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Executive summary

Examining Shared Mental Models of Air Traffic Controllers: What do they entail and what is shared?

Report no.
NLR-TP-2009-639

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Report classification
UNCLASSIFIED

Date
May 2010

Knowledge area(s)
Training, Simulation and Operator Performance

Descriptor(s)
shared mental models
air traffic control
card sorting

Problem area
Current developments in Air Traffic Management (ATM), such as the Single European Sky ATM Research (SESAR) program, the Functional Airspace Blocks (FAB) initiative, or the internal Masterplan of Air Traffic Control the Netherlands (LVNL), foresee a change from active air traffic control (ATC) to more passive monitoring. Increasing automation will make early planning of trajectory based routes possible and envisions a shift from voice communication to datalink communication. These changes will affect air traffic controllers' responsibilities, competences, and team performance.

NLR participates in the program "Human Factors in future ATM" of the Knowledge and Development Centre (KDC) Mainport Schiphol, which focus on safe and efficient air traffic in the future. Different projects investigate the conditions which will influence the operators' task, such as the organizational model, training design, and team performance. In line with the program, the current study looks into the role of shared mental models (SMM) in ATC teams. A common understanding of the task and team, i.e. a SMM, is predicted to be increasingly important to ATC teams in order to perform efficiently now and in future.

This report is based on a presentation held at the Human Factors and Ergonomic Society European Chapter Conference, Linköping, Sweden, 14-16 October 2009.

Description of work

The paper gives a short introduction to SMM theory and its role in ATC. The development of an ATC-tailored SMM framework is briefly described and subsequently evaluated. The evaluation focuses on validating the framework and assessing the degree of sharedness of air traffic controllers' mental models. It is assumed that the framework is valid throughout the ATC domain and that controllers of the same team have a common understanding of their task and team functioning irrespective of their function, age or work experience. One hundred air traffic controllers of two Air Navigation Service Providers (ANSPs) participated in the study in order to cover a broad pool of functions and organizational influences.
Moreover, the comparison of the two authorities provides additional insights, since ANSP 2 recently changed team structures from fixed into flexible teams. It is supposed that these changes can cause a restructuring of the controllers' mental models. By means of a web-based card sorting task the SMM framework's validity and the similarity between controllers is tested.

Results and conclusions

Averaged over the ATCOs in the study a medium agreement with the framework was found. In line with this result the applicability of the card sorting approach for validity and similarity purposes is called into questions. It is suggested that other, more applied methods are needed to capture the full depth of SMM.
As was expected, the framework better represents the mental model's structures of controllers at ANSP 1 than at ANSP 2. Within the organisations, however, the agreement with the framework was the same, irrespective of age, function, or work experience.
Regarding the similarity of mental models between controllers, a moderate agreement was identified. Controllers of ANSP 1 had slightly higher agreement scores than controllers at ANSP 2.
The findings the latter controllers can identify less with the framework and share less knowledge contents than controllers at ANSP 1 are in line with the hypotheses. The recent reorganisation at ANSP 2 is an explanation for the results.

Applicability

The described elements of shared mental models including mental model types and contents give insights into the required knowledge structures of ATCOs. These are crucial to possess and share in order to work efficiently together at current and future ATM environments. The study gives insights into the usability of the card sorting method for SMM research. Future research is needed to evaluate SMM of ATCOs in applied contexts, i.e., during task execution and should focus on how teams transfer and communicate important information.

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Examining Shared Mental Models of Air Traffic Controllers: What do they entail and what is shared?

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This report is based on a presentation hold at the Human Factors and Ergonomic Society European Chapter Conference, Linköping, Sweden, 14-16 October 2009.

The contents of this report may be cited on condition that full credit is given to NLR and the authors.

This publication has been refereed by the Advisory Committee AIR TRANSPORT.

Customer	NLR
Contract number	----
Owner	NLR
Division NLR	Air Transport
Distribution	Unlimited
Classification of title	Unclassified
	May 2010

Approved by:

Author	Reviewer	Managing department
25/11	15-11-'11	13-11-'11

Summary

Air traffic control is a very dynamic and complex team task which requires a high degree of coordination and information exchange. Foreseen changes in Air Traffic Management of the next decades will result in more automation, pre-flight planning and electronic communication. This novel situation increasingly requires controllers to anticipate information requirements and meet team and task demands in circumstances when time demands are high. Shared mental models enable a team to take appropriate actions and fulfil teammates' needs by ensuring a common understanding of the task and team. Therefore, the current research explored shared mental models of air traffic controllers which have been shown to contribute to efficient team performance. By means of a cognitive task analysis the mental models controllers have, were identified and resulted in an air traffic control specific framework of shared mental models. In order to validate the framework and assess the degree of sharedness of controllers' mental models, a web-based card sorting task was undertaken recently. Several teams of two air navigation service providers in the Netherlands participated in the research including Tower/Approach Controllers (N=15), Area Controllers (N=22) and en-route controllers (N=63). The results are presented and discussed in terms of their importance for future air traffic management.

Contents

Abbreviations

ACC	Area Control Centre
ANSP	Air Navigation Service Provider
ATM	Air Traffic Management
ATC	Air Traffic Control
ATCO	Air Traffic Controller
CTA	Cognitive Task Analysis
EC	Executive Controller
FAB	Functional Airspace Blocks
LVNL	The Dutch Air Traffic Control The Netherlands
MM	Mental Model
PLC	Planner Controller
SESAR	Single European Sky ATM Research
SMM	Shared Mental Model
SUP	Supervisor
TWR/APP	Tower/Approach

1 Introduction

Shared mental model theory is an extension of the mental model theories and research that started in the ‘80s to accommodate a need for richer knowledge constructs than simple facts (e.g., “radio frequency of Schiphol = 123.9”), concepts (“aircraft separation”), or rules (“During a peak period 2+1 runway is applied”). Mental models (MMs) are meaningful integrations of such simple knowledge structures and as such they can function as “mechanisms whereby humans generate description of system purpose and form, explanation of system functioning and observed system states, and prediction of future system states” (Rouse & Morris, 1986, p. 360). Research into mental models often focuses on the development of individual MMs (Langfield-Smith & Wirth, 1992) or on the individual differences in novices’ and experts’ MMs (Redding & Cannon, 1992).

Team performance however, not only depends on the quality of an individual’s mental model, but also on a common understanding among the team players about the tasks, goals, ways of cooperation and communication, and the situation at hand. An air traffic controller (ATCO) constantly works together with his teammates and other teams, such as the cockpit crew. Especially among these distributed teams, expectations about the system, i.e. the tasks, procedures, roles, responsibilities and so forth, must be shared among operators to successfully achieve collective goals (Matthieu, Heffner, Goodwin, Salas, & Cannon-Bowers, 2000). Such shared mental models (SMM) are defined by Cannon-Bowers, Salas and Converse (1993) as:

> *“knowledge structures held by members of a team that enable them to form accurate explanations and expectations for the task, and, in turn to coordinate their actions and adapt their behavior to demands of the task and other team members”* (p. 228).

Several types of mental models have been identified that can be shared among team members (e.g. Cannon-Bowers & Salas, 2001; Langen-Fox, Anglim, & Wilson, 2004; Matthieu et al., 2000; Mohammed & Dumville, 2001). In general, two major content domains have been differentiated: job/task mental models and team mental models. Competent operators not only have to be proficient in task execution, but must engage in efficient team work in order to be successful. Other types of mental models include equipment models (Cannon-Bowers & Salas, 2001), task-action models (Young, 1983), domain and device models (Mogford, 1991) and mental models that represent the situation (Mohammed & Dumville, 2001). The number of models appears to depend on the domain and the team type being analysed. Although shared mental models are often interdependent (Cannon-Bowers et al., 1993), they differ on various characteristics, e.g. a shorter or longer lifecycle or technical vs. human relational contents.

2 Building a framework of SMM for air traffic controllers

In the future aviation environment many modifications are expected to ensure safe and efficient management of the ever growing air traffic. Many of these changes are assumed to affect the task and team performance of air traffic controllers. Shared mental models will become increasingly important to ensure high-level performance within and between flexible air traffic control (ATC) teams. It is therefore necessary to study SMM in this specific context. The application of SMM theory to a particular profession requires the selection and construction of an appropriate set of MM categories and the identification of mental models' functional contents. In this study, cognitive task analysis (CTA) was applied to explore MMs of en-route ATCOs. Often, cognitive activities are not completely open to an operator's introspection. In effect, it has been repeatedly suggested that task analysis is a prerequisite for studying shared mental models (Klimoski & Mohammed, 1994; Matthieu, Heffner, Goodwin, Cannon-Bowers, & Salas, 2005). In this context, CTA is viewed as a suitable and necessary method for analysing (shared) cognitive activities in complex and dynamic environments (Seamster, Redding and Kaempf, 1997). It attempts to objectively describe and explain mental components such as knowledge, and mental processes such as strategies required to carry out a task (Klein & Militello, 2001). In order to cover various cognitions and increase the validity of the CTA, different elicitation methods were combined. The CTA applied in this study had a focus on team aspects and included document analysis, observations, and interviews. Observations and interviews were conducted at the Area Control Centre of a Dutch Air Navigation Service Provider (ANSP).

Five MM categories were identified by the CTA: (1) Equipment, (2) Task, (3) Team Interaction, (4) Team and (5) Situational MMs. The structure of the framework describing each MM category including its knowledge contents and ATC-specific examples is shown in the Appendix. The framework builds on the SMM typology developed earlier by Cannon-Bowers, Salas and Converse (1993). The categories are domain general as they have been found in different teams and domains in previous research (e.g. Matthieu et al., 2005; O'Connor & Johnson, 2006). The framework also included the so-called Situation MM which applies to highly dynamic domains (Lim and Klein, 2006) and thus is potentially relevant to ATC performance.

The knowledge contents belonging to these MM categories enable an operator to work with the equipment, accomplish a task, interact with and anticipate the behaviour of team members, and assess situational cues. Knowledge contents are more specific as they depend on the task. In ATC teams for instance, the content "task procedures" make up an important part of the tasks whereas in creative project teams this might only rarely be the case.

The task analysis revealed that the ATCOs verbal report was not always consistent with the observational data. Moreover, ATCOs sometimes stated that tasks are not always executed on the work floor in the way they were theoretically described. For example, a shift change or changeover should take place according to specific procedures in order to ensure that all relevant information is transferred. In the operation room, however, a controller simply looks over his working colleagues’ shoulder to scan the radar and collect information. Changeover is automated so well that a thorough explicit information exchange only happens in case of unusual events. Consequently, operators may verbally reflect on their task and responsibilities differently than they actually apply this knowledge during operational work. The specific situation and individuals involved seem to determe how knowledge is applied. This distinction accounts for a 2-level approach of SMM which includes (1) the Reflection level and (2) the Action level. The Reflection level can be described as a broad picture of a profession. It depicts how an individual thinks about his work and what he considers important on a task and team level in order to execute this work. Components of the Reflection level are therefore not explicitly acquired by an individual. Rather they emerge as an opinion about the job by doing the job. The Reflection level of SMM can be assessed by asking people to describe their profession. The Action level of a SMM is very situation specific and therefore sensitive to the environment and the individuals involved. This level captures how knowledge is actually applied in multiple contexts depending on both external and internal factors. Therefore, it can only be assessed during task execution.

3 The study

In order to strengthen the theoretical fundament of the framework the current study focused on the Reflection level. It aimed at validating the SMM framework and assessed the degree of sharedness of air traffic controllers’ mental models. It was assumed that the framework is valid throughout the ATC domain. This means that ATCOs of different sectors and units should recognise the categories and knowledge contents to a similar degree. On this conceptual level, as it was tested here, air traffic controllers have a common understanding of their task and team functioning irrespective of their function, age or work experience.

In order to test these assumptions a broad pool of controllers was involved. Two Air Navigation Service Providers were asked to participate in the study, which will be referred to as ANSP 1 and ANSP 2. ANSP 1 has two control units, the Area Control Centre (ACC) and the Tower/Approach (TWR/APP). ACC controllers are part of a flexible team. They have several duties per week which typically results in ever-changing compositions of team members. For this reason, each controller is capable of fulfilling roles of both an executive controller (EC) and

a planner controller (PLC). Completely certified controllers work at all sectors of the area control centre at the airport. The main task of ACC controllers is to maintain safe and efficient air traffic control between 9500 ft and 24500 ft. They accompany aircraft on their way to and from the airport.
TWR/APP is the unit at ANSP 1 which is responsible for approaching, departing and local air traffic at the airport. There are different functions for TWR control (runway, ground, delivery, start-up ATCO) and APP control (departure, arrival ATCOs, approach planner) but a certified operator can work at either position. The area of responsibility comprises traffic flying beneath 9500 ft or taxing on the airfield. The task of TWR/APP is often described as more direct – compared to the more pre-planned actions at ACC – because of smaller error margins as aircraft are separated by at least five miles. The team and task environment at ANSP 1 can be described as stable since the last reorganisation took place in 1998.
The airspace of ANSP 2 is divided into three sectors, Hannover, Delta-Coastal and Brussels, and each sector is controlled by a unique team of en-route controllers and overseen by one sector supervisor. The sectors have their own procedures and ATCOs are certified for one sector only. The teams comprise a heterogeneous pool of controllers, accustomed to a varied team assembly, similar to ANSP 1. ANSP 2 employs 28 nationalities, working together in one environment. The task of an en-route controller is comparable to that of ACC controllers: they maintain safe and efficient air traffic control for all aircraft flying en-route at 24500 ft to unlimited, i.e. upper air space. The multinational area of responsibility includes parts of the Netherlands, North West of Germany, Belgium and Luxembourg.
Although the task of en-route and ACC controllers are very similar we included both groups since there are some interesting organizational differences. ANSP 2 underwent a reorganisation in October 2008 including roster changes. Since 1970 there were six fixed teams of six controllers per sector and controllers never worked together with members of other teams, the so called blind teams. To increase productivity, flexible team structures were formed in the reorganisation. As a result, team assembly and prior contact may vary on a daily basis. These changes make a comparison between the two ANSPs interesting, based on the assumption that the changes may have considerably restructured the controllers' mental models. It makes sense that some knowledge contents need to be adjusted to accommodate unfamiliar team members within the new team structures. Such an adaptation should cause the mental models to be temporary less stable.

In sum, we were interested in the validity of the framework and the similarity of mental models among different controllers. We assumed that the framework is valid throughout the ATC domain since tasks and competencies are very similar disregarding the specific function of a controller. However, because ANSP 2 controllers recently underwent organizational changes the recognition with the theoretical framework may be less strong.

> Hypothesis 1: The developed SMM framework is less valid for ATCOs at ANSP 2 than at ANSP 1.

In contrast to the organizational differences we expect to find consistency between controllers within teams of one organization. Even though there are individual differences, all controllers work in the same environment and underwent the same training.

> Hypothesis 2: Within teams the validity scores are consistent and unaffected by age, function or tenure.

Independent of the validity index of the framework, we propose differences in the amount of mental model sharedness between the two ANSPs. The new team roster structure at ANSP 2 may have activate different mental models per controller in order to adjust to the new situation. At ANSP 1 in contrary, past mental models still apply.

> Hypothesis 3: The ANSP 2 controller's mental models are less coherent with weaker SMM agreement in comparison to ANSP 1 controllers.

Finally, since the reorganization at ANSP 2 mainly concern team aspect we assume that the team type mental models are most affected.

> Hypothesis 4: The differences in mental models between ANSP 1 and ANSP 2 are most prevalent for the team interaction and the team mental model.

4 Method

4.1 Participants

In total 100 air traffic controllers participated in the study. Thirty seven participants (30 were male[1]) were employed at ANSP 1 at either ACC or TWR/APP. Sixty three participants (51 males) were en-route controllers at the ANSP 2.

4.2 Procedures

An e-mail invitation was sent to all ATCOs at ANSP 1 and ANSP 2. In the e-mail the purpose of the study was explained and controllers were asked to participate in a web-based card sorting task which they could access via a web link. Once they decided to participate they were redirected to a webpage comprising of instructions about how to complete the card sorting. On the next page participants could accomplish the sorting task by simple drag 'n drop technique. The task was successfully completed if all cards had been sorted. After the card sorting task a short questionnaire regarding demographic data followed. Participation was fully voluntary and possible for a period of three weeks.

4.3 Measures

Demographic data. Participants completed a questionnaire concerning personal data, i.e. gender, and age, and professional information, i.e. function(s), unit and the number of years they have been certified as an air traffic controller.

SMM framework validity and SMM similarity. In order to validate the SMM framework and compare MM similarity between air traffic controllers, a web-based card sorting task was developed. Card sorting is a time-efficient technique (Harloff & Coxon, 2007; Mohammed, Klimoski, & Rentsch, 2000), has good face validity (Langen-Fox, Code, & Langfield-Smith, 2000), and has recently been applied to assess mental models (e.g. Smith-Jentsch, Campbell, Milanovich, & Reynolds, 2001). Figure 1 shows a schematic interface of the application. The technique required participants to sort items along preliminary specified categories (here: blue columns). They were instructed to sort items (here: green rows) on the basis of perceived relatedness to each other. In Figure 1 for example, a participant just drags the item "Insight in each other" to the category "Team Category". "Insight in each other" in this case belongs to team knowledge and is related to the card "Mutual card" for instance. If a participants reconsider the sorting, he can easily drag a card to another category.

[1] Two participants did not specify their gender

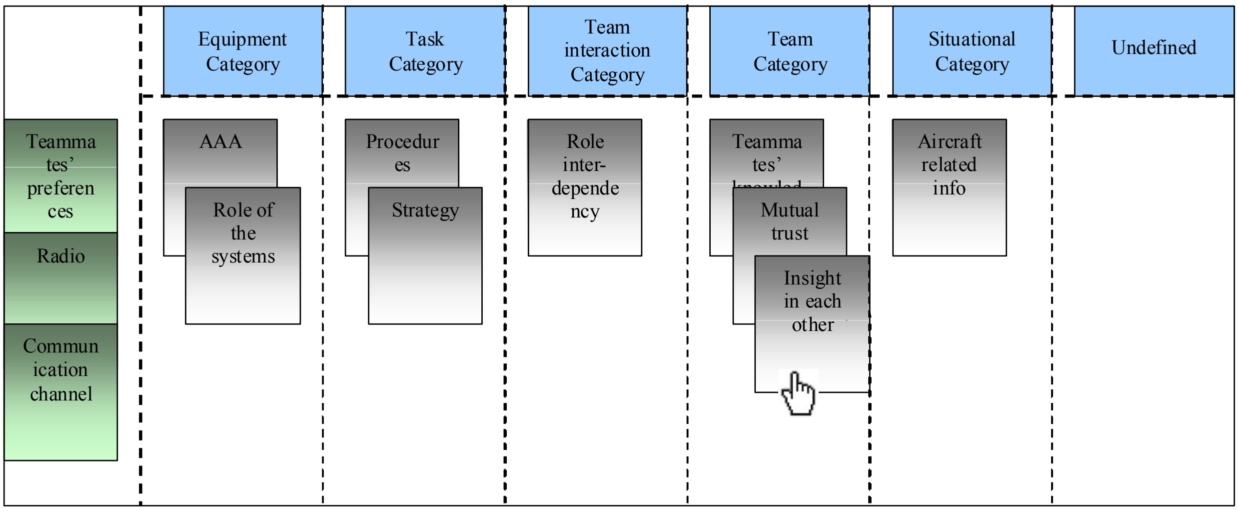

Figure 1. Schematic interface of card sorting task

The selection of the categories and the items was based on the previously defined five MM categories and the thirty knowledge contents of the SMM framework (see Appendix A). To prevent categorisation of irrelevant concepts, a sixth category "Undefined" was included. Additionally, ambiguous items were annotated with examples to create common understanding between controllers.
To check both, item labelling (since this was developed in cooperation with controllers from ANSP 1) and the usability of the task, five staff members from ANSP 2 took part in a pilot card sorting. Some items belonging to the Equipment MM were customised cause the systems have different names at ANSP 1 and ANSP 2 respectively.

5 Results

5.1 Demographic measures

Participants had an average age of 36 years (N = 93, SD = 8) and were in service for 12 years (N = 95, SD = 8) on average. Seven, respectively four data points were missing but were not replaced with the mean because of the relatively large number of missing data points. Of the 100 ATCOs 22 worked at ANSP 1 as TWR/APP controller and 15 as ACC controller. From the employees at ANSP 2 29 worked at the Hannover sector, 15 at Brussels and 19 at the Delta Coastal sector. In addition to their regular controller function, 22 participants were supervisors and 33 worked as operational experts[2]. Table 1 shows the distribution of the demographic variables over all participants and divided in the two ANSPs.

Table 1. Demographic variables

		N	SUP	OE	age	experience (in years)
ANSP 1	TWR	15	9	13	39 (*N* = 37, *SD* = 9)	14 (*N* = 37, *SD* = 9)
	ACC	22				
ANSP 2	HAN	29				
	BRU	15	13	20	34 (*N* = 56*, *SD* = 7)	10 (*N* = 58**, *SD* = 7)
	DEC	19				
Total	/	100	22	33	36 (*N* = 93*, *SD* = 8)	12 (*N* = 95**, *SD* = 8)

Note. * Seven missing data points. ** Five missing data points.

5.2 Validity of SMM framework

In order to evaluate the validity of the SMM framework each participant's sorting data was compared with the sorting of the framework. Cohen's Kappa was computed as a measure of agreement between the framework and a participant. For example, according to our theoretical framework the card "Insight in each other" belongs to the category "Team Mental Model". Cohen's Kappa then checks if a participant put this card into the same category while taking chance into account. Doing this comparison for each possible card results into one Cohen's Kappa for each participant. The average agreement of all air traffic controllers ($N = 100$) with the SMM framework was 0.39 ($SD = 0.14$). An independent sample t-test was conducted to compare the validity scores of ANSP 1 and ANSP 2 (hypothesis 1). ANSP 1 controllers' agreement with the framework was significantly higher ($M = 0.43$, $SD = 0.14$) than the agreement of ANSP 2 controllers ($M = 0.37$, $SD = 0.14$), as substantiated by the t-test ($t(98) = 2.33$, $p < .05$). This result confirms hypothesis 1. Validity scores within the organisation but between units were compared by conducting an independent t-test and a one-way ANOVA respectively. No significant difference was found between ACC ($M = 0.42$, $SD = 0.14$) and TWR/APP ($M = 0.45$, $SD = 0.14$; $t(35) = 0.65$, $p = .52$), nor between Hannover, Brussels and Deco ($F(6, 56) = 0.89$, $p = .64$). Furthermore, validity scores did not differ for age, work experience or function which is in accordance with hypothesis 2.

In order to gain more insight into shared and unshared components with the framework a qualitative analysis was conducted. Examining the individual data revealed two things. First, some knowledge contents were not assigned systematically to a specific category. The item "Information source" for example, was sorted inconsistently across all categories (see Figure 2). Second, as some items were either sorted into the Team MM or the Team Interaction model. It

[2] Operational experts are air traffic controllers who have a side track career in supporting activities in ATC.

was verified whether the two categories should be combined in order to gain a more realistic representation of controllers' mental models. After combining the Team MM and Team Interaction MM categories Cohen's Kappa amounted to 0.49 (*SD* = 0.12). In addition, a dependent t-test showed that controllers' mental models were more similar to the framework when the categories were merged than kept separated ($t(99) = -10.8$, $p < .01$).

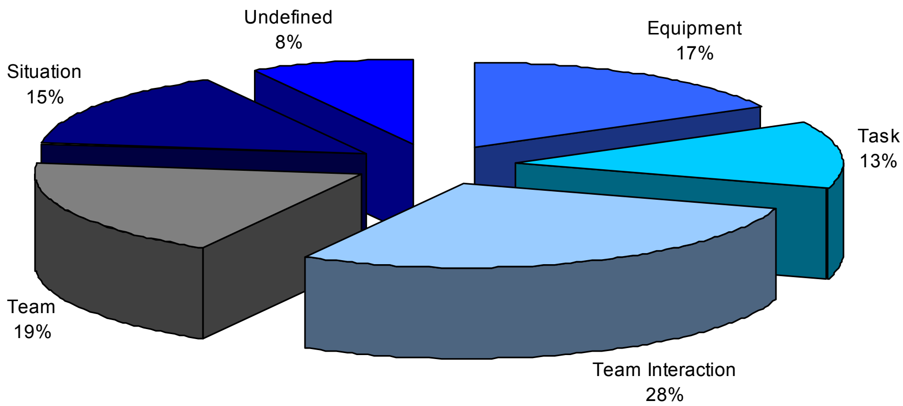

Figure 2. Category sorting of Information Source card

5.3 Similarity among participant

In order to assess the similarity of controllers' card sorting data Fleiss' Kappa was computed. Fleiss' Kappa is a generalisation of Cohen's Kappa for multiple raters. It is therefore is a good indication if controllers sorted items into the same categories, i.e. if they think similar. Fleiss' Kappa takes into account that some agreement between raters might be by chance only (Fleiss, 1971). The statistic is label dependent, i.e. not only takes into account if participants rate the same items to be related, but whether they are sorted in the same category, too. The values given here are the exact Fleiss' Kappa since this is the most reliable indicator for multiple rater agreement (Conger, 1980). When calculating Fleiss' Kappa, an overall value for the raters is given, i.e. the agreement between raters, as well as a value per category, i.e. the agreement within categories. This allows analysis of the agreement score in more detail.

The total agreement between all air traffic controllers was 0.37. The highest similarity score was found for the Equipment MM (*Kappa* = 0.67) and the lowest agreement score for the Team Interaction MM (*Kappa* = 0.23). The same pattern was prevalent when examining similarity scores split up in controllers of ANSP 2 (*Kappa* = 0.35) and ANSP 1 (*Kappa* = 0.41). These results give evidence for hypothesis 3 but not hypothesis 4. The main results regarding validity and similarity scores are depicted in Figure 3. Taking the demographic variables into account the similarity scores for those subgroups were checked. From all these groups the supervisor at ANSP 1 and the experienced controllers (i.e. 5-10 years of work experience) at ANSP 2 had the

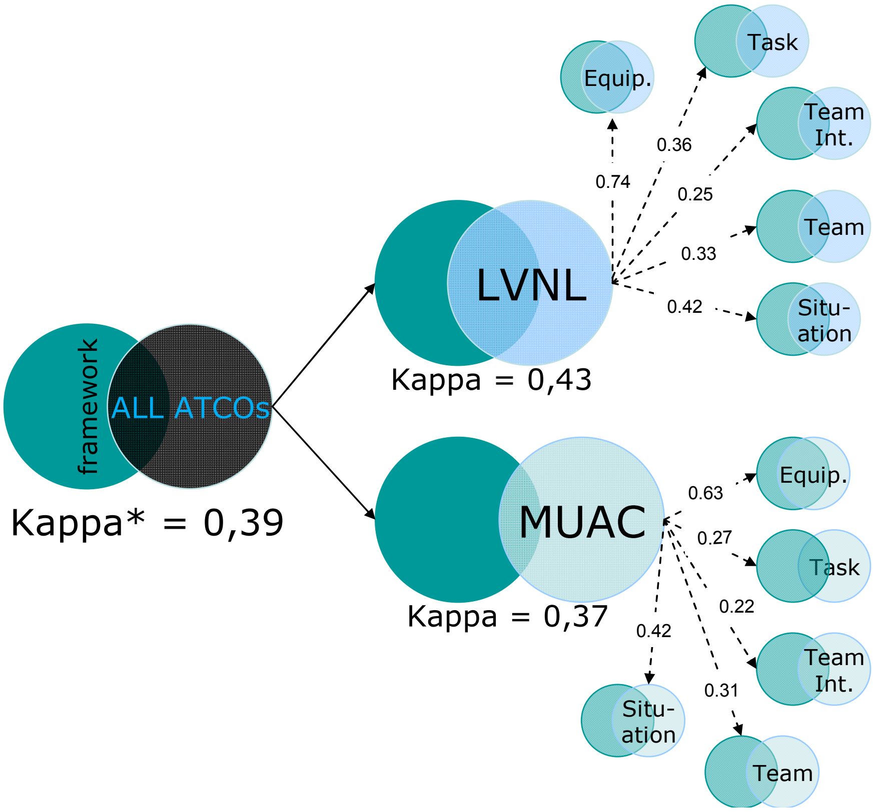

Figure 3. Summary of Agreement between ATCOs and within categories

Note. *=Cohen's Kappa; Equip. = Equipment; Team Int. – Team Interaction

highest agreements on the MMs. Within ANSP 1 it was noticeable that MM agreement of ACC controllers was slightly lower (*Kappa* = 0.39) than agreement between TWR/APP controllers (*Kappa* = 0.45) whereas at ANSP 2 agreement in the three different sectors was very similar (*Kappa* = 0.35 or 0.36). The variation at ANSP 1 is mainly due to a substantial difference in the Team MM for which TWR/APP has a Kappa of 0.43 and ACC has a Kappa of 0.28. Results indicate that ACC and TWR/APP have a different understanding of team concepts although they belong to the same organisation and have similar team structures. There might be a latent factor, such as team attitude, which should be assessed in future analyses.

6 Discussion

The aim of the current study was (a) validating an earlier developed shared mental model framework tailored for air traffic controllers and (b) assessing the degree of sharedness among controllers. Averaged over the ATCOs in the study a medium agreement with the framework was found. In other words, when ATCOs categorize simplified knowledge elements into mental model categories, they chose different categories than we would assume on a theoretical background. Comparable rather low scores were found in a card sorting study elsewhere (Smith-Jentsch et al., 2001), which call the applicability of card sorting for validity and similarity purposes into question. The card sorting task was chosen for the present study because it has the advantage of being time and cost efficient, approaching a high number of participants, and reflecting the human cognitive architecture. However, the question remains, whether this method is appropriate to captures SMM in their full depth. The results show that participants had problems categorizing the more abstract and less tangible items. An explanation is that the terminology used for the items might not have matched with the terminology of the controllers. However, a more precise and applied description of the items is beyond the scope of card sorting since the core of the method is the categorisation of concepts. It may be concluded that card sorting is adequate but restricted to assess SMMs on a Reflectional level. This implies that the framework at the moment covers a relatively theoretical representation of the controllers' knowledge structures. A more deep understanding requires an expansion to the SMM's Action level. This level can be approached by focusing on how controllers apply their (shared) knowledge during task execution, which may include rather complex aspects such as communication analysis or evaluation of behavioural markers.

As expected, the framework better represents the mental model's structures of controllers at ANSP 1 than at ANSP 2. However, agreement on the framework was the same within each organisation, irrespective of age, function, or work experience. A qualitative analysis of the data revealed inconsistent sorting of items belonging to either the Team or Team Interaction MM category. A combination of the two categories better represents controllers' cognitive structures. This implies that the framework does not necessarily need to differentiate between Team and Team Interaction MM.

Controllers showed a moderate agreement of categorising mental models. ANSP 1 controllers had slightly higher agreement scores than ANSP 2 controllers. However, the hypothesis that these differences are most prevalent for the Team Interaction and Team MM could not be confirmed. A detailed examination of the ratings instead showed that participants substantially agreed upon the knowledge contents of the Equipment MM and poorly upon the contents of the Team Interaction MM.

The finding that controllers at ANSP 2 identify less with the framework and share less knowledge contents than controllers at ANSP 1 agrees with the hypotheses. The recent reorganisation at ANSP 2 explains these results. At both ANSPs, operators may work together now but have not cooperated for a couple of weeks. Controllers at ANSP 2, however, are unfamiliar with this new team composition and might still be adapting to it. They need to adjust and expand their knowledge about team functioning or processing, and explore how these changes fit into existing knowledge structures, resulting in less stable mental models. For example, the item “roles and responsibilities” refers to knowledge contents about how roles in a team are assigned and which responsibilities this entails. It helps a team member to understand what another member is doing in the team, when and why. For ATCOs at ANSP 2, however, it might be difficult to adequately judge their position in a team since the team structures have changed recently. The ANSP 2 controller necessarily falls back to clearly defined task procedures to determine roles and responsibilities in the team. In this case “roles and responsibilities” are thus more related to the Task MM than to the Team Interaction MM. Regarding SMM theory the present results imply that SMM can be subject to change and can be dynamically adjusted when external circumstances change. From a practical point of view, organisations should be aware of this dynamics if they plan reorganisations. Eventually, knowledge that is applied inconsistently or wrongly will lead to severe consequences for performance.

To conclude, the present study describes the different categories of MMs and their knowledge contents connected to air traffic control functions. The moderate agreement scores of controllers with the previously developed framework and with each other provide insight into the MMs that were compared in different organisations. The usefulness of card sorting, to assess validity and similarity scores, was discussed. Since the method mainly focuses on the Reflection level of SMM, future research should focus on the Action level of SMM to fully understand SMM theory in applied team contexts, namely during task execution. This approach allows gathering explicit information about how shared knowledge guides behaviour and leads to efficient and successful team performance.

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Appendix A SMM framework of air traffic controllers

MM categories	MM knowledge content	Examples
Equipment MM = knowledge about role and limitation of the most important systems	Radar system	Features of the radar systems
	Radio	Features of the radio
	Flight data progressing	Features of the data processing
	Role of the systems	Indispensability
	Limitations of the equipment	System failure
Task MM = knowledge about guidelines & rules how to execute the ATC task under different circumstances and external limitations	Task procedures	Contact military if loss of contact of an aircraft is more than two minutes
	Generic guidelines	Handover guidelines; briefing sheets
	Likely contingencies/ unusual occurrences	Thunderstorm
	Likely scenarios	(Morning) peak; holding
	Task strategies	Solve inbound sequence always in team
	Environmental constraints	Inactive area
	Organizational influences	Error culture
	Cultural influences	Nationality
Team Interaction MM = knowledge about how to interact within and between teams	Roles & Responsibilities	The EC[a] delivers service to all general air traffic flights in the executive area
	Role interdependency	PLC[b] filters information for EC
	Information source	Colleague; radar
	Information flow	From PLC to EC to pilot
	Communication medium	Verbal or datalink
	Interaction pattern	PLC coordinates for EC
	Giving and receiving feedback	Debriefing after shift
Team MM = knowledge about the team members, others teams and relational knowledge	Teammates KSAs[c]	Teammates English skills
	Teammates' personal preferences	Display settings
	Teammates' operational preferences	Direct routing
	Insight in each other	PLC tries to look into EC's head
	Mutual trust	Teammates help each other out
Situation MM = actively collected info and the combination of it to one mental picture	Situation assessment	Being aware what is happening around you
	Aircraft related information	Aircraft position
	Information sharing at right point in time	Transfer information according to workload at a specific moment