop van tijd afneemt. Onbeperkte communicatie is dan wellicht alleen belangrijk voor het *actueel* houden van situatiekennis. Dit is onderzocht in experiment 7. Om ervoor te zorgen dat teamkennis aanwezig was hebben we alle teamleden uitgerust met een *team-interactieschema*. Het blijkt dat onbeperkte communicatie de prestatie verbetert in onbekende situaties maar niet in routine situaties. Het hielp bij het uitwisselen van situatiekennis en het gezamenlijk bepalen van strategieën. Kortom, wanneer teams voldoende teamkennis hebben ontwikkeld dan is onbeperkte communicatie alleen nodig in onbekende situaties.

Op basis van experiment 4 tot en met 7 concluderen wij dat communicatie vooral belangrijk is voor onervaren teams. Het helpt hen bij het ontwikkelen van team- en situatiekennis. Is deze kennis eenmaal ontwikkeld, dan moeten teams hun communicatie zoveel mogelijk beperken. De prestatie kan dan worden gehandhaafd wanneer teamleden elkaar tijdig de noodzakelijke informatie geven zonder expliciet te coördineren.

Toch kan communicatie zinvol zijn omdat het teamwerk zoals het gezamenlijk bepalen van strategieën faciliteert. Dit is minder belangrijk voor volledig getrainde teams die werken in routine situaties dan voor ongetrainde teams of teams die werken in onbekende situaties. De vraag of teams juist wel of niet moeten communiceren is dus niet eenvoudig te beantwoorden. In het algemeen geldt dat teams niet moeten communiceren over datgene wat vaststaat in het teamwerk. Dat betekent dat teams a) geen team- en situatiekennis moeten uitwisselen in routine situaties, b) niet expliciet moeten coördineren en communiceren over "wie doet wat" en "wie heeft welke informatie wanneer nodig" en c) elkaar niet continu om informatie moeten vragen. Het inperken van deze communicatie geeft teamleden de ruimte om hun individuele taken zo goed als mogelijk uit te voeren. Bovendien blijft dan zo veel mogelijk communicatiecapaciteit beschikbaar voor dat type communicatie dat belangrijk is voor de prestatie. Teams kunnen dan communiceren om elkaars prestatie te volgen en te verbeteren, te evalueren, en gezamenlijk strategieën te bepalen en, *alleen* in veranderende of onbekende situaties, situatiekennis uit te wisselen.

Het onderzoek van dit proefschrift heeft ondersteuning gevonden voor een aantal hypotheses wat betreft het gemeenschappelijke mentale modellen concept (zie hoofdstuk 10). Het concept kan dan ook goed worden gebruikt voor het verklaren en voorspellen van teamprocessen en prestatie in teams die werken onder hoge tijdsdruk en in snel veranderende situaties. Vanaf midden jaren negentig (toen het onderzoek voor dit proefschrift begon) heeft het concept behoorlijk aan populariteit gewonnen. Nemen we het totale onderzoek in ogenschouw (zie hoofdstuk 2 voor een overzicht), dan is echter nog veel onduidelijk over hoe gemeenschappelijke mentale modellen precies werken, kunnen worden gemanipuleerd en gemeten. De verschillende onderzoeken geven geen consistent beeld en hebben zelfs tegenstrijdige resultaten opgeleverd. Het probleem is dat onderzoekers het concept zodanig verschillend interpreteren, definiëren en meten dat het moeilijk is om eenduidige verklaringen te geven en voorspellingen te doen. Zodoende is het gevaar dat het gemeenschappelijke mentale modellen concept zijn bruikbaarheid verliest. Vooralsnog heeft het onderzoek geen onweerlegbaar bewijs geleverd voor het bestaan en de werking van gemeenschappelijke mentale modellen.

Toekomstig onderzoek moet meer duidelijkheid verschaffen over wat gemeenschappelijke mentale modellen zijn, hoe ze werken en hoe ze moeten worden gemeten. Belangrijke thema's daarin zijn de mate van gemeenschappelijkheid, de veronderstelde organisatie van de kennis in de mentale modellen en hoe ze teamprocessen precies beïnvloeden.

Tenslotte heeft het onderzoek beschreven in dit proefschrift ons veel geleerd over teamfunctioneren in het algemeen en communicatie in teams in het bijzonder. Op basis hiervan hebben we praktische aanbevelingen kunnen doen over teamontwerp, -training en -ondersteuning.

SUMMARY

Background

Communication among team members is an important contributor of performance in teams. Especially when teams work in conditions characterized by high time pressure and rapidly changing situations. Teams working in military command and control, aircraft cockpits, crisis management often work in such conditions. In such teams, communication can be problematic. Communication is needed because team members depend on each other's information. In addition, communication is needed because it helps team members to evaluate and improve task performance, jointly determine strategies, and keep each other up-to-date with the changes in the situation. Nevertheless, potential problems are that there is too little time to communicate and that it disrupts the individual task performance of team members.

Communication can be especially problematic in conditions of high time pressure. In those conditions, there is no time to discuss extensively about "who is responsible for what task" or "who needs what information and when." Moreover, team members can be too late with exchanging the necessary information. In effective teams, members adapt to such conditions by providing each other the necessary information in advance of requests. Hence, team members anticipate on each other's informational needs. There are *no* extensive discussions to coordinate and there are *no* unneeded requests for information. This is called *implicit coordination*. The blind pass in basketball, where a player passes the ball over his or her shoulder to another player without looking and talking, is an example of implicit coordination.

In sum, communication has its benefits and costs and effective teams are able to adapt their communication when necessary. Teams should restrict their communication as much as possible, and communicate only if it is necessary or contributes to performance. The question is how teams can achieve this. Thus, how can teams limit their communication and when is communication needed?

Recent literature has advanced the construct of *shared mental models* among team members as an underlying mechanism of team processes and performance in teams. Shared mental models are organized knowledge structures that allow team members to describe, explain, and predict the teamwork demands. It comprises *team knowledge* such as knowledge about the tasks, responsibilities, and informational needs of the team members and *situation knowledge* such as knowledge of the ongoing developments in the external situation. The explanations and expectations generated by the shared mental models allow team members to anticipate on each other's task-related needs by providing each other information, resources, or other support in time.

With respect to communication, shared mental models allow team members to explain and predict the informational needs of teammates. Therefore, communication can take place efficiently and effectively. Efficiently, because explicit and extensive communication to ask for information or to make arrangements concerning "who does what when" and "who provides which information when" are not needed. Effectively, because team members are able to provide each other with a) the information needed to complete the tasks successfully, b) without explicit communication, and c) on the time in the task sequence of a teammate when this information is needed. In other words, shared mental models allow team members to coordinate implicitly. The result is the smooth team functioning of team members who are in sync with each other, and who know exactly when to talk and what to say.

Although shared mental models may result in efficient and effective communication, communication is also important for the development and maintenance of shared mental models. Communication during task execution refines team members' shared mental models with contextual cues. For example, team members can inform each other precisely which information they need. For maintenance purposes, communication is needed to keep the shared mental models up-to-date with the changes that occur during task execution. Especially in dynamic or novel situations, communication is needed to preserve an up-to-date shared mental model of the situation and to adjust strategies or develop new ones to deal with the situation. Shared mental models in changing and novel situations enable team members to make suggestions, provide alternative explanations, employ their expertise, generate and test hypotheses, and offer information useful to determine strategies in that particular situation. In contrast to implicit coordination, which implies that mature teams are silent teams, this emphasizes the need for explicit communication to arrive at a joint interpretation of the situation and the generation of strategies to deal with that situation.

Present research

The shared mental model construct explains how communication can be limited. Team members that rely on their mental models provide each other the necessary information in time, that is, in advance of requests. It also explains why and when communication is needed: to develop shared mental models and to keep them up-to-date. These notions inspired us to perform the research described in this thesis. The main objective was to investigate empirically the relationship among communication and performance in teams. This was investigated from two different perspectives.

From the first perspective, we were interested in how communication can be limited by communicating as efficiently and effectively as possible. We expected that communication and performance in teams could be improved when the knowledge in team member's mental models is fostered. The research question for this first perspective was: *how can communication and performance be improved by fostering the knowledge team members have in their mental models?*

To answer this question we conducted three experiments. In Experiment 1 and 2 (see chapter 5), we provided teams with a cross training method in which members were trained in each other's tasks. In Experiment 3 (see chapter 6), we provided team members with information that contained an explicit description of each other's tasks and which information should be exchanged when. For both methods we expected that team members would develop team knowledge of each other's tasks, responsibilities, and informational needs. Based on this knowledge, team members can anticipate on each other's informational needs by exchanging the necessary information in time.

To investigate these methods, we used an experimental team task for two members (see chapter 3). This task was especially designed to investigate team processes of teams that work in time-pressured and rapidly changing situations. A cognitive team tasks analysis showed that the task is suitable to investigate team processes in relation to shared mental models (see chapter 4). This task is (in different, enhanced versions) also used for the experiments that were conducted from the second perspective.

From the second perspective, we were interested in how team members can use their communication to improve their performance. In contrast to the first perspective, in which we investigated how communication could be limited, we were now interested in how performance can be improved by expanding the communication. We expected that the performance of teams can be improved because communication fosters the development and maintenance of the knowledge in team members' mental models. The research question for this second perspective was: *how and when does communication improve performance by fostering the knowledge team members have in their mental models?*

To answer this question we used an opportunity of the experimental team task to manipulate the communication. The task was designed such that the necessary information could be exchanged by sending standardized electronic messages. By giving teams, on top of the electronic message exchange, the opportunity to communicate verbally or not, we could design conditions in which teams could communicate restrictedly or unrestrictedly. In the unrestricted communication conditions, team members could transfer team and situation knowledge and perform teamwork that consists of performance monitoring, evaluation, and determining strategies. Therefore, we expected that unrestricted communication would improve performance.

Experiment 4 and 5 were the first experiments in which we investigated the effect of unrestricted communication on performance (see chapter 7). Although unrestricted communication can have a positive effect on team performance, it can be argued that the effect of unrestricted communication diminishes with time. All team and situation knowledge is then transferred and teams are possibly better trained. Communication to transfer knowledge, evaluate, and determine strategies is then not needed any more. Therefore, we investigated in Experiment 6 the effect of unrestricted communication in two subsequent sessions (see chapter 8). Finally, in Experiment 7, we investigated the effect of unrestricted communication in novel versus routine situations (see chapter 9).

Results and conclusions

With respect to the first research question: training in each other's tasks did *not* improve communication or performance in Experiment 1 and 2. Training in each other's tasks is *not* an effective method to provide team members with the knowledge needed to develop an understanding of what information must be exchanged at what moments. Given the sparse support for the assumed effect of training in each other's tasks, from our experiments as well as from the experiments of other researchers, we conclude that the effectiveness of this type of cross training method is questionable.

Better results were obtained with training methods, such as the provision of team information, that are directly aimed at the development of team knowledge. In Experiment 3, this improved communication and resulted in better team knowledge. Moreover, the scores on the questionnaire that measured this knowledge were positively correlated with several communication measurements. This indicates that the better the team knowledge, the better the communication. Surprisingly, the improved communication did not result in improved performance. We explain this by the individual task performance of team members. Although team members improved their teamwork and communicated more efficiently and effectively, they failed to perform well on their taskwork. Therefore, we expect that the effectiveness of the provision of team information will be further improved when team members are fully skilled in their taskwork.

In conclusion, more work is needed to find the best method for improving communication and performance in teams. For now, we demonstrated that the provision of team information is an effective method to improve communication and possibly performance given adequate taskwork.

With respect to the second research question, the results of Experiment 4 to 7 show that unrestricted communication improves performance, however, not in all conditions. In Experiment 4 and 5, unrestricted communication did improve performance. The communication was analyzed by means of verbal protocols and rated using a classification schema developed on the basis of the literature (see chapter 4). The analysis shows that teams transferred team and situation knowledge. Moreover teams communicated to perform additional teamwork that consisted of performance monitoring, evaluation, and determining strategies. This supports our explanation that team performance improved because communication supports the development and maintenance of up-to-date team knowledge and facilitates teamwork.

The results of Experiment 6 further support this explanation. Teams that communicated unrestrictedly had higher scores on the knowledge questionnaire than teams that communicated restrictedly. This indicates that unrestricted communication fosters team and situation knowledge. Experiment 6 further shows that, after communicating *un*restrictedly in one session, teams performed better in a subsequent session when they communicated restrictedly. Based on the knowledge developed through unrestricted communication in Session 1, team members could, despite the restricted communication, improve their performance in Session 2. The team and situation knowledge developed in Session 2, supported teams in exchanging the necessary information with a limited number of messages.

Nevertheless, things went wrong for the teams that continued to communicate unrestrictedly in Session 2. Compared to the teams that communicated restrictedly, their performance decreased in Session 2. We had expected that communication was needed to preserve up-to-date situation knowledge (the situation changed continuously). An explanation for this performance decrease is that too much communication in periods with high workload distracted team members from executing their individual tasks. A post-hoc analysis of the verbal communication showed that team members indeed did *not* adapt to high workload periods. They communicated as much in high workload periods as in low workload periods.

Experiment 6 shows that the effect of unrestricted communication diminishes after time. Unrestricted communication might be needed only to preserve up-to-date situation knowledge. This was investigated in Experiment 7. To ensure that team knowledge was present, we equipped team members with a team knowledge schema. The results show that unrestricted communication improved performance during the novel scenarios but not during the routine scenarios. Thus, when teams have developed sufficient team knowledge, unrestricted communication is only needed in novel situations and not in routine situations.

Based on Experiment 4 to 7, we conclude that communication is especially important in the beginning of a team's lifetime. Communication is beneficial to develop team and situation knowledge. Once this knowledge is developed, teams should limit their communication as much as possible. In that case, performance can be maintained when team members exchange the necessary information without explicit coordination.

Nevertheless, communication can be beneficial because it facilitates additional teamwork such as jointly determining strategies. For teams that perform in routine situations and are fully trained, communication is less important than for teams that are *not* fully trained or encounter novel situations. Hence, the answer to the question whether teams should communicate or not, cannot be easily answered with a simple yes or no. In general, we conclude that teams should limit their communication with respect to the fixed elements in team functioning. More precisely, teams should a) not transfer team and situation knowledge in routine situations, b) not coordinate explicitly and communicate about "who does what" and "who needs what information and when," and c) not continuously request each other for information. Limiting this type of communication should leave team members free to perform their own tasks as well as they can. At the same time, this would leave as much spare communication capacity available for that type of communication that is important for performance. That is, for performance monitoring, evaluation, and determining strategies together and, only in changing or novel situations, to transfer situation knowledge.

The research in this thesis found support for several hypotheses with regard to the mental model construct (see chapter 10). The shared mental model construct is a powerful construct to explain team processes and performance in teams that work in time-pressured and rapidly changing situations. From the mid nineties (at the time the research described in this thesis started) the construct has gained substantial attention. When looking across the total body of research, however, there is still confusion about how shared mental models exactly operate and can be measured and manipulated. The various studies do not show a consistent picture and even yield conflicting results. The problem is that researchers employ such different interpretations, definitions, and measurements of the shared mental model construct that it is difficult to give unequivocal explanations and to make predictions. The danger is that the shared mental model construct becomes meaningless. The research so far yields no indisputable evidence for the existence and working of shared mental models.

Future research must clarify what shared mental models are, how they work, and how they can be measured. Important topics to consider are the extent of sharedness, the hypothesized organization of knowledge in mental models, and how they exactly influence team processes.

Finally, the research described in this thesis has taught us much about team behavior in general, and, more specifically, communication in teams. This helped us to formulate several practical implications with respect to team design, training, and support.

CURRICULUM VITAE

Peter Rasker was born in Schiedam, The Netherlands on June 13, 1970. He attended secondary school at Cals College in Nieuwegein. In August 1991, he began to study Psychology at Utrecht University with a major in Cognitive Psychology and Organizational Psychology. In April 1996, he received his master's degree in Cognitive Psychology. From June 1996 until present, he has been affiliated with the institute of Human Factors of the Netherlands Organization for Applied Scientific Research (TNO). He participated in various projects varying from software usability tests to performance analyses of military command and control systems. His research interests include team performance in complex situations, naturalistic decision making, and methods for (cognitive) task analysis. Peter Rasker is also interested in the topic of shared knowledge in organizations and how psychologically motivated theories can help to solve knowledge sharing problems in practice.