A Second-Order Adaptive Network Model for Shared Mental Models in Hospital Teamwork

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Abstract. This paper describes a second-order adaptive network model for mental processes making use of shared mental models for team performance. The paper illustrates the value of adequate shared mental models for safe and efficient team performance and in cases of imperfections of such shared team models how this complicates the team performance. It is illustrated for a context of a medical team performing a tracheal intubation. Simulations illustrate how the adaptive network model is able to address the type of complications that can occur in realistic scenarios.

Keywords: Shared mental model, second-order network model, hospital, team performance, healthcare safety.

1 Introduction

The concept of a shared mental model (SMM) has recently received increased attention in medical team performance literature as well as in other domains. SMM's are often brought in relation to the quality of team performance and safety [4, 5, 16, 24, 25, 30]. A team has a shared mental model when relevant knowledge structures concerning how reality works or should work are held by all team members and when there is sufficient alignment in the internal representations of these knowledge structures [11, 18, 20]. Like mental models in general, shared mental models are used in mental processes for internal mental simulation and decision making based on their outcomes; e.g., [6]. Moreover, they often are adaptive in the sense that they can be learnt or forgotten, and for such adaptation usually a form of control is applied. These aspects of shared mental models are all addressed in the current paper. It is illustrated in particular for the mental processes of members of a medical team. The real-world challenge addressed here is to cover (1) the errors and other imperfections that are daily practice in such teams and (2) the way in which such teams handle them.

In Section 2, a general introduction and background is described. This section also describes the domain specifics of the example scenario addressing a tracheal intubation performed by a medical team consisting of a specialist and a nurse. In Section 3 the design of the adaptive network model for this type of shared mental model is presented. Section 4, then, describes the illustrative simulation example. Section 5 provides a discussion of the adaptive network model to support healthcare safety.

2 Background

The second-order adaptive network model introduced here integrates knowledge of mental models from psychology, team mental models from social sciences, hospital protocols from medical- and safety sciences, and the AI-domain of network modeling.

Mental models. In his book Craik [6], describes a mental model as a *small-scale model* that is carried by an organism within its head as follows; see also [29]:

> 'If the organism carries a "small-scale model" of external reality and of its own possible actions within its head, it is able to try out various alternatives, conclude which is the best of them, react to future situations before they arise, utilize the knowledge of past events in dealing with the present and future, and in every way to react in a much fuller, safer, and more competent manner to the emergencies which face it.' ([6], p. 61)

Note that this quote covers both the usage of a mental model based on so-called internal mental simulation ('try out various alternatives') and the learning of it ('utilize the knowledge of past events'). For more on mental models, see, e.g., [2, 3, 7, 27].

Shared mental models. Team errors have often been linked to inadequacies of the shared mental model and the lack of adaptivity of it [4, 5, 16, 24, 25, 30] . This has major implications for health care and patent safety in the operation room, e.g., concerning open heart operation and tracheal intubation [16, 24].

Case description. The general setting of the addressed case is an emergency department where an emergency team is coming together for preparing to intubate a critically ill patient with deteriorating conscious state. The airway has been assessed as being normal and there is no expectation that there are going to be any difficulties with intubation. A doctor (D) is called in to perform a tracheal intubation in collaboration with a nurse (N). In general, a tracheal intubation induces stress for D and A. The call of the doctor triggers the activation of the initial state of a shared mental model with separate roles and activities for the tracheal intubation for the D and N. The roles and activities are unique for D and N. The roles for the doctor are: team leader, prepare team, prepare for difficulties and the role of intubator. The roles for the nurse are: intubator's assistant, prepare patient, prepare equipment, prepare drugs, give drugs, monitoring the patient, cricoid force, and the role of runner for help and/or additional equipment. In addition to the allocation of roles, the shared mental model contains the corresponding (temporal) sequence of activities for D and N. For the chosen example scenario based on an imperfect shared mental model considered here, this consists of the following sequence. The nurse prepares the patient. According to the protocol she should then have performed the preparation of the equipment; but she forgets this and goes on to perform the preparation of the drugs. The doctor executes pre oxygenation and starts with the preparation of the team and the preparation for difficulties. The nurse listens and observes to the doctor's team preparation. The nurse gives drugs to the patient and applies cricoid to the patient. Then the doctor initiates the executing of plan A Larynscopy and starts the first intubation attempt. The nurse assists the doctor in the intubation attempt. The nurse monitors the patient. When the first attempt is finished, the nurse seeks confirmation of its success by monitoring the capnograph. Then N realizes the earlier omission and sees that the capnograph is not active. The intubation attempt is repeated with the exclusion of the preparation and the giving of the drugs to the patient by N. Also the preparation of the team for the intubation and for difficulties are not performed by D. All other tasks are repeated in a second round and when this is not successful also in a third attempt. According to the protocol the doctor should have asked for help when the third attempt is not successful. But she does not do this.

Network-oriented modeling. The Network-Oriented Modelling approach from [26] is a suitable modeling approach to represent causal relations and the way they can be processed to generate mental processes, as needed for the use of shared mental models as described above. In particular, in [26] it is described how adaptive networks of different orders can be modelled relatively easily. Therefore, following the cognitive architecture for mental models described in [27], this approach was used to design a second-order adaptive network model for using shared mental models in team members' mental processing and acting.

Network nodes X have state values indicated by real numbers $X(t)$ that vary over time t; nodes are also called states. The characteristics defining a network model are *connection weights* $\boldsymbol{\omega}_{X,Y}$ for connectivity, *combination functions* $\mathbf{c}_Y$ for aggregation of impact, and *speed factors* $\boldsymbol{\eta}_Y$ specifying timing of states. The numerical representation created by the available dedicated software environment is based on the following equations based (where $X_1, \ldots, X_k$ are the states from which state Y gets incoming connections):

$$\mathbf{impact}_{X,Y}(t) = \boldsymbol{\omega}_{X,Y}\, X(t) \quad (1)$$

$$\mathbf{aggimpact}_Y(t) = \mathbf{c}_Y(\mathbf{impact}_{X_1,Y}(t), \ldots, \mathbf{impact}_{X_k,Y}(t)) = \mathbf{c}_Y(\boldsymbol{\omega}_{X_1,Y} X_1(t), \ldots, \boldsymbol{\omega}_{X_k,Y} X_k(t)) \quad (2)$$

$$\begin{aligned} Y(t+\Delta t) &= Y(t) + \boldsymbol{\eta}_Y\, [\mathbf{aggimpact}_Y(t) - Y(t)]\, \Delta t \\ &= Y(t) + \boldsymbol{\eta}_Y\, [\mathbf{c}_Y(\boldsymbol{\omega}_{X_1,Y} X_1(t), \ldots, \boldsymbol{\omega}_{X_k,Y} X_k(t)) - Y(t)]\, \Delta t \end{aligned} \quad (3)$$

A computational network engine developed within this software environment based on the generic equations (3) takes care for the processing of all network states thereby using their connections and other network characteristics.

Self-modeling networks to model adaptivity and control. First-order adaptation (also called *plasticity*) is applied here to the relations (connections) within a mental model using Hebbian learning [15]. Second-order adaptation is applied to model *metaplasticity* [1, 13], for a control effect of the contextual stress on the first-order adaptation process of learning and forgetting. These are modeled using *self-models* in the network: for some of the network characteristics $\boldsymbol{\omega}$, $\mathbf{c}$, $\boldsymbol{\eta}$ as mentioned above, network states are added to the network that represent their value. For some connection weights $\boldsymbol{\omega}_{X,Y}$ an additional state $\mathbf{W}_{X,Y}$ (called *self-model state*) is added to the network that represents this weight and is used for that weight in the processing. Next, for the combination function of such a self-model state $\mathbf{W}_{X,Y}$, a persistence parameter $\boldsymbol{\mu}_{\mathbf{W}_{X,Y}}$ is used that is represented by another self-model state $\mathbf{M}_{\mathbf{W}_{X,Y}}$. The latter network state is a *second-order self-model state* as it represents a network characteristic related to (first-order) self-model state $\mathbf{W}_{X,Y}$.

3 The Adaptive Network Model using a Shared Mental Model

The second-order adaptive network model introduced here follows the generic three-level cognitive architecture for mental models described in [27]. It has connectivity as depicted in Fig. 1; for an explanation of the states, see Tables 1 to 3. The scenario concerns a sequence of actions with actors assigned performing them and their temporal order, according to the realistic case described in Section 2.

Base level: overview. Within the base plane, the world states indicating the actual steps in the world for this scenario are depicted in Fig. 1 by the blue nodes with their connections in the middle area of the base plane. A contextual stress factor is represented by the green node on the left. The actor is indicated within a world state name by D for doctor or N for nurse. The shared mental model consists of two individual mental models for D and N. These mental models are shown in the base level plane and reflect the ordered structure specified in the addressed use case. They are depicted by the red nodes (in the long light-red oval) and yellow nodes (in the yellow-green oval) in the base plane and their connections, respectively.

Table 1 Overview of the world states (WS) and the mental model states for the doctor (DS) and nurse (NS) reflecting these world states

World, Doctor and Nurse				Explanation
WS0			Context	Contextual stress factor
WS1	DS1	NS1	Call_intub	External call for intubation
WS2	DS2	NS2	Prep_p_N	Preparation of the patient by the nurse
WS3	DS3	NS3	Prep_eq_N	Preparation of the intubation equipment by the nurse
WS4	DS4	NS4	Prep_dr_N	Nurse prepares drugs for the patient
WS5	DS5	NS5	Pre_oxy_D	Doctor executes pre oxygenation
WS6	DS6	NS6	Prep_team_D	Doctor prepares the team for intubation
WS7	DS7	NS7	Prep_dif_D	Doctor prepares the team for difficulties
WS8	DS8	NS8	Give_dr_N	Nurse gives the patient drugs
WS9	DS9	NS9	Give_cr_N	Nurse applies cricoid to the patient
WS10	DS10	NS10	E_A_D	Doctor executes plan A Laryngoscopy
WS11	DS11	NS11	E_intub_D	Doctor intubates the patient
WS12	DS12	NS12	Mon_p_N	Nurse monitors patient
WS13	DS13	NS13	Obs_c_N	Nurse observes capnograph
WS14		NS14	Verb_fail_N	Nurse verbalizes failure of intubation
WS15		NS15	Verb_succ_N	Nurse verbalizes success of intubation
WS16	DS16		Verb_fail_D	Doctor verbalizes failure of intubation
WS17	DS17		Verb_succ_D	Doctor verbalizes success of intubation
WS18	DS18	NS18	Call_help_D	Doctor calls for help

The states within the mental models refer to the world states they model and like these world states they also specify an actor, indicated by D for doctor or N for nurse. The two individual mental models are two instances of an overall team mental model incorporating both the course of actions and the roles of the different team members for these actions. These individual instances of the team mental model can have differences, as in general not all team members will possess a perfect team mental model.

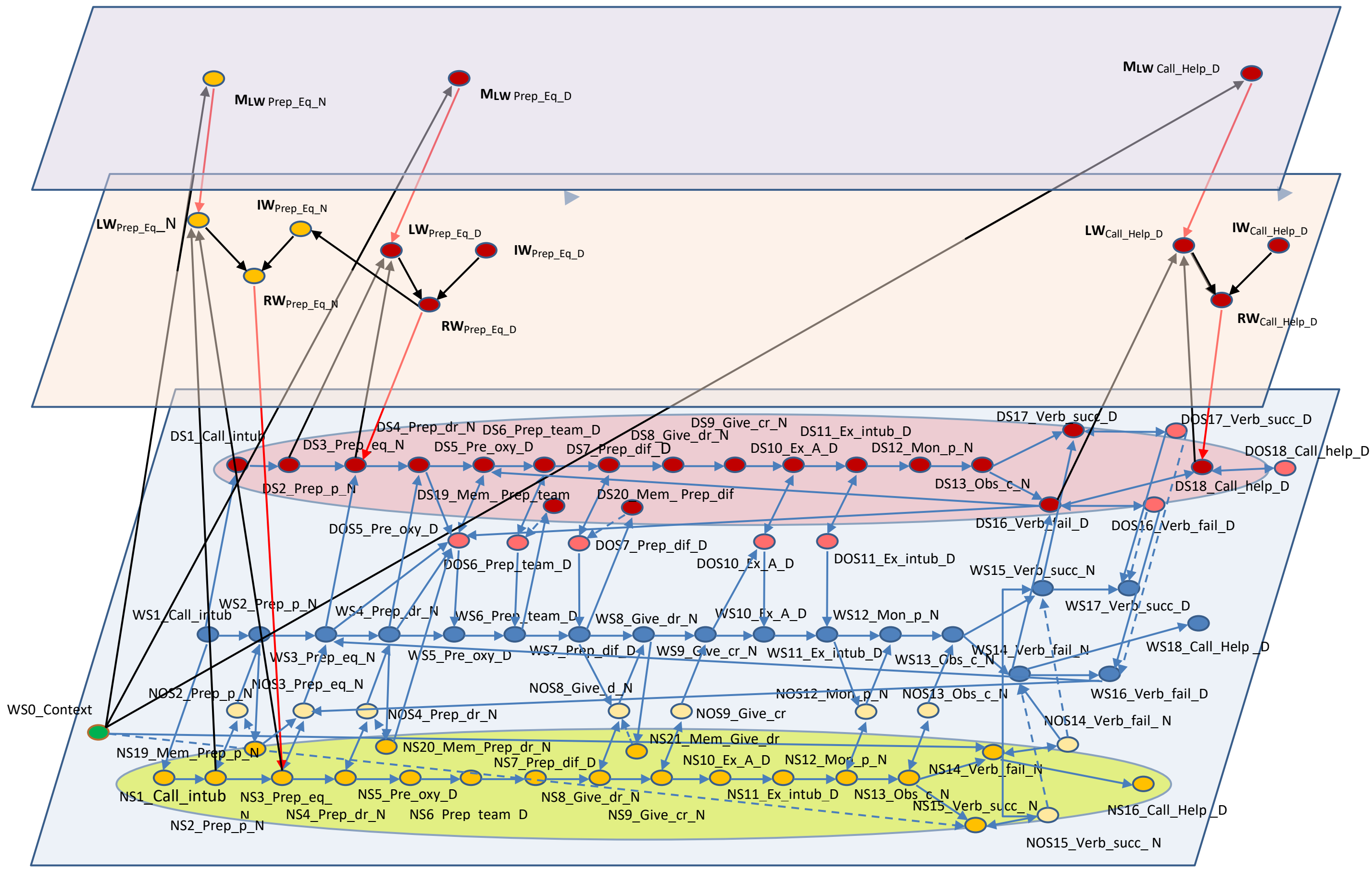

Fig. 1 Connectivity of the designed adaptive network model for the shared mental model. It includes the two mental models of the nurse (long yellow oval) and of the doctor (long red oval) and the self-models for the first-order (the pink plane) and second-order (the purple plane) adaptation. Dashed connections indicate connections with negative weights.

Base level: memory states in the mental models. Within the mental models some specific states enable to take into account what has occurred in the past; these mental model states are called *memory states*. These are particularly useful if parts of the processes have to be repeated because of failures. Usually then only some of the actions have to be redone, while other actions can be skipped, as is illustrated in the addressed scenario. For example, preparation of the patient does not need to be redone, but preparation of the equipment has to be redone when the process has to be repeated. The memory states within the mental models are a crucial element to obtain this form of flexibility as they enable to model such issues in a context-sensitive manner taking into account the history of the process.

Base level: action ownership states. By each of the two team members, their own mental model is used to determine their actions in the world. This goes through the member's action ownership states (indicated in light red for the doctor and in light yellow for the nurse). These ownership states not considered to be part of the mental models. Instead, they use input from the mental models and realise a form mediation from mental model to the real world by initiating the execution of the indicated actions, which leads to affecting the related world states. In this way, the mental models affect the decisions for actions activating the world states. Conversely, connections from world states to corresponding mental model states are (at some points) used to feed information about the world into the mental models.

Middle level: adaptation of the mental models (plasticity). The middle (blue) plane addresses the mental processes for learning and forgetting of the mental models. In particular, this addresses the connection within the nurse's mental model from the mental model state for preparation of the patient to the mental model state for preparation of the equipment. Inspired by [2, 3], where it was shown how instructional learning and observational learning of mental models can be integrated, in a similar manner two types of learning are covered here:

Table 2 Overview of the memory states and ownership states for the doctor and nurse

Name		Explanation
DS19	Mem for Prep team D	Memory state of Doctor for the action of preparing the team
DS20	Mem for Prep dif D	Memory state of Doctor for the action of preparing the team for difficulties
DOS5	DOS for Pre_oxy_D	Ownership state for the action of preoxygenation
DOS6	DOS for Prep_team_D	Ownership state for the action of preparing the team
DOS7	DOS for Prep_dif_D	Ownership state for the action of preparing the team for difficulties
DOS10	DOS for E_A_D	Ownership state for the action of plan A Laryngoscopy by doctor
DOS11	DOS for E_intub_D	Ownership state for the action of intubating first attempt by doctor
DOS16	DOS for Verb_fail_D	Ownership state for the action of verbalizing that attempt has failed by doctor
DOS17	DOS for Verb_succ_D	Ownership state for the action of verbalizing that attempt has succeeded by doctor
DOS18	DOS for Call_help_D	Ownership state for the action of call for help, by doctor
NS19	Mem for Prep_p N	Memory state of Nurse for the action of preparing the patient
NS20	Mem for Prep_dr N	Memory state of Nurse for the action of preparing the drugs
NS21	Mem for Give_dr N	Memory state of Nurse for the action of giving the drugs
NOS2	NOS for Prep_N	Nurse Ownership State for Preparation patient
NOS3	NOS for Prep_eq_N	Nurse Ownership State for Preparation equipment
NOS4	NOS for Prep_dr_N	Nurse Ownership State for preparing drugs
NOS8	NOS for Give_d_N	Nurse Ownership State for Nurse gives drugs
NOS9	NOS for Give_cr_N	Nurse Ownership State for Nurse gives cricoid
NOS12	NOS for Mon_p_N	Nurse Ownership State for Nurse monitors patient
NOS13	NOS for Obs_c_N	Nurse Ownership State for observing capnograph
NOS14	NOS for Verb_fail_N	Nurse Ownership State for verbalizing that attempt has failed
NOS15	NOS for Verb_succ_N	Nurse Ownership State for verbalizing that attempt has succeeded

- Learning by instruction from the Doctor (modelled by the Nurse's **IW**-state and its incoming connection from the Doctor's **RW**-state)

- Hebbian learning [15] based on internal simulation, among others triggered by observation (modelled by the Nurse's **LW**-state with its incoming connections from the two relevant Nurse's mental model states)

The values of these two states are integrated in the **RW**-state, which represents the overall value that is actually used as connection weight in the internal simulation at the base level. The Hebbian learning applied for the **LW**-state includes a persistence factor μ that represents the fraction (of the learnt value) that persists per time unit. For example, if μ is 0.9, then every time unit 10% of the learnt value is lost (forgotten).

Table 3 Overview of the first-and second-order self-model states

Name		Explanation
W1	$\mathbf{LW}_{\text{Prep p Nurse} \rightarrow \text{Prep eq Nurse}}$	First-order self-model state for the Nurse's weight of the connection from the preparing the patient mental model state to the preparing the equipment mental model state as learnt by Hebbian learning
W2	$\mathbf{IW}_{\text{Prep p Nurse} \rightarrow \text{Prep eq Nurse}}$	First-order self-model state for the Nurse's weight of the connection from preparing the patient mental model state to preparing the equipment mental model state as learnt from instruction by the doctor
W3	$\mathbf{RW}_{\text{Prep p Nurse} \rightarrow \text{Prep eq Nurse}}$	First-order self-model state for the Nurse's overall weight of the connection from preparing the patient mental model state to preparing the equipment mental model state
W4	$\mathbf{LW}_{\text{Prep p N D} \rightarrow \text{Prep eq N D}}$	First-order self-model state for the Doctor's weight of the connection from preparing the patient by the Nurse mental model state to preparing the equipment by the Nurse mental model state as learnt by Hebbian learning
W5	$\mathbf{IW}_{\text{Prep p N D} \rightarrow \text{Prep eq N D}}$	First-order self-model state for the Doctor's weight of the connection from preparing the patient by the Nurse mental model state to preparing the equipment by the Nurse mental model state as known to the Doctor
W6	$\mathbf{RW}_{\text{Prep p N D} \rightarrow \text{Prep eq N D}}$	First-order self-model state for the Doctor's overall weight of the connection from preparing the patient by the Nurse mental model state to preparing the equipment by the Nurse mental model state
W7	$\mathbf{LW}_{\text{Verb fail D} \rightarrow \text{Call help D}}$	First-order self-model state for the Doctor's weight of the connection from verbalisation of failure mental model state to call for help mental model state as learnt by Hebbian learning
W8	$\mathbf{IW}_{\text{Verb fail D} \rightarrow \text{Call help D}}$	First-order self-model state for the Doctor's weight of the connection from verbalisation of failure mental model state to call for help mental model state as known to the Doctor
W9	$\mathbf{RW}_{\text{Verb fail D} \rightarrow \text{Call help D}}$	First-order self-model state for the Doctor's overall weight of the connection from verbalisation of failure mental model state to call for help mental model state
M1	$\mathbf{M}_{\mathbf{LW}\text{Prep p Nurse} \rightarrow \text{Prep eq Nurse}}$	Second-order self-model state for the persistence factor of the Nurse's weight of the connection from preparing the patient mental model state to preparing the equipment mental model state as learnt by Hebbian learning
M2	$\mathbf{M}_{\mathbf{LW}\text{Prep p N D} \rightarrow \text{Prep eq N D}}$	Second-order self-model state for the persistence factor of the Doctor's weight of the connection from preparing the patient by the Nurse mental model state to preparing the equipment by the Nurse mental model state as learnt by Hebbian learning
M3	$\mathbf{M}_{\mathbf{LW}\text{Verb fail D} \rightarrow \text{Call help D}}$	Second-order self-model state for the persistence factor of the Doctor's weight of the connection from preparing the patient by the Nurse mental model state to preparing the equipment by the Nurse mental model state as learnt by Hebbian learning

Upper level: control of the adaptation of mental models (metaplasticity). Within the adaptive network model, the persistence factor μ depends on circumstances: μ is made adaptive by including a second-order self-model **M**-state within the upper-level plane that represents it (metaplasticity, e.g., [1, 13]). For the considered scenario, it is assumed that in particular a high stress level leads to a decreased value of the **M**-state; in this way forgetting due to stressful circumstances is modelled, in line with [13]. This is specified by the (suppressing) upward connections from the stressful context state in the base level to the **M**-states.

The combination functions from the combination function library available within the software environment used here are shown in Table 4.

Table 4 Combination functions from the library used in the introduced network model

	Notation	Formula	Parameters
Steponce	**steponce(*V*)**	1 if $\alpha \leq t \leq \beta$, else 0	α start, β end time
Scalemap	**scalemap$_{\lambda,\upsilon}$(*V*)**	$\lambda + (\upsilon - \lambda)\, V$	Lower bound λ; Upper bound υ
Advanced logistic sum	**alogistic$_{\sigma,\tau}$**($V_1, \ldots, V_k$)	$[\frac{1}{1+\mathrm{e}^{-\sigma(V_1+\cdots+V_k-\tau)}} - \frac{1}{1+\mathrm{e}^{\sigma\tau}}](1+\mathrm{e}^{-\sigma\tau})$	Steepness $\sigma > 0$ Excitability threshold τ
Hebbian learning	**hebb$_\mu$**(V_1, V_1, W)	$V_1V_2\,(1-W) + \mu\, W$	V_1,V_2 activation levels of the connected states; W activation level of the self-model state for the connection weight μ persistence factor

4 Simulation for the Example Scenario

Recall from the introduction that the main real-world challenge addressed for the designed adaptive network model is that it is able to cover (1) the errors and other imperfections that are daily practice in medical teams and (2) the way in which such teams handle them. This can be considered a performance indicator against which the model can be validated. In this section, it will be shown by the realistic example simulation scenario from Section 2 how the model indeed satisfies this performance indicator. In this simulation, a repeatedly unsuccessful intubation process is shown.

The network characteristics defining the network model introduced above have been specified in a standard table format (called role matrices) that can be used as input for the available dedicated software environment; see also the Appendix as Linked Data at URL https://www.researchgate.net/publication/351282051. The example simulation discussed here was run over a time interval of 0 to 180 with step size $\Delta t = 0.5$. This provides graphs of state activations based on the values chosen for the network characteristics. The contextual stress level has been set relatively high (0.5). For reasons of clarity, the figures have split the world states (Fig. 2), the doctor's states (Fig. 3), the nurse's states (Fig. 4), and the adaptivity states (Fig. 5), but they all happen in the same simulation at the indicated time points.

The world states Fig. 2 shows the simulation output for how the actual process in the world proceeds. In time period t = 10-30 a call for intubation takes place, which sets in motion the intubation sequence for the scenario. After this call, the Nurse starts preparing the patient (the light green line). In this scenario, the purple line indicating the preparation of the equipment starting at time t = 15 does not reach an adequate level of activation, only around 0.375, meaning that this preparation of equipment is not (sufficiently) executed in the world. However, the next step in the scenario of preparing the drugs becomes active around $t = 33$ and does get activated enough. Subsequently, also the rest of the steps in the scenario continue as prescribed by the shared mental model. Between $t = 40$ and $t = 45$, the doctor's first actions become activated: the pre-oxygenation of the patient, the preparation of the team and the preparation for difficulties. After this, the nurse continues with giving the drugs to the patient (dark green around $t = 47$), and applies the cricoid force right after. Now, the execution of the attempt laryngoscopy A, and the intubation action itself both become activated between $t = 47$ and $t = 50$. This also activates the nurse's actions to monitor the patient, around $t = 55$, and to observe the capnograph equipment around $t = 60$. Around this time, the nurse will realize she did not prepare the equipment (remember the non-activated prepare equipment state), and verbalize the failed intubation attempt as a result, around $t = 67$. Soon after, around $t = 69$, the doctor confirms this by also verbalizing the failed intubation attempt.

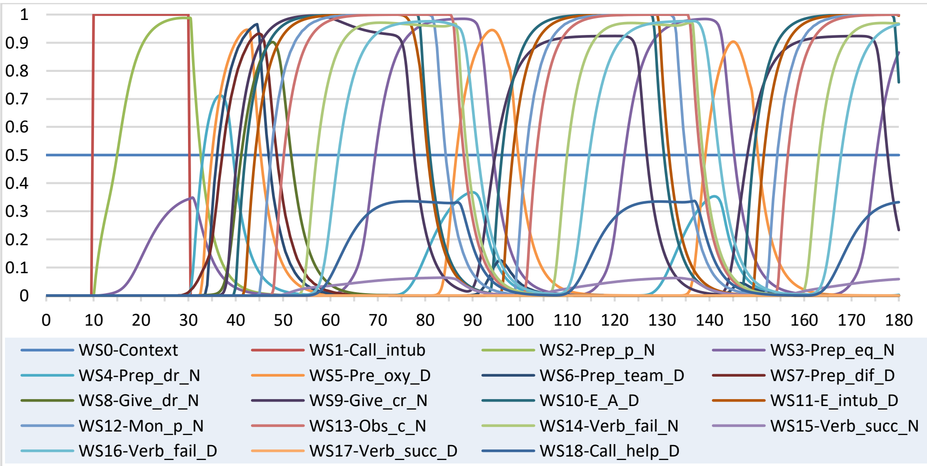

Fig. 2: World states of a repeated failing intubation process

After this verbalization of failure, the doctor and nurse will start their second attempt. This time, it starts with the nurse preparing the equipment: the light purple prepare equipment line now does reach activation around $t = 77$. This time, the preparation of the patient and drugs are skipped by the nurse because they do not need to happen more than once. There is a slight gap, until the pre-oxygenation gets activated around $t = 93$: the orange line. After this, the doctor skips the preparation of the team and for difficulties, because these steps already happened and do not need to be repeated. Around $t = 100$, the nurse gives cricoid force, and the doctor starts the second intubation attempt. Again, the nurse monitors the patient, and the capnograph, but unfortunately also this intubation attempt fails. The nurse verbalizes this failed attempt around $t = 120$, and the doctor verbalizes the failure around $t = 125$. The team now continues with a third intubation attempt, see the activation of the preparation of the equipment at $t = 133$. The third pre-oxygenation becomes activated around $t = 145$, and the nurse applies the cricoid around $t = 155$. This activates the third intubation attempt and intubation action, and the monitoring of the patient and the capnograph by the nurse. Note that also in this attempt the same actions are skipped as in the second attempt, because they do not need to happen again. This attempt fails too and this is verbalized by the nurse at $t = 170$, and right after by the doctor as well. In the simulation the same pattern keeps on repeating after this time point. Note that after the failure verbalisations the 'call for help' state (the dark blue line) gets a low level of activation, up to around 0.35, but this is not enough to actually happen, so no help is called in this simulation scenario. Figs. 3 and 4 show for the addressed scenario, what precedes the world state activations described above: the internal simulations by the doctor and nurse of their own mental model and activating their ownership states for the actions accordingly.

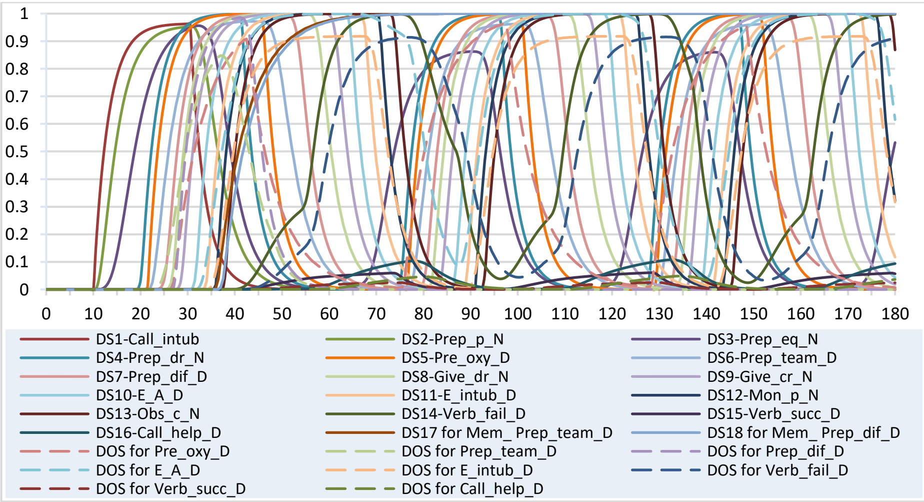

Fig. 3: The doctor's mental model states (solid lines) and ownership states (dashed lines) for a repeated failing process

The doctor's mental processes based on her mental model. Fig. 3 shows the doctor's mental model states and the doctor's ownership states simulated over time. After the call for intubation at $t = 10$, the doctor's mental model for the nurse preparing the patient, equipment and drugs gets activated at $t = 15$ (note that at this point this action only happens in the doctor's mental model, but not in the real world). Then the mental model states for the doctors first own actions get activated: to pre oxygenate the patient, prepare the team and prepare for difficulties, around $t = 20$. Now, the doctor's ownership states for the doctors' actions (pre oxygenate, preparing the team and for difficulties) get activated at $t = 30$, which will ultimately lead to the corresponding real-world actions. Around $t = 32$ some mental model states of actions the nurse have to do, become activated: to give the patient drugs and to apply cricoid force. This triggers the doctor's mental model state of starting plan A of intubation, and the actual intubation, also around $t = 32$, and slightly after that around $t = 35$ the ownership states for these actions. At around $t = 37$, the nurse's actions activate in the doctor's mental model: to monitor the patient and to observe the capnograph. This leads to the doctor to verbalize failure in her mental model around t = 50, and to develop activation of ownership of this verbalisation action after that. The call for help does not get proper activation. This round ends around t = 75, after which the next round starts as an emergent process.

The nurse's mental processes based on her mental model. Fig. 4 shows the nurse's mental model states and the nurse's ownership states over time. Right after the call for intubation at t = 10, the nurse's mental model for herself preparing the patient gets activated at t = 15, and right after also the ownership state for the first action gets activated, meaning the nurse executes the preparation of the patient.

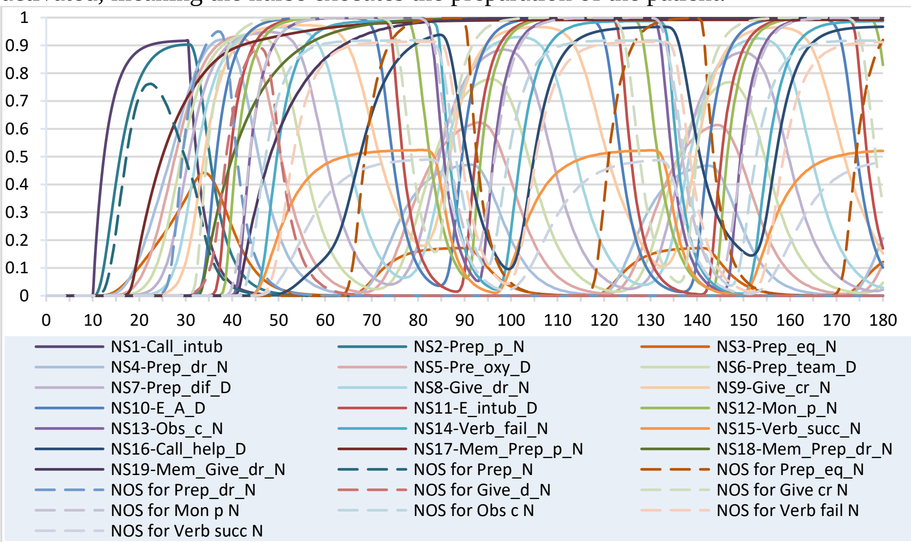

Fig. 4: The nurse's mental model states (solid lines) and ownership states (dashed lines) for a repeated failing intubation process

At around t = 25, the memory state of the nurse for preparing the patient reaches activation, meaning that the nurse can remember that she did this and does not have to repeat this action. Around this time, the prepare equipment mental state reaches partial activation, but not enough to activate the ownership state for this action. From t = 24 until around t = 37, the mental model states for the preparation and execution actions of the intubation get activated, with the mental model state for the intubation reaching activation around t = 39. Also, the ownership states for most actions become activated in this time period, although the ownership state for 'prepare equipment' does not become activated, indicating that the nurse does not execute this action. At t = 40, the mental model state for monitoring the patient, and around t = 44 the mental model state for observing the capnograph become activated. At t = 49 the nurse's mental model state for verbalizing failure gets activation, and interestingly at t = 69, the nurse's mental model state for calling for help gets activated, even though this does not get executed by the doctor in the real world.

Note how also the memory states for preparing the patient, preparing the drugs and giving the drugs become activated at respectively t = 25, t = 45 and t = 54, after the ownership states for the same actions, causing the nurse to remember and not execute these actions in following rounds. At $t = 70$, the ownership state for preparing the equipment becomes activated, indicating the start of the second attempt at intubation. Note that the mental model state for the equipment preparation does not reach activation, showing that the nurse gets this input from an external source (the verbalization of failure of the intubation, by the doctor).

The learning and forgetting states. Fig. 5 shows the activation levels of the states involved in adaptation (learning and forgetting) of the mental models, as shown in the first- and second-order self-model levels in Fig. 1.

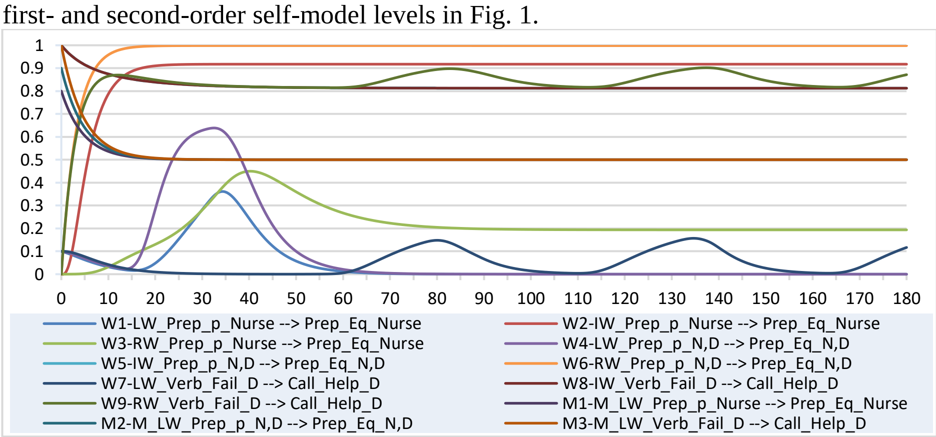

Fig. 5: The first- and second-order self-model states for adaptation (learning and forgetting) and control of it (stress leading to forgetting)

For the sake of simplicity there are only three places in the model where learning and forgetting have been incorporated: in the nurse's mental model between the 'prepare equipment' state and the 'prepare drugs' state, in the doctor's mental model between the 'prepare equipment' state and the 'prepare drugs' state, and finally in the doctor's mental model between the 'verbalization of failure' state and the 'call for help' state. In each of these cases, the applied adaptation mechanism was built upon three sub-mechanisms:

- **LW**-states, representing the Hebbian learning. This means that the person learns by activation of connected states of the mental model, for example, by using the mental model for internal simulation or triggered by observing the corresponding states in the real world. In the model, an **LW**-state is activated from the source and destination mental model states of the learnt connection. The persistence involved in the adaptation represented by an **LW**-state is controlled by an **M**-state in the second-order adaptation level (which represents the persistence factor μ).
- **IW**-states, representing instructional learning. This means that the nurse learns by getting information from the doctor, either during the process or before. The doctor applies previously acquired knowledge for this.
- **RW**-states, which models just a combination of the above two states.

In Fig. 5, the above three mechanisms are shown in a simulation graph. All three **M**-states start at a high level (0.8, 0.9 or 1) and due to the high stress level drop to 0.5 around $t = 10$. There are a few states that get activated around $t = 15$: **RW** for preparing the equipment in the doctor's mental model (W6), **RW** for the verbalization of failure by the doctor (W9) and **IW** for calling for help by the doctor (W8). Besides that, none of the learning states really reach proper activation. Therefore, while the learning mechanisms in principle are working as can be seen from the changing activation levels, they only have an overall negative impact, due to the forgetting that is induced by the high stress level [13], making the persistence factor representations **M** low. This negative effect contributes to the omission of the preparation of the equipment by the nurse in the first round and also to not calling for help after each failed round.

5 Discussion

In this paper, a quite flexible second-order adaptive computational network model was introduced enabling simulation of mental processes involving a shared mental model for teams, illustrated for a doctor and a nurse performing tracheal intubation of a patient. The model allows for the representation and processing of the actions in the world, the preceding internal simulation of the two mental models of the nurse and doctor and the dynamics of the interactions between them via the ownership states that represent how the actors actually decide based on the internal simulation and perform the actions. A contextual stress factor is included that determines the effects of stress on these mental processes, in particular forgetting parts of a mental model as a negative effect of metaplasticity [1] as described in more detail in [13]. Accordingly, in simulation experiments it was shown how learning and forgetting of shared mental models can happen and how failing team processes and redoing them can be modelled in a context-sensitive and flexible manner.

The computational model was developed based on the network-oriented modeling approach described in [26] and its dedicated software environment described in [26], Ch 9. Other computational approaches such as described in [9, 22, 23], use agent-based models (which usually brings more added complexity), dynamical system models or program code. This lacks a well-defined description at a modelling level and makes it hard if not impossible to incorporate second-order adaptation in a transparent manner in the model, as needed here. Otherwise it is hard to cover the positive and negative effects of metaplasticity as described in [13]. In contrast, the current paper describes at a modelling level a very flexible second-order adaptive network model. It addressing shared mental models for teamwork and illustrates this by a hospital teamwork scenario.

A less flexible precursor of the second-order adaptive network model introduced in the current paper was described in [28]. The latter network model only addressed parts (not including memory states) of the base level. Therefore, it was nonadaptive and also did not cover errors and other imperfections of the team members occurring in their daily practice. It was shown that the adaptive network model introduced here is able to model forgetting part of a shared mental model as illustrated in the simulated scenario, failure of the action and redoing the process in a context-sensitive manner after it has turned out to fail. In this way, the current model has been shown to be much closer to real-world team processes.

To achieve this, the two levels of self-models for first-order and second-order adaptation are new in the current model; this enabled modelling the positive and negative effects of metaplasticity as described in [13] in the form of learning and forgetting parts of a mental model. In addition, also the use of memory states to be able to redo a failed attempt in a history-context-sensitive manner is new, providing a mechanism for only redoing the actions that are needed and skipping the ones that are not needed again as can be observed naturally in practice; the precursor model from [28] is much more rigid and lacks also this type of flexibility.

A next step will be to model the occurrence of a wider variety of errors and incidents - and their solutions - that are specific for team and group performance. Examples are: false consensus, group think, escalation of commitment and group polarization [18]. Another relevant issue would be to examine the effect of group dynamics as a function of the team size. Often it is suggested that increasing the team, would lead to more safety and efficiency [16] but increasing group size also leads to new group dynamics with corresponding potential problems. As mentioned, shared mental models are used in a variety of safety-related situations such as aviation, firefighting teams, dealing rooms, shipping control, etc. An important line for future research is to examine the descriptive validity of our model and further extensions of it for such domains.

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