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# Simulation of Team Cooperation Processes in En-Route Air Traffic Control

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Additional information is available at the end of the chapter

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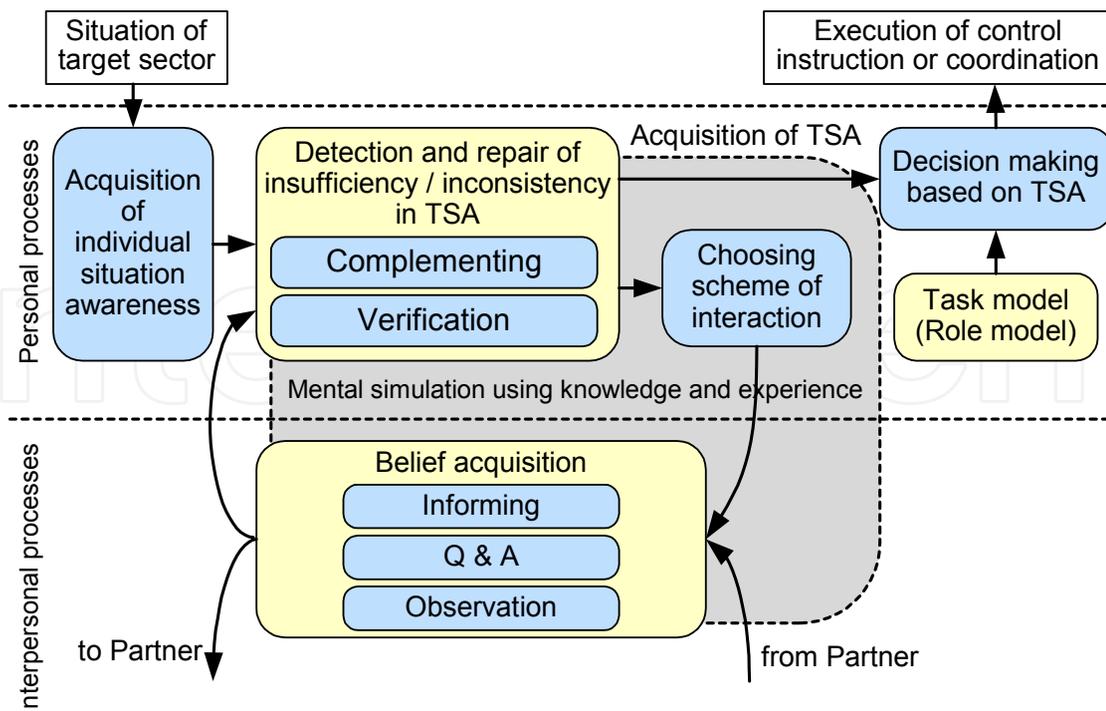
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## 1. Introduction

Recent increase in air traffic demands makes the role of Air Traffic Control (ATC), which supports safety and efficiency of aviation, more important than ever. As aviation technologies have progressed, automation and computer supports are being introduced in cockpits, but ATC still heavily relies on human expertise of Air Traffic Control Officers (ATCOs). It is therefore necessary to understand ATC tasks from a viewpoint of ATCOs' cognitive behaviour in order to assess and improve task schemes and training programs for ATC.

There are a few different phases in ATC, but this study exclusively focuses on en-route ATC. En-route ATC is performed by a team of ATCOs usually made up with a Radar Controller (RC) and a Coordination Controller (CC). RC monitors the radar screen, communicates with air pilots by radio, and gives instructions to them, while CC makes coordination with CCs in charge of other sectors, and supports RC. Team cooperation is therefore a key issue for good control performance, and study on team cooperation processes is an important issue.

We have been studying team cooperation processes in en-route ATC based on ethnographic field observation, and already proposed a cognitive model of team cooperation in en-route ATC as shown in Fig. 1 (Furuta et al., 2009; Soraji et al., 2010). In this model, establishment of Team Situation Awareness (TSA) on the air traffic is a key process for smooth cooperation. TSA here can be defined as a combination of individual situation awareness (Endsley, 1995) and mutual beliefs on it (Shu & Furuta, 2005). Once TSA has been established, individual tasks will be planned and executed almost implicitly, and TSA almost determines decision by ATCOs. The cognitive processes of a controller team after TSA acquisition are well described by a distributed version of the recognition-primed decision model (Klein, 1997).



**Figure 1.** Cognitive model of team cooperative processes

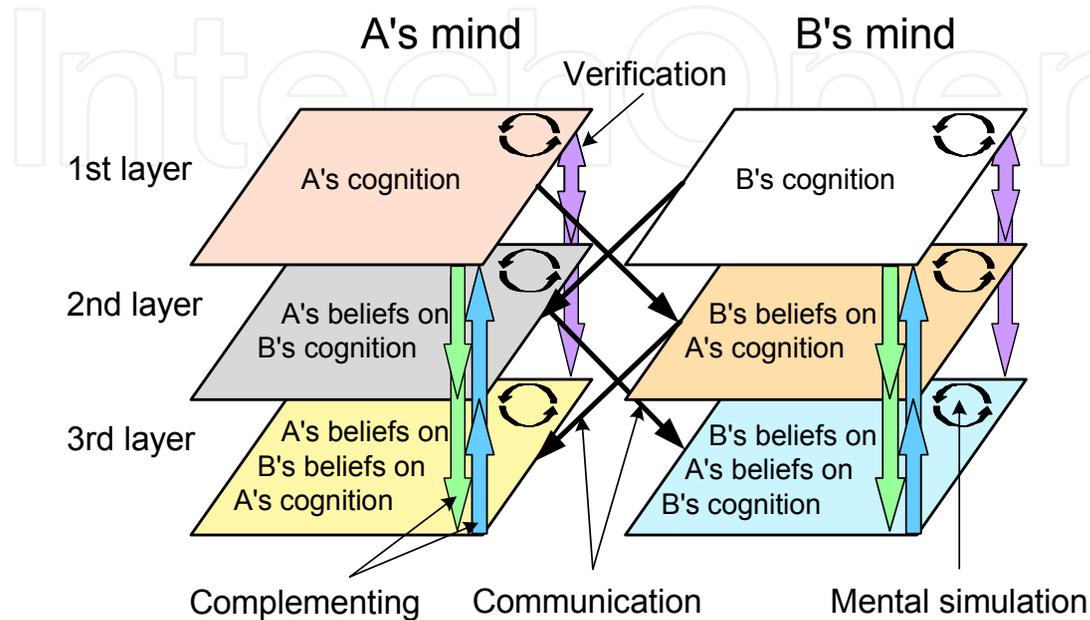
Though the proposed cognitive model can explain the primary features of team cooperation in en-route ATC, it is still static and cannot explain dynamics of the processes. The aim of this research is to study detailed cognitive processes and communication strategies for establishing TSA using computer simulation. Computer simulation has been a useful tool in cognitive systems engineering for validation and sophistication of cognitive models (e.g., Furuta & Kondo, 1993; Cacciabue & Cojazzi, 1995; Cacciabue, 1998; Chang & Mosleh, 2007; NASA, 2011), because no ambiguities are allowed in coding executable computer programs for simulation. Interaction schemes and communication strategies for establishing TSA were discussed in our previous study, and computer simulation is a good approach also to reveal how ATCOs organize these schemes and strategies in their actual field settings.

## 2. Theoretical backgrounds

This study as well as our previous study relies on the Mutual Belief Model (MBM) as the theoretical basis. MBM is represented as a three-layered structure of items believed by team members, and it is a framework to explain how a team of individuals can coordinate their tasks smoothly to achieve shared team goals (Kanno, 2007). It is premised in MBM that there is a layered structure of human beliefs for all cognitive constructs and that establishing its consistency enables one to cooperate his/her partners. Figure 2 illustrates MBM for a team with two members, A and B. The layered structure theoretically repeats ad infinitum, but considering the first three layers will be enough in the real situation.

The first layer is the place to describe ones own cognition: what are perceived, recognized, believed, predicted, intended, planed, and so on. The second layer is for describing ones

beliefs on his/her partner's cognition, and it reflects partner's first layer. The third layer describes ones beliefs on partner's beliefs on his/her own cognition, which are the self-image through the partner. Information not only on the environment but also on partner's cognition is used in team cooperation, and all of them are described in the layers of beliefs in MBM.



**Figure 2.** Mutual Belief Model and interaction schemes

Each belief item in this structure is obtained through internal or interpersonal interactions as well as through perception directly from the environment. There are four types of interactions: verbal and nonverbal communication, mental simulation (inference), complementing (presumption), and verification (consistency check). Communication is a process to transfer some belief item from one person to another by explicit utterance or observation. Mental simulation is a process to derive new belief items from some others within the same MBM layer by inference. In complementing, some belief item will be copied from one MBM layer to another within the same person. Verification is comparison of belief items between different MBM layers within the same person to check consistency among mutual beliefs.

Manifestation styles of interpersonal interactions are threefold: informing, query and answer (Q&A), and observation. Informing is an interaction to transfer some information from one person to another. This interaction is carried out by writing into a flight data strip as well as by verbal communication in ATC. Q&A is a combination of requesting information and corresponding reply to the request. This interaction is carried out almost verbally and it is used primarily for verification. Query is also used for the purpose of informing, and no replies are returned often in such a case. Observation is guessing partner's cognitive processes or mental states from his/her performance. The observed obtains a belief that he/she is being observed in most cases.

### 3. Review of field observation

#### 3.1. Field observation

This work is based on the same data from the field observation of our previous work [1, 2]. The field observation was performed at the Tokyo Area Control Centre from 7 to 11 of May, 2007 during time periods of around three hours a day with relatively heavy traffic in the daytime so that the traffic imposed a certain level of workload on ATCOs. Different RC-CC pairs who were on a shift for the target sector were observed, but neither other sectors nor shift supervisors were observed. The target of observation was a sector called "Kanto-north" (T03), which spreads over the northern area of Tokyo. A lot of air traffic that departs from and arrives at two hub airports, the Tokyo International Airport (HND) and the Narita International Airport (NRT), smaller airports, and Air Force Bases (AFBs) passes through this sector.

Behavior of ATCOs was vide-recorded with two home video cameras, and another one recorded the radar screen of an auxiliary console where the same screen image was displayed that RCs were monitoring. An IC recorder attached on the controller console above the radar screen was used to record conversation between ATCOs. Flight data and radio communication records were also provided from the control centre. Combined video-audio records were made from the audio data and the video data of the radar screen synchronizing their time stamps. Radio communication and conversation between ATCOs were then transcribed, and speakers and listeners of conversation were identified. Actions of ATCOs were next recognized from the video data and added to the transcribed protocol data.

With the help of a rated ATCO, we segmented the protocol data by the basic unit of ATC instruction, clarified relations between segments, and identified expert knowledge and judgment behind them. Distributed cognitive processes among ATCOs were then inferred and reconstructed from the field data following the classification framework of MBM interactions. First we did not classify utterances themselves into particular categories but focused on reconstruction of MBM interactions. When we constructed a team cooperation model afterwards, we considered correspondence between the both and interaction schemes to classify utterances considering manifestation of communication.

#### 3.2. Reclassification of interactions

The classification of interactions given in the previous chapter is a little ambiguous to describe precise processes of team cooperation; we will modify the classification slightly. Since interactions are basically information transfer from somewhere to somewhere, they are classifiable by the origin and the destination of information transfer. Table 1 summarizes the new classification.

Perception is a special interaction that the perceiver acquires information actively or passively from his/her working environment rather than another person. The acquired information is added into the first layer of the perceiver. Transmission (informing) is a verbal communication to

transfer information from the speaker to the listener. If the speaker talks his/her own cognition, the information is transferred from speaker's first layer to listener's second layer. If the speaker talks his/her belief on listener's cognition, the information is transferred from speaker's second layer to listener's third layer. Observation is a nonverbal communication of observing partner's behavior to get belief on his/her belief in observer's second layer. Completion is a subcategory of complementing in the previous chapter. It is a process to accept what is believed by ones partner as his/her own belief; it is achieved by copying the belief item from the second to the first layer. Assumption is another subcategory of complementing, where one assumes that what he/she said to the partner is accepted. It is achieved by copying the belief item from the third to the second layer. Completion and assumption are mirroring processes between the speaker and the listener. Inference is the same process as the mental simulation in the previous chapter that derives new belief items from some others within the same layer. Query is a request of transmission for verification of the consistency of belief items in different layers.

Interaction	Type	Origin	Destination
Perception Transmission	Personal	Environment	1st layer
	Interpersonal	1st layer	2nd layer
		2nd layer	3rd layer
Observation	Interpersonal	1st layer	2nd layer
Completion	Personal	2nd layer	1st layer
Assumption	Personal	3rd layer	2nd layer
Inference	Personal	1st layer	1st layer
		2nd layer	2nd layer
		3rd layer	3rd layer

**Table 1.** Classification of interactions

### 3.3. Visualizing analysis results of field data

In order to exactly describe interactions between ATCOs including internal cognitive processes, we defined several classes of mental constructs, which are basic and unit description of beliefs in ATCO's MBM structure. Using the mental constructs, the results of cognitive task analysis of our previous work were transcribed down in a formal expression similar to predicate. The following are primary mental constructs and their meanings.

*focus(Aircraft1, Aircraft2, ...)*

*Attend and handle Aircraft1, Aircraft2, and so on in a group.*

*priority(Aircraft1, Aircraft2, ...)*

*The priority among Aircraft1, Aircraft2, and so on is in this order.*

*instruction(Aircraft, Parameter, Value)*

*Give Aircraft an instruction to keep Parameter at/below/above Value.*

*constraint(Aircraft, Parameter, Value)*

*Consider a constraint for Aircraft to keep Parameter at/below/above Value.*

*execute(Action, Arg1, Arg2, ...)*

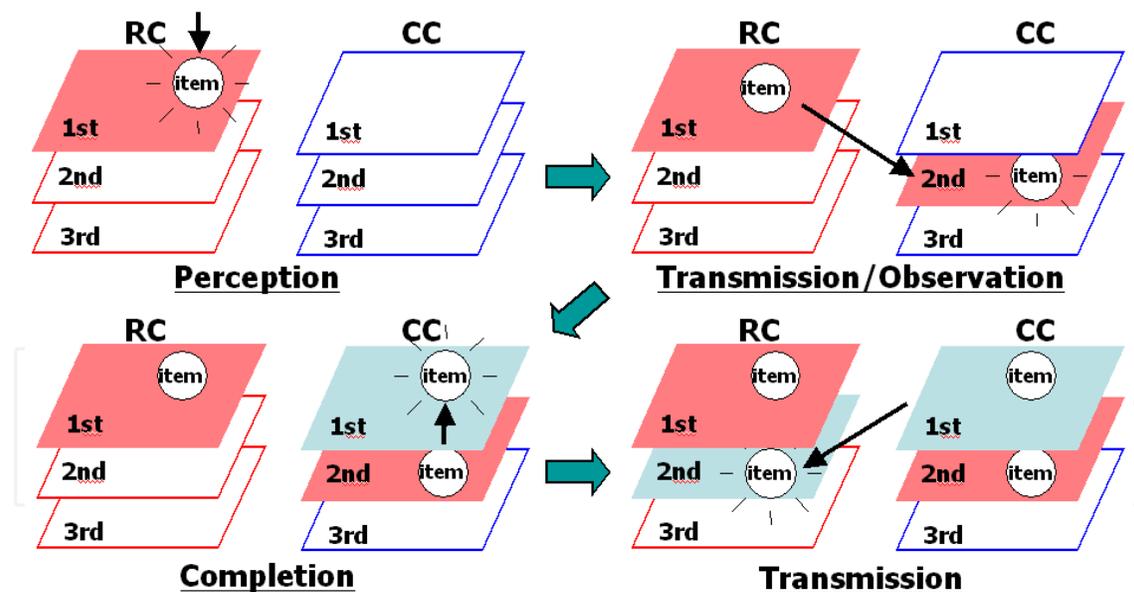
*Execute an Action with arguments of Arg1, Arg2, and so on.*

Describing analysis results in such a representation enables one to compare them easily with those of computer simulation.

### 3.4. Features of team interactions between ATCOs

In this study, we first developed a tool for visualizing the analysis results of the previous work on team interactions for detailed review. The same tool is also used later to visualize simulation results. The tool reads a file of formal descriptions of analysis or simulation results, and chronologically visualizes interactions between ATCOs by animating moves of information between MBM layers. Consequently, four features of team interactions have been found from the visualization. These features provide valuable hints and justifications in constructing a simulation model of team cooperation processes.

The first feature is the dominance of RC, which means that RC's cognition often starts a sequence of team cognitive processes. Perception by RC and succeeding transmission of the perceived information are frequently observed in the field data. Observation by CC on RC's behaviour is substitutive for transmission by RC in the above. Information transfer from RC to CC is more frequent than that in the opposite direction. Questioning by RC to CC is sometimes observed, but it is primarily for informing CC of RC's thought to request CC's support rather than literally asking CC's thought. Team cognitive processes are thereby paced by RC's cognition.



**Figure 3.** Interaction pattern for efficient TSA development

Secondly a recent topic is likely to be focused on in team interactions and deliberated further. It is the so-called recency effect, which is frequently observed in general cognitive processes.

The third finding is that an efficient pattern of TSA development often appears. Figure 3 shows a case where the pattern starts from perception of something by RC. The perceived

item is transferred to the second layer of CC by transmission or observation in the next moment. CC then copies the item to the first layer by completion and informs RC of his/her belief to make another copy of the item in RC's second layer. Having finished all these steps successfully, the team has copies on the same belief item in both the first and the second layer, and they form sound TSA. The complementary pattern exists that starts from perception by CC.

Finally, after having acquired TSA, ATCOs will start interactions for deepening their thoughts based on the acquired TSA like considering strategies for the focused issue.

## 4. Simulation model

### 4.1. Flow of simulation

Computer simulation of interactions between RC and CC has been developed. Each member of the team is modelled as an agent in the simulation system: RC agent and CC agent. The both agents repeat choosing and executing a cognitive task to modify beliefs by referring to its own mutual belief module. Figure 4 illustrates the flow of simulation.

Each agent first looks at the mutual belief module and create a list of cognitive tasks applicable to the current situation. A cognitive task is represented as a production rule, which consists of the condition part and the action part. The general rules related to basic interactions for establishing TSA are hard-coded in the agents, and their implementation is explained below.

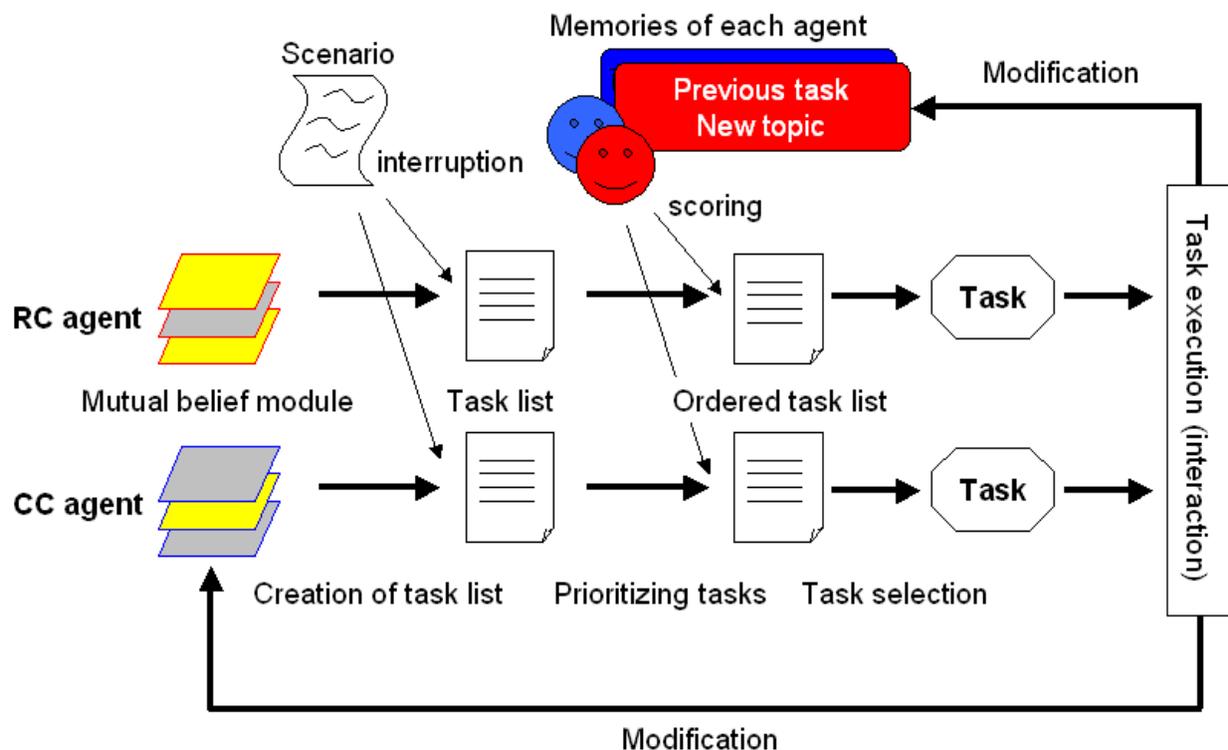


Figure 4. Flow of simulation

**Observation (obs):** If an agent executes any task visible to the partner agent, the latter will see the task and create the corresponding belief item in its second layer.

**Completion (com):** If any belief item contained in the second layer of an agent is missing in the first layer, the agent tries to copy the item into the first layer.

**Assumption (ass):** If any belief item contained in the third layer of an agent is missing in the second layer, the agent tries to copy the item into the second layer.

**Inference (inf):** A production rule fetched from the rule base is applied, if the rule is applicable to the present situation. Since this simulation exclusively focuses on team cooperation processes, it does not deal with the domain expertise specific to ATC explicitly. Expert judgment and inference are modelled as simple application of predefined rules that are very specific to each simulation case.

**Perception (per):** All perception tasks are predefined in the simulation scenario and they are triggered by time as interruption. Simulation scenarios are to be set up based on the field observation data, if simulation is to be done for the situations observed in the field.

**Transmission (trn):** If any belief item in agent's first layer does not exist in its second layer, the agent attempts to inform the item to the partner agent, i.e., tries to copy the item into the second layer of the partner agent. In execution of transmission, the transmitter agent also copies the item also into the third layer of its own, assuming that transmission is successfully done.

There is another kind of cognitive task, execution (exe), which is to execute some control action like hand-off, point-out, or giving a control instruction to a pilot. Execution is triggered as a result of rule application by inference. Query (qry) is not yet implemented in the present simulation model.

## 4.2. Prioritization of cognitive tasks

The agents next prioritize cognitive tasks in the created task lists. Cognitive tasks are scored referring not only to the basic score predefined for each task type but also to the past records of simulation hold in the memory models. When a cognitive task is triggered, its basic score shown in Table 2 is first given. The recency effect observed in the field data can be taken into consideration by adding a bonus if the task is related to the belief item created in the previous simulation step. If a particular sequence appeared between the successive tasks, another bonus will be added, which promotes the interaction pattern for efficient TSA development discussed in the previous chapter. After scoring, the task with the highest score is chosen and executed.

The scores have been adjusted so that simulation can well replicate the interactions observed in the actual ATCOs, and Table 2 lists the final scores.

The degree of match between the analysis of observation data and the simulation results was evaluated in three levels. If simulation could predict exactly a task appeared in the field

data, it is labelled “perfect match.” An internal task that is unobservable from the outside of an individual but predictable will be labelled “predictive match,” if it is included in the simulation results. “Essential match” means that a pair of tasks in the observation data and the simulation results has the same effects on mutual beliefs, though they are different in appearance.

Task type or task sequence	Score	Explanation
Perception (per)	600	Basic score
Transmission (trn)	100	Basic score
Observation (obs)	0	Basic score
Completion (com)	100	Basic score
Assumption (ass)	100	Basic score
Inference (inf)	200	Basic score
Execution (exe)	500	Basic score
Transmission → Assumption	300	Bonus for efficient TSA development
Perception → Transmission	100	Bonus for efficient TSA development
Inference → Transmission	100	Bonus for efficient TSA development
Transmission → Completion	100	Bonus for efficient TSA development
—	100	Bonus for the recency effect

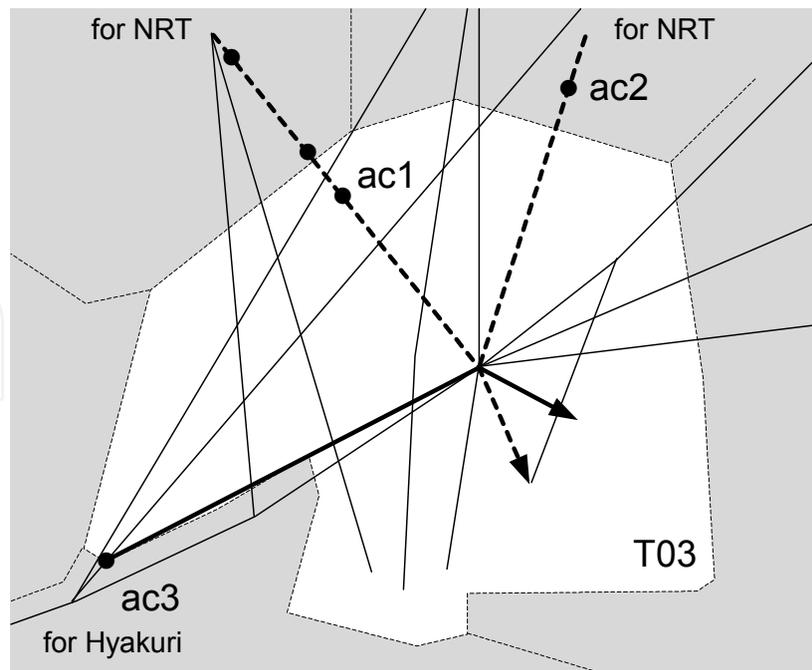
**Table 2.** Scores for prioritizing cognitive tasks

A measure of TSA appropriateness is completeness, which is defined as the ratio of belief items shared by the two corresponding belief layers of a team over the total number of belief items in the mirrored layer of the pair [4]. In these case studies, completeness of the second MBM layers was evaluated, and one should notice that just belief items relevant to related aircrafts were considered in simulation. Consequently, the results are more extreme than in the real situation, where ATCOs conceive belief items irrelevant to related aircrafts. Another measure, soundness, was ignored in this study, because no error mechanism was considered in the simulation model of this work and the soundness of TSA will be almost 100% in any case.

### 5.1. Case 1 (P.M, may 7, 2007)

In the first case (Fig. 5), the controller team dealt with a situation where three aircrafts bound for NRT from the northwest, the first one of which is denoted ac1 below, and another one from the north, ac2, was entering the sector almost at the same time. In addition, a warplane, ac3, were approaching from the southwest to cross over the flight path towards NRT, and it might interfere one of the four aircrafts. The controller team discussed and decided the order of aircrafts descending toward NRT while managing separation of the warplane from the others.

Table 3 compares simulated and observed interactions in this case. Items printed in italics were given in the simulation scenario and those in bolds show matched items between simulation and observation.



**Figure 5.** Situation of traffic in Case 1

Having watched the radar screen, RC judged the priority between ac1 and ac2 as ac1 should go first. CC recognized that RC was considering the order of ac1 and ac2 through observation of RC, CC asked a question on RC's judgment in the field, while RC transmitted its judgment explicitly to CC in simulation. RC then recognized that ac3 would interfere the other aircrafts, and CC proposed to instruct ac3 to go down in advance. RC agreed and proposed a particular altitude of descent as FL130, but CC came to know that ac3 should be kept above FL170 as a result of coordination with Hyakuri AFB control. Meanwhile, RC continued monitoring the positions of aircrafts, and CC observed these actions. CC proposed to change the order of aircrafts as ac2 should go first, and transmitted this judgment to RC.

Among 26 interactions that were extracted from the field data, four items were used to setup the simulation scenario, and simulation successfully replicated 18 items: 81.8% (18/22) of interactions observed in the field data. The order of appearance of interactions was almost the same. Two queries observed in the field were simulated as transmissions, and two transmissions by CC were not simulated. Four transmissions by RC predicted by simulation were not executed actually, and no assumptions were observable in the field.

The assessment result of TSA is shown in Fig. 6. Completeness of both RC and CC sometimes degrades, when one of them perceived new information or generated new belief items by inference. It was however recovered soon by verbal communication. TSA completeness of CC was slightly better than that of RC, but difference was very small, because they kept close verbal communication for deciding the priority of related aircrafts.

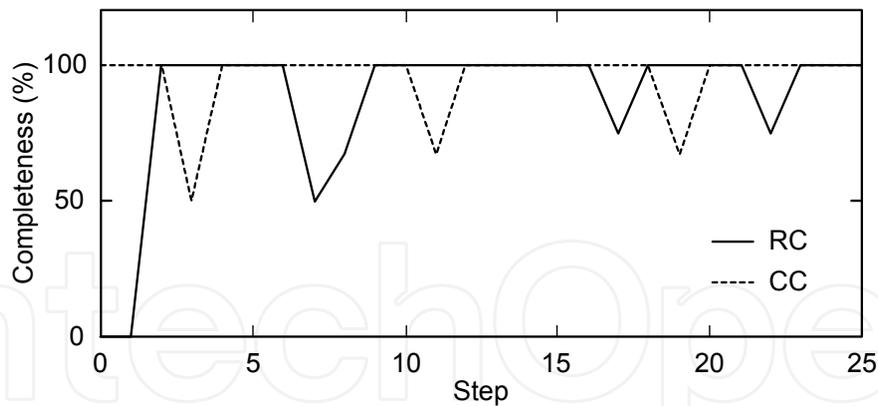
Simulation		Observation	
Step	Actor and action	Time	Actor and action
0	<i>RC: per - focus(ac1, ac2)</i> <b>CC: obs - focus(ac1, ac2)*</b>	14:07:40	<i>RC: per - focus(ac1, ac2)</i> <b>CC: obs - focus(ac1, ac2)*</b>
1	RC: trn - focus(ac1, ac2) <b>CC: com - focus(ac1, ac2)+</b>	14:07:47	<b>RC: inf - priority(ac1, ac2)+</b> <b>CC: qry - priority(ac1, ac2)^</b>
2	RC: ass - focus(ac1, ac2)		<b>CC: com - focus(ac1, ac2)+</b>
3	<b>RC: inf - priority(ac1, ac2)+</b>		<b>CC: com - priority(ac1, ac2)+</b>
4	<b>RC: trn - priority(ac1, ac2)^</b>	14:08:09	CC: trn - priority(ac1, ac2)
5	RC: ass - priority(ac1, ac2) <b>CC: com - priority(ac1, ac2)+</b>		
6	<i>RC: per - focus(ac1, ac2, ac3)</i> <b>CC: obs - focus(ac1, ac2, ac3)*</b>		<i>RC: per - focus(ac1, ac2, ac3)</i> <b>CC: obs - focus(ac1, ac2, ac3)*</b>
7	RC: trn - focus(ac1, ac2, ac3) <b>CC: com - focus(ac1, ac2, ac3)+</b>		<b>CC: com - focus(ac1, ac2, ac3)+</b>
8	RC: ass - focus(ac1, ac2, ac3) <b>CC: inf - instruct(ac3, alt down)+</b>	14:08:22	<b>CC: inf - instruct(ac3, alt, down)+</b>
9	<b>CC: trn - instruct(ac3, alt, down)*</b>		<b>CC: trn - instruct(ac3, alt, down)*</b>
10	<b>RC: com - instruct(ac3, alt, down)+</b> CC: ass - instruct(ac3, alt, down)		<b>RC: com - instruct(ac3, alt, down)+</b>
11	<b>RC: inf - instruct(ac3, alt, 130)+</b>		<b>RC: inf - instruct(ac3, alt, 130)+</b>
12	<b>RC: trn - instruct(ac3, alt, 130)*</b>	14:08:48	<b>RC: trn - instruct(ac3, alt, 130)*</b>
13	AC: ass - instruct(ac3, alt, 130) <b>CC: com - instruct(ac3, alt, 130)+</b>		<b>CC: com - instruct(ac3, alt, 130)+</b> CC: trn - instruct(ac3, alt, 130)
17	<i>CC: per - constraint(ac3, alt, 170)</i>	14:08:57	<i>CC: per - constraint(ac3, alt, 170)</i>
18	<b>CC: trn - constraint(ac3, alt, 170)*</b>	14:09:51	<b>CC: trn - constraint(ac3, alt, 170)*</b>
19	<i>RC: per - focus(ac1', ac2')</i> CC: ass - constraint(ac3, alt, 170)		<i>RC: per - focus(ac1', ac2')</i>
20	<b>RC: trn - focus(ac1', ac2')^</b>	14:10:01	<b>RC: qry - focus(ac1', ac2')^</b>
21	AC: ass - focus(ac1', ac2') <b>CC: com - focus(ac1', ac2')+</b>		<b>CC: com - focus(ac1', ac2')+</b>
22	<b>RC: com - constraint(ac3, alt, 170)+</b> <b>CC: inf - priority(ac2, ac1)+</b>	14:10:27	<b>CC: inf - priority(ac2, ac1)+</b>
23	<b>CC: trn - priority(ac2, ac1)*</b>	14:10:55	<b>CC: trn - priority(ac2, ac1)*</b>
24	<b>RC: com - priority(ac2, ac1)+</b> CC: ass - priority(ac2, ac1)		<b>RC: com - priority(ac2, ac1)+</b> <b>RC: com - constraint(ac3, alt, 170)+</b>

*Italics:* Items given in the simulation scenario.

**Bolds:** Items matched between simulation and observation.

(\* Perfect match + Predictive match ^ Essential match)

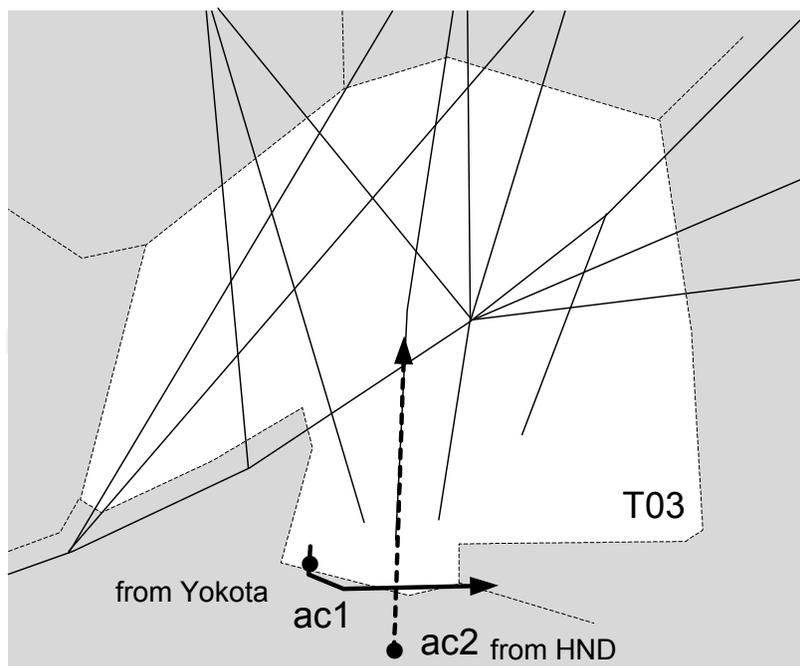
**Table 3.** Comparison of simulated and observed interactions in Case 1



**Figure 6.** Completeness of the second MBM layers in Case 1

### 5.2. Case 2 (P.M. may 11, 2007)

In the second case (Fig. 7), an aircraft, ac1, departed from Yokota AFB and flew along the southernmost boundary of Sector T03 eastward to the Pacific Ocean. Many aircrafts departed from HND and NRT passed through the area during this time period; ATCOs had to concern about traffic interference. Another aircraft, ac2, departed from HND was climbing northward. Since the approach areas of NRT, HND and Yokota as well as neighboring sectors overlap in this area, demands for coordination with other sectors are relatively high.



**Figure 7.** Situation of traffic in Case 2

Table 4 compares simulated and observed interactions in Case 2. At first, RC recognized the necessity of pointing out ac1 to HND control. CC who feared interference between ac1 and

ac2 intended to lower ac2 to fly below ac1. Since ac2 still was under the control of HND, CC made coordination with HND departure control to limit its altitude below FL130. Ac1 would enter the control area of NRT due to its low altitude and CC recognized the necessity of pointing out ac1 to NRT control. CC communicated this possibility to RC. Having heard this communication, RC verified CC by a query with which control of NRT to make coordination: center (C) or departure (D) control. This query in the field data was substituted with transmission and completion in simulation.

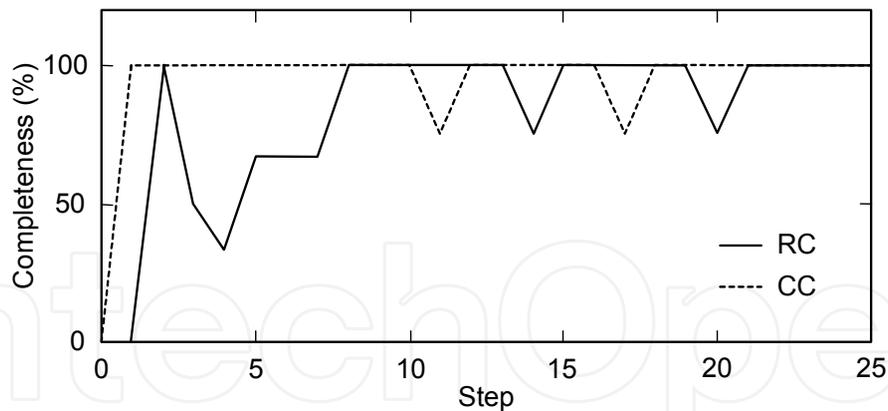
Simulation		Observation	
Step	Actor and action	Time	Actor and action
0	<i>RC: per - point_out(ac1, HND)</i>	12:08:40	<i>RC: per - point_out(ac1, HND)</i>
1	<b>RC: trn - point_out(ac1, HND)*</b>		<b>RC: trn - point_out(ac1, HND)*</b>
2	<i>RC: ass - point_out(ac1, HND)</i> <b>CC: com - point_out(ac1, HND)+</b>		<b>CC: com - point_out(ac1, HND)+</b>
3	<i>CC: per - focus(ac1, ac2)</i>		<i>CC: per - focus(ac1, ac2)</i>
4	<b>CC: inf - coordinate(ac2, alt)+</b>		<b>CC: inf - coordinate(ac2, alt)+</b>
5	<b>CC: trn - coordinate(ac2, alt)*</b>	12:09:10	<b>CC: trn - coordinate(ac2, alt)*</b>
6	<b>RC: com - coordinate(ac2, alt)+</b> <i>CC: ass - coordinate(ac2, alt)</i>	12:09:26	<b>CC: trn - focus(ac1, ac2)*</b> <b>RC: com - focus(ac1, ac2)+</b>
7	<b>CC: exe - coordinate(ac2, alt)*</b>		<i>RC: trn - focus(ac1, ac2)</i>
8	<b>CC: trn - focus(ac1, ac2)*</b>		<b>RC: com - coordinate(ac2, alt)+</b>
9	<b>RC: com - focus(ac1, ac2)+</b> <i>CC: ass - focus(ac1, ac2)</i>	12:09:31	<b>CC: exe - coordinate(ac2, alt)*</b> <i>CC: trn - coordinate(ac2, alt, 130)</i>
10	<i>RC: per - enter(ac1, NRT)</i>		<i>RC: com - coordinate(ac2, alt, 130)</i>
11	<b>RC: trn - enter(ac1, NRT)*</b>		<i>RC: per - enter(ac1, NRT)</i>
12	<i>RC: ass - enter(ac1, NRT)</i> <b>CC: com - enter(ac1, NRT)+</b>	12:12:24	<b>RC: trn - enter(ac1, NRT)*</b> <b>CC: com - enter(ac1, NRT)+</b>
13	<b>CC: inf - point_out(ac1, NRT)+</b>		<b>CC: inf - point_out(ac1, NRT)+</b>
14	<b>CC: trn - point_out(ac1, NRT)*</b>		<b>CC: trn - point_out(ac1, NRT)*</b>
15	<b>RC: com - point_out(ac1, NRT)+</b> <i>CC: ass - point_out(ac1, NRT)</i>		<b>RC: com - point_out(ac1, NRT)+</b>
16	<b>RC: inf - point_out(ac1, NRT, C)+</b>		<b>RC: inf - point_out(ac1, NRT, C)+</b>
17	<b>RC: trn - point_out(ac1, NRT, C)^</b>		<b>RC: qry - point_out(ac1, NRT, C)^</b>
18	<i>RC: ass - point_out(ac1, NRT, C)</i> <i>CC: com - point_out(ac1, NRT, C)</i>		
19	<b>CC: inf - point_out(ac1, NRT, D)+</b>		<b>CC: inf - point_out(ac1, NRT, D)+</b>
20	<b>CC: trn - point_out(ac1, NRT, D)*</b>	12:12:31	<b>CC: trn - point_out(ac1, NRT, D)*</b>
21	<b>RC: com - point_out(ac1, NRT, D)+</b> <i>CC: ass - point_out(ac1, NRT, D)</i>		<b>RC: com - point_out(ac1, NRT, D)+</b> <i>RC: trn - point_out(ac1, NRT, D)</i>

*Italics:* Items given in the simulation scenario.

**Bolds:** Items matched between simulation and observation.

(\* Perfect match + Predictive match ^ Essential match)

**Table 4.** Comparison of simulated and observed interactions in Case 2



**Figure 8.** Completeness of the second MBM layers in Case 2

Among 25 interactions extracted from the field data, three items were predefined in the simulation scenario, and simulation could predict 17 items, 77.3% (17/22) of the observed. The query observed in the field was substituted with transmission and completion, and no assumptions were observable in the field. Three transmissions and one completion were not simulated.

Figure 8 shows completeness of TSA in Case 2. Dominance of RC appears here, that means, RC leads team cognitive processes and CC follows by eagerly obtaining mutual beliefs on them. Consequently, completeness of TSA is a little better for CC than RC.

### 5.3. Case 3 (P.M. may 11, 2007)

The third case shows how RC and CC resolved conflict on control strategy. An aircraft, ac1, which departed from Hyakuri AFB, might interfere with another aircraft, ac2, bound for HND (Fig. 9). CC made coordination with Hyakluri AFB control before hand-off for ac1 to fly north around a fix with identification code GOC. RC, however, instructed ac1 to fly south around GOC. Having heard RC's instruction, CC noticed RC's intention and recovered from the conflicting state of mutual beliefs.

Table 5 compares simulated and observed interactions in the last case. CC expected that RC would give ac1 an instruction to fly north around GOC and made coordination with Hyakuri AFB control for its preparation. RC, however, thought the southern rout is better and gave an instruction to fly south around GOC. CC recognized RC's intention by observation and remedied the conflicting mutual belief.

There were 13 interactions from the field data, two of them were used for the simulation scenario, and 9 of them appeared in the simulation result. The hit rate was 81.2% (9/11). Simulation missed one transmission and one inference, and no assumptions were observable in the field data.

Figure 10 shows the assessment result of TSA completeness. Completeness of TSA was worse for both RC and CC in this case than in the other cases, because there was a conflict on control strategy between RC and CC. Finally CC recognized the conflict by observing

RC's instruction to the pilot, and CC's completeness recovered at the end of simulation. RC, however, did never recognize that CC had conceived a different strategy, and RC's completeness remained low till the end of simulation. Completeness of TSA thereby can be a good measure that exactly shows whether or not the members of a cooperating team share situation awareness.

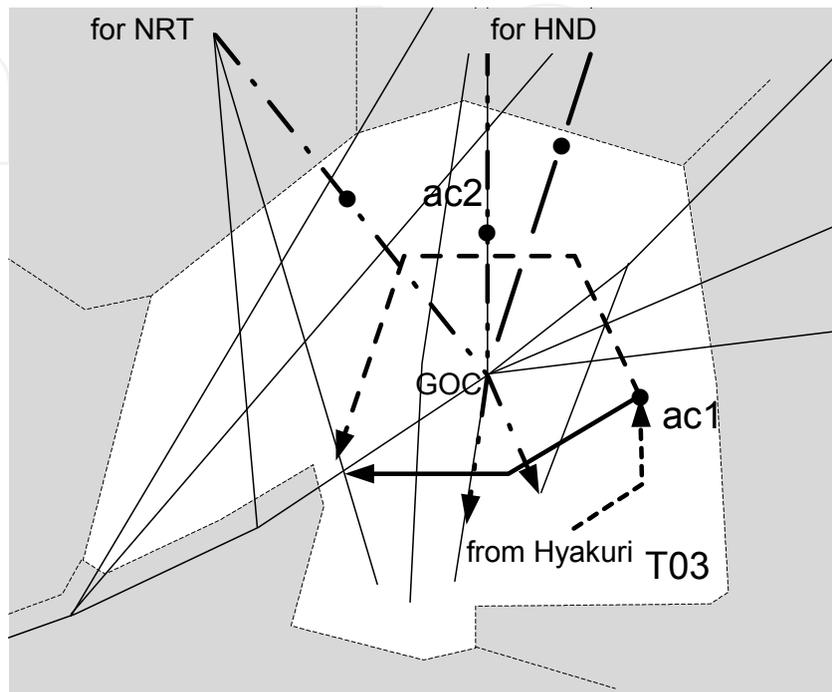


Figure 9. Situation of traffic in Case 3

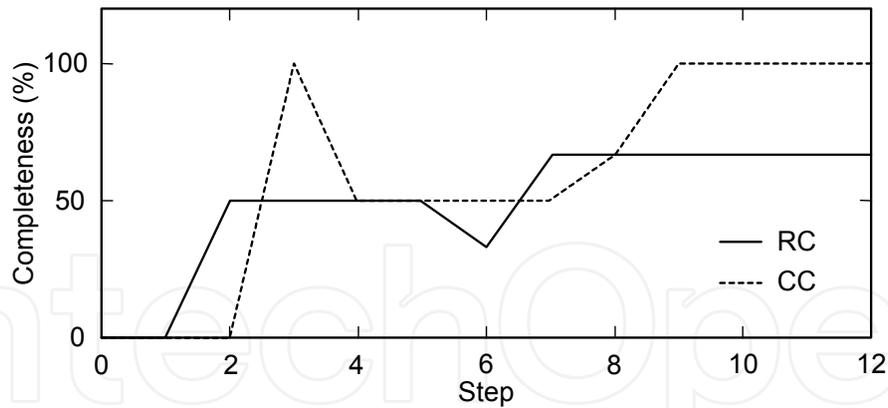
Simulation		Observation	
Step	Actor and action	Time	Actor and action
0	<i>CC: per - focus(ac1, ac2)</i>		<i>CC: per - focus(ac1, ac2)</i>
1	<b>CC: inf - instruction(ac1, dir, N)+</b>	14:05:27	<b>CC: inf - instruction(ac1, dir, N)+</b>
2	<b>CC: trn - focus(ac1, ac2)*</b>	14:06:26	<b>CC: trn - focus(ac1, ac2)*</b>
3	<b>RC: com - focus(ac1, ac2)+</b> <i>CC: ass - focus(ac1, ac2)</i>		<b>RC: com - focus(ac1, ac2)+</b> <b>RC: inf - instruction(ac1, dir, S)+</b>
4	<b>RC: inf - instruction(ac1, dir, S)+</b>	14:08:27	RC: trn - focus(ac1, ac2)
6	<i>CC: per - hand_off(hyakuri, ac1)</i>	14:09:17	<i>CC: per - hand_off(hyakuri, ac1)</i>
7	<b>CC: trn - hand_off(hyakuri, ac1)*</b>	14:09:53	<b>CC: trn - hand_off(hyakuri, ac1)*</b>
8	<b>RC: com - hand_off(hyakuri, ac1)+</b> <i>CC: ass - hand_off(hyakuri, ac1)</i>	14:10:22	<b>RC: com - hand_off(hyakuri, ac1)+</b> <b>RC: exe - instruction(ac1, dir, S)*</b>
9	<b>RC: exe - instruction(ac1, dir, S)*</b> <b>CC: obs - instruction(ac1, dir, S)*</b>		<b>CC: obs - instruction(ac1, dir, S)*</b> <b>CC: com - instruction(ac1, dir, S)+</b>
10	<b>CC: com - instruction(ac1, dir, S)+</b>		<b>CC: inf - instruction(ac1, dir, S)</b>

*Italics:* Items given in the simulation scenario.

**Bolds:** Items matched between simulation and observation.

(\* Perfect match + Predictive match ^ Essential match)

Table 5. Comparison of simulated and observed interactions in Case 3



**Figure 10.** Completeness of the second MBM layers in Case 3

#### 5.4. Discussion

Simulation could successfully replicate most of the interactions, around 80% in all cases, observed in the field. Table 6 shows a summary of match between simulated and observed interactions. This good match indicates that the simulation model of team interactions including detailed implementation was appropriate. The details of the model here include the initiation conditions and the prioritization scheme of cognitive tasks, which are required for constructing an executable simulation program. Assumptions, which are completely unobservable from the third party, were simulated but not observed in the field. Human expertise required for en-route ATC is beyond the scope of this simulation, because it is represented as simplistic production rules.

Completeness of CC's second layer outperformed that of RC's second layer in all cases. It means that CC is relatively eager to obtain mutual beliefs compared with RC by following and monitoring RC's actions. In contrast, RC is relatively independent from CC in deciding control actions and their timing. It resulted in dominance of RC observed in the field. Interactions like perception and inference generate new belief items in MBM layers to lower completeness of TSA, but it is usually recovered immediately by some sort of communication. These tasks that lower completeness of TSA, however, contribute to deepen thought on the current issues. It seems a standard style to repeat such a tandem process of deepening thought and establishing TSA in cooperation of ATCOs.

Number of interactions	Case 1	Case 2	Case 3
Simulation scenario	4	3	2
Perfect match	6	7	4
Predictive match	12	10	5
Essential match	2	1	0
Not simulated	2	4	2
Observed interactions	26	25	13

**Table 6.** The degree of match between observed and simulated interactions

## 6. Conclusion

The results of analysis on field observation data in en-route ATC were transcribed using predefined cognitive constructs and visualized to reveal typical patterns of team interactions for establishing TSA. Computer simulation then has been developed based on the cognitive model of team cooperation processes of our previous study as well as the revealed typical interaction patterns, and simulation was performed for three cases from the field observation. Simulation could replicate around 80% of ATCOs' interactions and the typical features of interactions observed in the field. The good match indicates that the cognitive model of team cooperation processes proposed in our previous study has a reality. In addition, simulation can explain the cognitive mechanisms of team cooperation processes for not only verbal but also for non-verbal interactions.

Appropriateness of TSA was evaluated using the simulation results evaluating completeness of the second MBM layers. Dominance of RC observed in the field resulted in higher TSA completeness for CC than for RC. It is also shown that TSA completeness degrades when RC or CC obtains new belief items by perception or inference but it is soon recovered by verbal or nonverbal communication. Assessment of TSA by computer simulation is thereby a useful mean to visualize the degree of team cooperation.

The simulation model of this work still has many limitations though. Firstly, expertise required for en-route ATC was represented as simplistic production rules that are very specific to the cases to be simulated, and this implementation lacks generality. Secondly, this work considers no models of errors, and the interactions generated by this model are normative. Smooth and efficient team cooperation is certainly a key for error-free and safe ATC performance. It is expected but inconclusive from this work, however, if it leads also to a high throughput of the sector, because the observation data were obtained just for time periods with relatively heavy traffic in the daytime and no critical situations happened during the observation. These issues have been left for future studies.

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