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A controlled adaptive computational network model of a virtual coach supporting speaking up by healthcare professionals to optimise patient safety

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ABSTRACT

Previous reports show that a substantial proportion of (near) medical errors in the operating theatre is attributable to ineffective communication between healthcare professionals. Speaking up about observed medical errors is a safety behaviour which promotes effective communication between health care professionals, consequently optimising patient care by reducing medical error risk. Speaking up by healthcare professionals (e.g., nurses, residents) remains difficult to execute in practice despite increasing awareness of its importance. Therefore, this paper discourses a computational model concerning the mechanisms known from psychological, observational, and medical literature which underlie the speaking up behaviour of a health care professional. It also addresses how a doctor may respond to the communicated message. Through several scenarios we illustrate what pattern of factors causes a healthcare professional to speak up when witnessing a (near) medical error. We moreover demonstrate how introducing an observant agent can facilitate effective communication and help to ensure patient safety through speaking up when a nurse can not. In conclusion, the current paper introduces an adaptive computational model which predicts speaking up behaviour from the perspective of the speaker and receiver, with the addition of a virtual coach to further optimise patient safety when a patient could be in harm's way.

1. Introduction

Healthcare professionals in hospitals operate in a high-risk environment as even slight medical errors or unsafe events are hazardous to patient safety (Bienefeld & Grote, 2014; Schwappach & Gehring, 2014; Vogus & Iacobucci, 2016). Because of the threat to patient safety, prevention of medical errors is considered an important challenge in healthcare (Alyahya et al., 2021). The likelihood of medical errors is even greater in intensive care units and the operating theatre (OT) (Nacioglu, 2016). Prior studies have identified ineffective communication about preventable medical errors in OTs as one of the most frequent causes of patient morbidity (James, 2013; Pattni et al., 2019). Ineffective communication in this context comprises the hesitancy of healthcare professionals to address an aberration which could lead to harming the patient (Okuyama, Wagner, & Bijnen, 2014; Palatnik, 2016), thus jeopardising patient safety. Effective communication, on the other hand, in the form of speaking up is considered a safety behaviour associated with increased technical performance in the OT (Kolbe et al., 2012; Nacioglu, 2016).

In line with the existing literature, we define speaking up in the current paper as addressing concerns with patient safety in mind through clear communication about observations, the need for clarification, or suggestions for corrective measurements during the OT (Morrison, 2011; Okuyama et al., 2014).

Despite growing acknowledgement in healthcare concerning the importance of speaking up relative to error prevention and optimisation of care, consistent implementation is reportedly difficult in practice (Maxfield, Grenny, Lavandero, & Groah, 2011). There seems to be a hesitancy to speaking up, as healthcare professionals noticing a (near) deviation of the medical protocol are often ignored when speaking up or choose to stay silent (Okuyama et al., 2014). Considering that healthcare professionals are increasingly aware of the importance and benefits of speaking up yet hesitate to speak up, we can assume that motivations to speak up about patient safety are complex. Indeed, several lines of research have showed that speaking up may depend on specific combinations of individual, contextual, and interpersonal factors (Alyahya et al., 2021; Bienefeld & Grote, 2014). These studies mostly scrutinise the determining factors which cause the inability to speak up, while

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studies which include the state of the receiver of speaking up behaviour are scarce. Effective communication is dyadic after all—it is important to consider the response of the receiver as it can affect the perception of the sender regarding the acceptance of speaking up (Lemke, Burtscher, Seelandt, Grande, & Kolbe, 2021; Long, Jowsey, Garden, Henderson, & Weller, 2020).

With the increasing interest in the scientific literature concerning the cornerstones of speaking up behaviour among healthcare professionals (Alingh, van Wijngaarden, van de Voorde, Paauwe, & Huijsman, 2019; Lemke et al., 2021; Pattni et al., 2019; Peadon, 2020), several efforts were made to delineate speaking up through theoretical frameworks using (simulated) experiments and literature reviews (Long et al., 2020; Umoren, Kim, Gray, Best, & Robins, 2022). A framework which analyses these findings that specifies how constituents of speaking up interact, as well as how individuals interact with speaking up in a high-risk environment in a formalised causal computational manner, is lacking within this research domain. The current paper, therefore, aims to outline existing sources to design an adaptive network model using a computational modelling approach capable of representing such adaptive complex processes in a generative and causal manner (Treur, 2016, 2020b). Because of the reported hesitancy to speaking up, the paper introduces a mechanism named the Safe Coach (SFC) to control to prevent medical errors in the circumstance where a health care professional stays silent.

Literature from a variety of research domains (organisation, psychology, communication sciences) were explored to illustrate which causal pathways and processes underlie speaking up as well as the constituents to the receptivity to speaking up of the receiver, to therefrom design a computational model, substantiating the effects hypothesised (Section 2). Next, based on this exploration, we provide a brief description of the adaptive causal modelling approach (Section 3) followed by a description of the proposed adaptive causal network model (Section 4). Through simulation experiments, we show how the combination of individual and contextual factors facilitates speaking up (Section 5). Connections are furthermore exploited to depict the internal processes for the response of the receiver, as well as portraying a circumstance where the nurse chooses silence for the SFC to intervene. In the silence circumstance, internal processes of the SFC intervention will also be presented. At last, in this paper we briefly discuss how the model was verified by mathematical analysis.

2. Background information

This section contains a brief description of cornerstones to speaking up behaviour to delineate what causes the suggested hesitancy to speak up. Despite the scarcity of existing research about the impact and receptiveness to speaking up by the receiver, we will attempt to illustrate what factors cause a negative or positive response provided the argued significance of the response of the leader during the OT.

2.1. Speaking up behaviour

Psychological safety is the degree to which people in their work environment feel comfortable to take interpersonal risks without negative implications based on perceived team climate (O'Donovan & McAuliffe, 2020b; Roussin, Larraz, Jamieson, & Maestre, 2018). In a work environment where the perceived psychological safety is high, it is likely that these individuals would be more willing to share their concerns and opinions on task-related and organisational matters. Indeed, higher psychological safety has been associated with increased speaking up behaviour and a subsequent decline of silence behaviours (Edmondson, 1999; Newman, Donohue, & Eva, 2017; O'Donovan & McAuliffe, 2020a). Psychological safety is a concept that can be perceived by an individual, the team (team psychological safety), and at organisational level (organisational psychological safety) (Bienefeld & Grote, 2014). At the individual level, it can be assumed that a variety of factors influence the degree to which psychological safety is felt with top-to-bottom influence from perceived team and organisational psychological safety. Study findings suggest that fear is one facilitator for silence and is negatively associated with psychological safety (Hémon, Michinov, Guy, Mancheron, & Scipion, 2020; Kish-Gephart, Detert, Klebe Treviño, & Edmondson, 2009; Moore & McAuliffe, 2012; Okuyama et al., 2014). It is rooted in the fear of punishment or negative responses from others, which can be interpreted as the perceived fear of repercussion (Bienefeld & Grote, 2014). Other individual factors that affect the likelihood of speaking up are seniority and experience, with junior members being prone to low psychological safety (Nacioglu, 2016; O'Donovan & McAuliffe, 2020b), certainty about their own knowledge and skills (i.e., task-related efficacy) (Beament & Mercer, 2016; Okuyama et al., 2014), and prior training regarding communication within teams (Sayre, McNeese-Smith, Leach, & Phillips, 2012).

As a medical event occurs, the risk for patient safety increases: the healthcare professional perceives an increase in (possible) patient harm which can, at the very worst, lead to patient death. For instance, a newborn in need of resuscitation immediately after birth is typically hypoxic (i.e., low levels of oxygen in bodily tissues) and needs ventilation (Boldingh, Solevåg, & Nakstad, 2018). Inefficient ventilation may lead to infant death due to neonatal hypoxia-ischaemia or life-long (persistent) motor, sensory, and cognitive impairments (Boldingh et al., 2018; Millar, Shi, Hoerder-Suabedissen, & Molnár, 2017; Raju, Suresh, & Higgins, 2011). This perception of increased patient harm is suggested to be a motivation to speaking up, regardless of psychological safety (Okuyama et al., 2014). Increased stress, while assumed to be a constant mental state (Nacioglu, 2016), related to decision-making (i.e., speaking up or silence) can have a negative impact on the choice to speak up (Pabst, Brand, & Wolf, 2013) and may cause the healthcare professionals to stay silent instead.

2.2. Contextual and interpersonal influences on speaking up behaviour

Despite the scarcity of literature scrutinising the effects of the response of the receiver, it is still an aspect worthwhile to discuss. As described before, positive relationships and responses can facilitate higher degrees of psychological safety while negative consequences to behaviour such as speaking up can be detrimental to psychological safety. Therefore, positive responses are beneficial to psychological safety of the team members.

A study by Long et al. (2020) interviewed fully qualified surgeons, anaesthetists, nurses, and anaesthetic technicians in New Zealand. Participants expressed that the valence of their response was determined by stress and fatigue, with some insights about the respect and familiarity they held towards the sender. Specifically, participants have showed that when they respected the sender, they were more likely to respond in a positive manner. Similarly, when they were familiar with the sender and, notably, when they had worked together previously, they were more often positive in demeanour. In other words, the elements that influence receptivity to speaking up are (perceived) trust, familiarity, stress, and fatigue.

Positive interpersonal relationships, such as the doctor-nurse relationship, can furthermore affect the perception of psychological safety, in particular team psychological safety. Responses of healthcare professionals should therefore be highlighted. When the healthcare professional has a positive attitude, thus approach, to communication with the nurse, chances for effective communication may advance (Tan, Zhou, & Kelly, 2017). These positive attitudes promote feelings of trust, (team) support, and familiarity within teams which are accordingly pertinent to effective communication (O'Donovan & McAuliffe, 2020b). Literature suggests that these interpersonal factors to (effective) communication between healthcare professionals cultivate a positive relationship, which is beneficial to increase team psychological safety (O'Donovan & McAuliffe, 2020b), and subsequently the perceived psychological safety by an individual.

3. The modelling approach used

An adaptive causal network-oriented modelling approach (Treur, 2016, 2020b) was used to illustrate the causal relationships and pathways between contextual and psychological factors, speaking up as an outcome behaviour, and related situational consequences. This method allows for a generic, dynamic, and declarative depiction of various processes; see (Treur, 2020b) for more details.

A temporal-causal network comprises *states*, the *connectivity* between respective states, indicated by respectively *X* and *Y*, for which activation values *X(t)* and *Y(t)* are assumed (usually with an interval of [0, 1]) that can change over time *t*. A network model is defined by its network characteristics. One type of these characteristics is *connection weights* $\boldsymbol{\omega}_{X,Y}$ from state *X* to state *Y*, usually with an interval between [-1, 1] denote the strength of the connections. When there are multiple incoming connections to a state *Y*, *combination functions* $\mathbf{c}_Y$ address the aggregated effect on *Y*. There is a wide variety of combination functions available in a library depending on the type of effect to represent in the model. Table 1 presents which combination functions were applied for states. For clarity, the states in this table are denoted with X_n (see Appendix, Supplementary Materials, Table 2, for the full state description). The last network characteristic to consider is the *speed factor* η_Y which characterises the timing of the causal effects. The numerical representation of a temporal-causal network model is described as:

- **Single state causal impact** is defined by $\mathbf{impact}_{X,Y}(t) = \boldsymbol{\omega}_{X1,Y}X(t)$ for the effect from *X* on *Y* at time *t*.
- **Aggregation of multiple causal effects** is expressed by

$$\mathbf{aggimpact}_{X,Y}(t) = \mathbf{c}_Y(\mathbf{impact}_{X1,Y}(t), \ldots, \mathbf{impact}_{X1,Y}(t)) = \mathbf{c}_Y(\omega_{X1,YX1}(t), \ldots, \omega_{Xk,YXk}(t)) \quad (1)$$

where *Y* gets its incoming connections from the X_i

- **Timing of the causal effect** is expressed by

$$Y(t+\Delta t) = Y(t) + \eta_Y[\mathbf{aggimpact}_{X,Y}(t) - Y(t)]\Delta t \text{ or } \mathbf{d}Y(t)/\mathbf{d}(t) = \eta_Y[\mathbf{aggimpact}_{X,Y}(t) - Y(t)] \quad (2)$$

The literature on the emanation of speaking up behaviour described in Section 2 was used to render the relevant processes in the network characteristics of the network-oriented modelling approach.

4. The proposed adaptive network model

Fig. 1 presents a graphical representation of the complete temporal-causal network model containing causal connectivity between the states described in Table 2 in Appendix. This model illustrates the assumed conjunction of contextual and psychological elements as a cognitive process of evaluative decision-making regarding whether to speak up or stay silent when witnessing a (near) medical error. A similar evaluative decision-making system introduced the receptiveness towards speaking up from the recipient.

Table 1
Combination functions used in the network model.

Description	Formula	Parameters	Used for
Advanced logistic $\mathbf{alogistic}_{\sigma,\tau}(V_1, \ldots, V_k)$	$(1 + e^{-\sigma\tau})$	Steepness $\boldsymbol{\sigma}$ Excitability threshold $\boldsymbol{\tau}$	X_2 - X_{24}, X_{28} - X_{50}, X_{54} – X_{79}, X_{83} - X_{88}
Identity function	$\mathbf{id}(V) = V$	None	X_{25} - X_{27}, X_{51} - X_{53}, X_{80} - X_{82}, X_{89}
Step once $\mathbf{steponce}_{\alpha,\beta}(\ldots)$	1 if $\boldsymbol{\alpha} \leq t \leq \beta$ *else* 0 (time *t*)	Start time $\boldsymbol{\alpha}$ End time β	X_1

4.1. The overall structure of the adaptive network model

The adaptive network model consists of the world state model (**WS**), individual mental models for the nurse (**N**), doctor (**D**), and the safe coach (**SFC**), and the mental and social processes interacting with them and with each other. The world state model signifies the sequence of events that occurs over time in the real world. It is based on descriptions of actions taken by the healthcare professionals and their effects in the world, particularly when they need to perform interventions if a neonate is not transitioning adequately (Madar, Roehr, Ainsworth, Ersdal, Morley, Rüdiger, Skåre, & Szczapa, 2021). Interventions are initiated when the vital checkpoints of the neonate (tone, heart rate, breathing, and colour) are considered insufficient. The context state $\mathbf{WS1}_{call\_intervention}$ triggers activation of the model for which the assumption holds that the responsible healthcare professional calls the start of intervention. To design episodes in the model, the function $\mathbf{steponce}_{\alpha,\beta}(\ldots)$ was used. The subsequent states are to provide a general sequence of an intervention wherein both the doctor and the nurse execute their designated tasks. Provided that medical errors often occur through failure of planned action (Raju et al., 2011), such as using an insufficient technique or intervention, the patient physical wellbeing is stagnant despite the intervention and is reflected in $\mathbf{WS6}_{intervention\_insufficient}$. While the same intervention can be performed multiple times (with the same result), this specific part is not modelled, considering that it is not the focus of the current paper. In other words, $\mathbf{WS6}_{intervention\_insufficient}$ is a broad proxy for a (near) medical event. Next, patient general risk increases as the intervention continues to be insufficient, explaining the bidirectional connection between $\mathbf{WS6}_{intervention\_insufficient}$ to the world's context state $\mathbf{WC1}_{Patient\_Centr\_risk}$.

4.2. The nurse model

4.2.1. Evaluating speaking up through stimulus representation

While **WS** models actions in the real world, the individual mental model of the nurse comprises a mental model which the nurse utilises for internal simulation within cognitive processes. Specifically, mental model states **N1** to **N5** represent medical actions which are subsequently executed in **WS** as illustrated by the connections between the **WS** and **N** models. The individual **N** mental model also receives information from the **WS**, which models observation. For speaking up to occur, the information about the failed intervention prompts the detection of a medical event, as denoted by the outgoing connection from $\mathbf{WS6}_{intervention\_insufficient}$ to $\mathbf{N5}_{intervention\_insufficient}$. This incoming connection activates the cognitive process of evaluative decision-making for speaking up by the nurse. Its design is based on a what-if analysis approach making use of internal simulation of simulated action and perception pathways (Hesslow, 2002). First, the stimulus representation state (srs) for the error detection $\mathbf{N8}_{srs\_error\_detect}$ activates through the perceived insufficiency of the intervention, which subsequently connects two evaluation states representing the choice of speaking up or silence, $\mathbf{N10}_{eval\_SPU}$ and $\mathbf{N9}_{eval\_SL}$ respectively, which have a negative bidirectional connection between them (as indicated by the orange arrows). This negative bidirectional connectivity between the eval-states models an exclusiveness effect, so the ultimate choice of the nurse is either speaking up or silence. The eval-states are thereafter bidirectionally connected to individual srs-states; $\mathbf{N12}_{srs\_SPU}$ and $\mathbf{N15}_{srs\_SL}$. They encompass the concept of a person (in this case, the nurse) internally envisioning how either speaking up or silence would affect themselves and the real-world situation. For example, the nurse would ponder, 'If I speak up about this situation, how will that backfire on me?'. These states function as determining components of speaking up or silence. For instance, higher $\mathbf{N12}_{srs\_SPU}$ than $\mathbf{N15}_{srs\_SL}$ activity would suppress $\mathbf{N15}_{srs\_SL}$ which causes amplified activity in $\mathbf{N10}_{eval\_SPU}$ rendering the choice made by the nurse through internal what-if simulation.

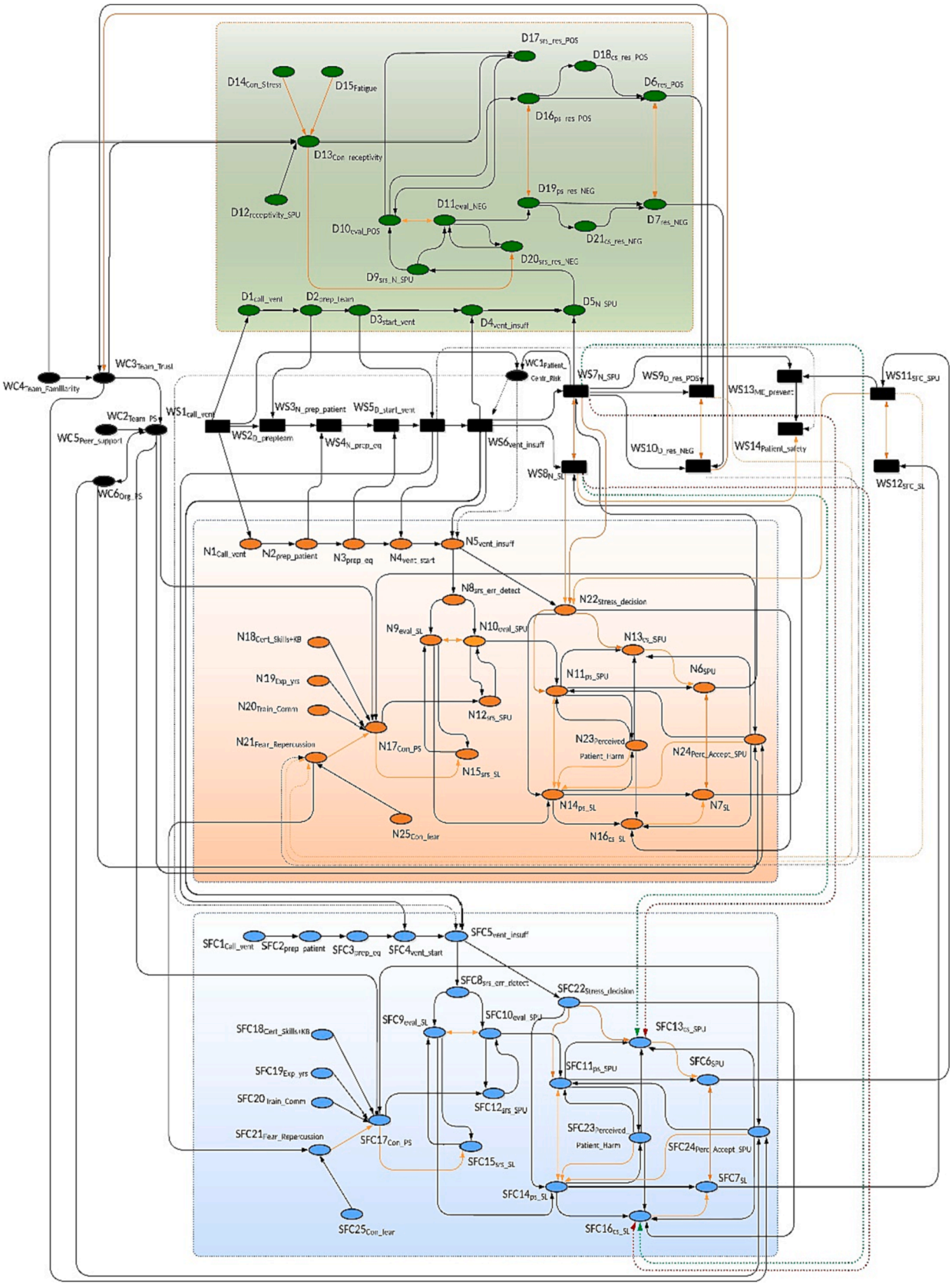

Fig. 1. Complete proposed temporal-causal network model for speaking up behaviour and related response.

4.2.2. Psychological safety enhancing stimulus representation

The srs-states address aspects of psychological safety, as illustrated in Fig. 2, considering that psychological safety is hypothesised to be a mediator to speaking up. For the sake of modelling, psychological safety is defined as the following. While the nurse is deciding, there is a sense of safety to speak up within the context, hence contextual psychological safety; $\mathbf{N17}_{con\_PS}$. Team psychological safety and individual factors directly affect contextual psychological safety, such as confidence in skills and knowledge, years of experience in position, prior training in communication, and (mainly) fear of repercussion to speak up. Team psychological safety is a context state which depends on organisational psychological safety, team trust, peer support and team familiarity. Fear of repercussion, while affected by the outcomes of speaking up, has a memory state representing prior experiences with speaking up which induced the fear of repercussion. The assumption is that high contextual psychological safety means that the nurse feels safe to speak up. This state henceforth amplifies $\mathbf{N12}_{srs\_SPU}$, the choice to speaking up, whilst the negative outgoing connection to $\mathbf{N15}_{srs\_SL}$ suppresses activity for the choice to stay silent. Low contextual psychological safety amplifies $\mathbf{N15}_{srs\_SL}$ through the negative feed-forward connection.

4.2.3. From evaluation to preparation for action

As activation from the srs-states are fed into the eval-states, the eval-states consequently activate the preparation states (ps) which entail the nurse internally preparing themselves to speaking up or be silent after they made the choice. Based on the all-or-nothing exclusiveness principle of this choice system, there is a bidirectional negative connection between $\mathbf{N11}_{ps\_SPU}$ and $\mathbf{N14}_{ps\_SL}$, indicating that the nurse cannot prepare for both situations as they are to choose only one of the two actions. While preparing for the chosen action, there are still factors that influence the ultimate choice. For instance, stress for deciding to speak up negatively affects the nurse while preparing for action, which could eventually lead to choosing silence regardless of the evaluation, as illustrated by the positive connection to $\mathbf{N14}_{ps\_SL}$ and negative connection to $\mathbf{N11}_{ps\_SPU}$. A similar principle was used to model the effect of perceived patient harm on the choice made, with higher perceived patient harm amplifying the choice to speaking up. Through modelling a loop between the state of perceived patient harm and the ps-states, the choice is further evaluated given that patient harm can be dynamic provided the link to the state of the patient. The last state to influence the ps-states is the perceived acceptability to speaking up. Along with contextual psychological safety, this state encompasses a historical context to prior experiences that shape how acceptable the individual perceives speaking up. The ps-states are consequently connected to control states (cs-states) which are connected to the execution states (es-states) $\mathbf{N6}_{SPU}$ and $\mathbf{N7}_{SL}$. These control states model general assumed hesitancy for making a risky choice, therefore, these cs-states have a slight repression effect on the es-states. Patient harm, acceptability of speaking up, and decision stress provide additional weight for hesitance for either choice. The es-states are ultimately connected to the corresponding **WS**-states demonstrating the execution of the chosen action of the nurse in the real world.

4.3. The doctor model

4.3.1. The evaluative decision-making system for responding to speaking up

The **D** individual model was designed similarly to the model of the nurse, see Fig. 3. The doctor also uses the mental model to process both internal simulation of medical actions through mental model states and an evaluation decision-making system for responding to speaking up. Indeed, this pattern will only activate if the nurse chose to speak up, illustrated by the connection from $\mathbf{WS6}_{N\_SPU}$ to $\mathbf{D5}_{N\_SPU}$. The above-mentioned connection activates the doctor's internal representation of the nurse speaking up. Following $\mathbf{D5}_{N\_SPU}$, the evaluation decision-making system for responding to speaking up denotes a similar eval-srs loop and eval-ps connectivity explained for the **N** individual model. These systems, however, differ in the choices for the agent. The doctor chooses whether to respond in a positive or negative manner. In like manner to the influence of contextual psychological safety on the srs-states in the **N** individual model, the state receptivity to speaking up entails how receptive the doctor is to a colleague speaking up within the moment. Contextual stress, fatigue, and a context state of receptivity

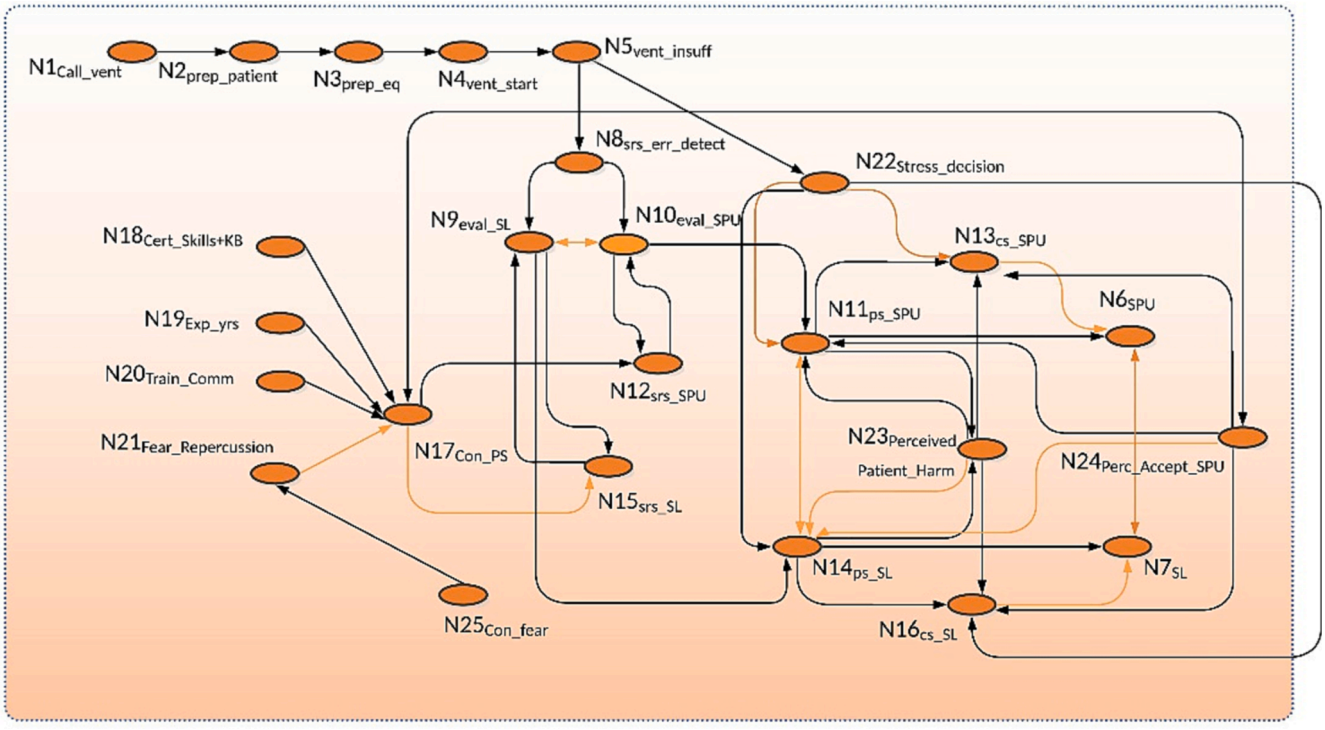

Fig. 2. Nurse individual model.

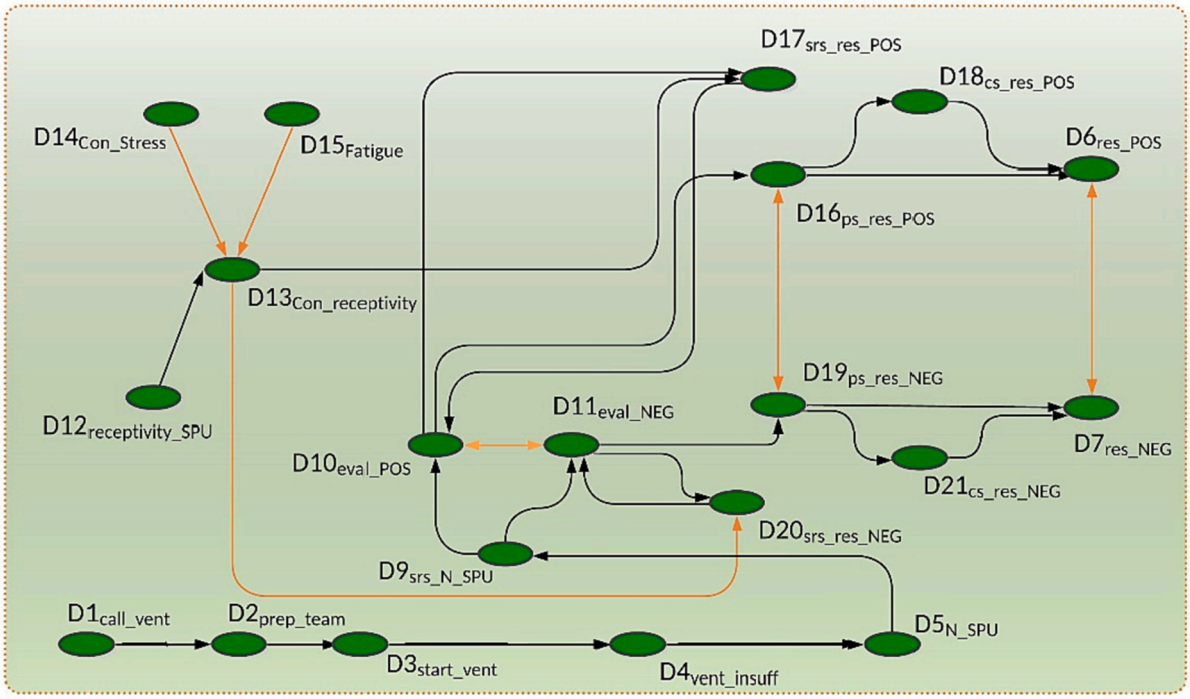

Fig. 3. Doctor model for evaluating and responding to the nurse.

that represents the individual value for receptiveness to speaking up by the doctor negatively affect this state. Receptivity to speaking up is further influenced by two context factors: team trust and team familiarity, as presented by the literature (O'Donovan & McAuliffe, 2020b). The receptivity to speaking up and srs-state connectivity assumes that a high value of receptivity to speaking up amplifies **D17**$_{srs\_res\_POS}$ while attenuating **D20**$_{srs\_res\_NEG}$. As described before, activity feeding back from srs-states to eval-states with the bidirectional negative connectivity between eval-states result in the doctor choosing either a negative or positive response. After activation of the ps-states, assumed hesitancy for response was modelled through subsequent cs-states which slightly repress the es-states to ultimately activate the corresponding **WS**-states.

4.3.2. Consequences of response

The doctor choosing to respond positively adversely affects the state fear of repercussion within the **N** individual model. When the doctor replies positively to the nurse speaking up, the fear felt for repercussion will decrease. A negative response from the doctor causes the reverse; the nurse will feel more fear for repercussion as they can consider the negative response as a detrimental consequence. The fear of repercussion and doctor response connectivity illustrates the influence the doctor has concerning psychological safety for both the team and the individual. To further emphasise the significance of the doctor's response on team psychological safety, the doctor response in the **WS** model both influence team trust (Weller & Webster, 2021). The positive response increases team trust, and the negative response reduces team trust, which consequently affects team psychological safety for future cases. It must be noted that the proposed network model assumes that once the nurse chooses to speak up, actions for prevention of the medical event are taken, leading to increased patient safety. Thus, a positive or negative doctor response does not affect patient safety in the current model because of the relational effects being out of scope for this paper.

4.4. The world state(s) in the designed model

As described before, the **WS** model includes the actions of both the nurse and the doctor in the world. As two of these actions, Fig. 1 depicts the **WS** for the nurse either having spoken up or having kept silent. When the nurse chooses to speak up, this is consequently being perceived by the doctor via mental model state **D5**$_{N\_SPU}$ which activates the evaluation decision-making system for responding to speaking up. This model assumes that speaking up is a safety behaviour with consequences for patient safety. For the sake of simplicity, the assumption holds that the doctor always incorporates the input of the nurse if the nurse chooses to speak up, regardless of the valence to the doctor response. Therefore, speaking up by the nurse in the **WS** causes actions by the doctor to prevent the medical error from happening; **WS13**$_{D\_ME\_Prevention}$, consequently increasing patient safety. In contrast, when the nurse chooses silence, patient safety decreases because no preventative measures are performed.

4.5. The Safe Coach model

The proposed model introduces a Safe Coach (**SFC**) model that monitors whether an issue occurs that may lead to speaking up and intervenes when the nurse chooses to not speak up. The assumption holds that this **SFC** individual model represents the 'perfect' nurse model, which entails the nurse mental model where speaking up is always chosen whenever relevant. The Safe Coach consistently chooses speaking up in such cases. Hence the individual model of the Safe Coach is a near identical copy of the nurse; see Fig. 1 for an overview of the **SFC** mental model relative to the **N** mental model. The Safe Coach only contains a copy of the individual mental model of the nurse due to the coach being proposed as a mechanism to control speaking up behaviour. Speaking up is less common than would be expected in health care and explicates a greater likelihood that nurses and residents do not always possess the 'perfect' mental model for speaking up in the real world. Nurses and residents exercise a higher threshold to speaking up than the Safe Coach implied by the modelled hesitancy through cs-states. The **SFC** model therefore functions to predict the speaking up behaviour of the nurse by comparing the **N** mental model outcomes (i.e., **WS7**$_{SPU}$ and **WS8**$_{SL}$) to its own outcomes. To facilitate comparison, the SFC initially needs the same input as the nurse. This initial input is assumed to be **WS6**$_{intervention\_insufficient}$ as the Safe Coach is presumed to perceive a (near)

medical error in like manner to the nurse. Diverging model outcomes prompt the Safe Coach to intervene by executing a form of speaking up related to the ME at hand. This comparison is modelled through the connection between **WS8**$_{SL}$ and the cs-state for speaking up by the Safe Coach; **SFC13**$_{cs\_SPU}$. This cs-state functions slightly differently compared to the **N** mental model. Since the Safe Coach does not 'hesitate', it controls for activation of the subsequent es-states by functioning as a gateway. If and only if the activation for this cs-state is sufficient, the es-state for speaking up by the Safe Coach can activate. The excitability threshold $\boldsymbol{\tau}$ of this cs-state is set to a high value to prevent the Safe Coach intervention if the nurse chooses to speak up but is slower than the SFC. For the sake of completeness, **WS7**$_{SPU}$ is negatively connected to **SFC13**$_{os\_SPU}$ and positively connected to **WS16**$_{os\_SL}$ so the Safe Coach does not intervene when the nurse chooses to speak up. To ensure the SFC intervenes properly, **WS8**$_{SL}$ has an additional negative connection to **WS16**$_{os\_SL}$. Furthermore, the intervention of the Safe Coach leads to medical event prevention, subsequently improving patient safety, as well as reducing decision stress and fear of repercussions by the nurse. The assumption holds that this intervention models speaking up behaviour, which could lead to fear reduction for the nurse. However, due to the artificial nature of the Safe Coach, this connection is rather weak.

5. Simulation experiments without the safety coach

In this section, some of the multiple simulation experiments which were performed in MATLAB R2021a (https://nl.mathworks.com/?s_tid=gn_logo) are discussed. They are based on the following case:

> "After delivery, the neonate is not transitioning well. After birth, there is a very low heart rate, the tone is floppy, its colour is blue, and the neonate is not breathing, despite drying and stimulating the neonate. Following the first assessment by the medical team, they start with administering 5 inflation breaths by applying a facemask with positive pressure ventilation, as is recommended by the newborn resuscitation and support of transition at birth protocol. This series of inflation breaths and a subsequent attempt did not help the neonate stabilize; there were no chest movements the heart rate was still low. The nurse notices by this point what the error is. As this suggestion pertains to the doctor, the nurse will have to choose to speak up or remain silent (H. R. Taal, personal communication, August 24, 2022)."

5.1. Baseline: No speaking up required

The following situation that is modelled serves as a baseline for the narrative at hand. This simulation demonstrates the behaviours of the actors when there is no (near) medical error, which therefore renders speaking up from both the nurse and Safe Coach unnecessary. To model this lack of necessity, it is assumed that ventilation is sufficient, causing the incoming weight of **WS5**$_{intervention\_start}$ to **WS6**$_{intervention\_insufficient}$ to be zero; $\boldsymbol{\omega}_{WS5_{intervention\_start},WS6_{intervention\_insufficient}}$. For the sake of clarity, only the relevant graphs relating to the description are displayed. Fig. 4 demonstrates the states and actions in the world. As the call for intervention is made (**WS1**$_{call\_intervention}$), both **D** and **N** act according to their position. However, under the presumption that no error occurs, the neonate stabilises because of the intervention. The state patient safety illustrates the stabilisation. Fig. 4 shows the steady increase of patient safety after ventilation starts. This simulation above all demonstrates that the states **WS7**$_{SPU}$ and **WS8**$_{SL}$ do not activate as the evaluation decision-making system is not activated by **WS6**$_{intervention\_insufficient}$. In a subsequent manner, neither evaluation-decision making systems for either **D** or **SFC** are activated, which results in neither corresponding **WS**-state to be active.

5.2. Speaking up

To model speaking up behaviour by the nurse, initial values of states 'certainty of skills and knowledge', 'prior training in communication', and 'experience in years' were all set to 0.6 given the direct connection to perceived contextual psychological safety. Contextual fear was set at 0.45 causing fear for repercussion to suppress perceived contextual psychological safety for a more realistic simulation of speaking up. Fig. 5 depicts the situation where the nurse chooses to speak up due to the initial values mentioned. The figure includes the same sequence of **WS**-

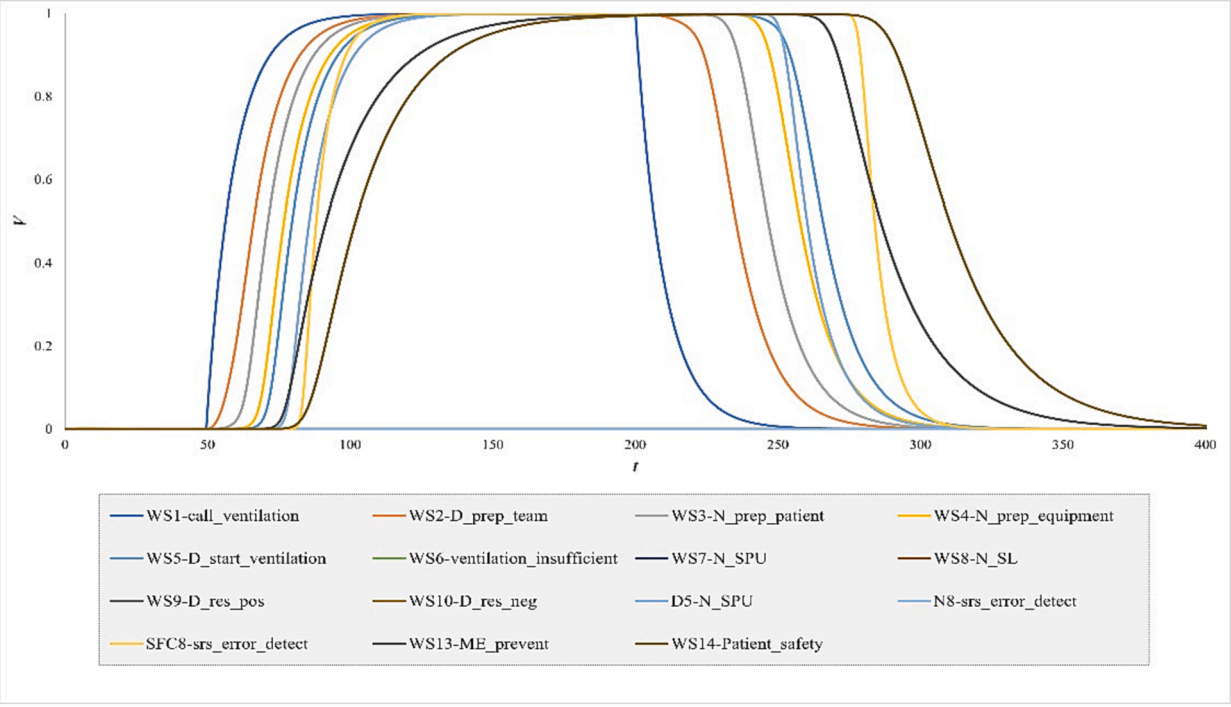

Fig. 4. Patient is safe, therefore no speaking up behaviour is desired.

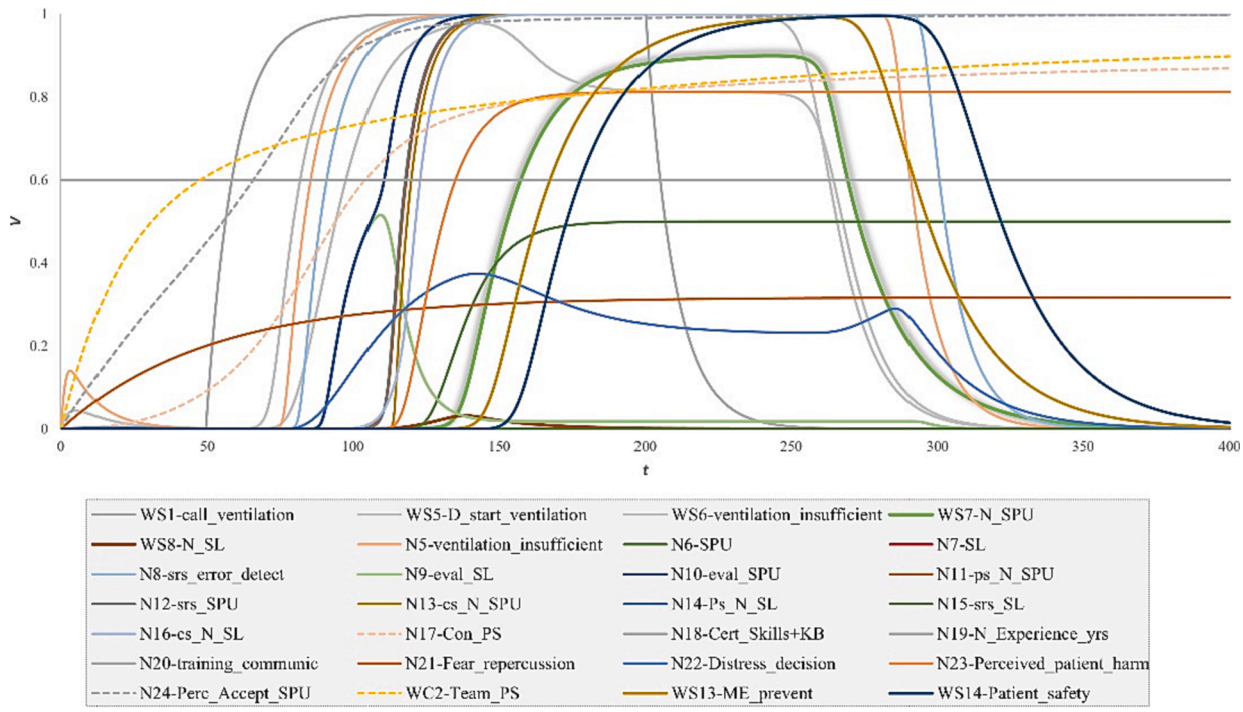

Fig. 5. Nurse perceives a threat to patient safety, therefore speaks up for it.

states as simulated in the baseline. In this case, however, ventilation is not sufficient. To model this activation, the connection weight $\omega_{WS5intervention\_start,WS6intervention\_insufficient}$ was changed to 1. Because of this $\mathbf{WS6}_{intervention\_insufficient}$ becomes active at $t = 73$, the evaluation-decision making system for speaking up in the N individual model was activated through the connectivity from $\mathbf{N5}_{ventilation\_insufficient}$ to $\mathbf{N8}_{srs\_error\_detect}$. Subsequently, 'patient risk' also increases at a similar time point. Fig. 5 illustrates the subsequent activation of the eval-states after $\mathbf{N8}_{srs\_error\_detect}$ starting around $t = 87.5$. These eval-states trigger the activation for the corresponding srs-states at $t = 104.5$. Through the relatively high activity from states relating to 'team psychological safety', 'perceived acceptability to speaking up', 'experience in years', 'certainty of skills

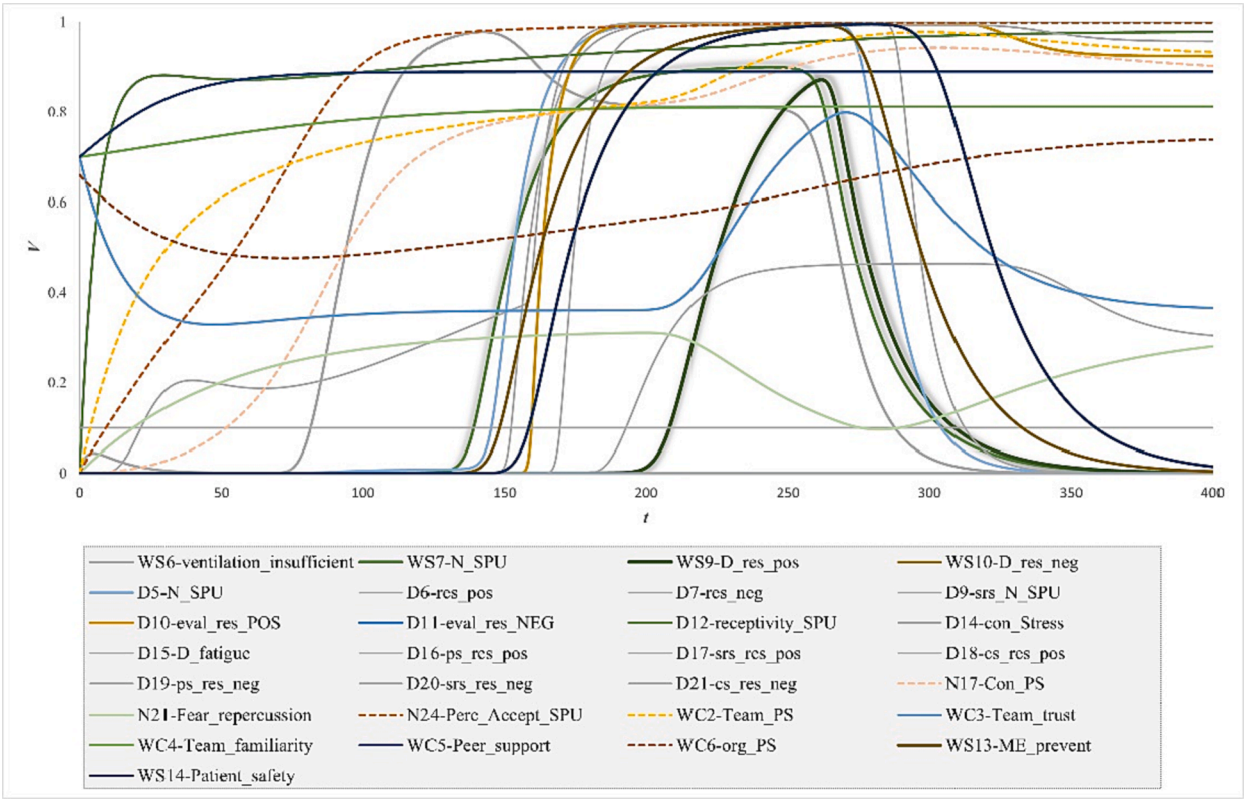

Fig. 6. Speaking up and an affirmative response from the doctor.

and knowledge', 'prior training in communication', and low 'fear for repercussion' ($t = 113.5$; $V = 0.28$) the value for 'perceived contextual psychological safety' amounts to 0.67 at $t = 106.5$. Due to the higher activation value for 'perceived contextual psychological safety', the $\mathbf{N12}_{srs\_SPU}$ activation increases while $\mathbf{N15}_{srs\_SL}$ decreases because of the eval-srs loop. As depicted in the simulation, $\mathbf{N9}_{eval\_SL}$ peaks at $t = 109$ due to continued suppression by 'perceived contextual psychological safety' through $\mathbf{N15}_{srs\_SL}$ and consequently decreases. In contrast, $\mathbf{N10}_{eval\_SPU}$ increases at the same time point. Activation for this eval-state causes $\mathbf{N11}_{ps\_SPU}$ to activate at $t = 107.5$ with consecutive activation of $\mathbf{N13}_{cs\_SPU}$. With high values of 'perceived patient harm' and 'perceived acceptability to speaking up' at $t = 106$, $\mathbf{N11}_{ps\_SPU}$ is further augmented with slight suppression from $\mathbf{N13}_{cs\_SPU}$, whilst the opposite states continue to be repressed. $\mathbf{N6}_{SPU}$ then activates at $t = 121$, followed by activation of $\mathbf{WS7}_{N\_SPU}$ (i.e., the nurse speaking out in the real world). The nurse choosing speaking up causes an expected decrease in 'decision stress' which had been increasing at $t = 79.5$ after the nurse assessed insufficient ventilation ($\mathbf{N5}_{intervention\_insufficient}$) and decreases after activation of $\mathbf{N6}_{SPU}$ (i.e., the eventual choice). At last, the nurse speaking up in the real-world causes actions for medical event prevention ($t = 139.5$) which leads to increased patient safety ($t = 148.5$) (see Fig. 6).

5.2.1. Speaking up with a positive response

The next simulation highlights the response of the doctor when the nurse chooses to speak up. To achieve this simulation, initial values of the states pertaining to receptivity to speaking up were set to the following: contextual receptivity = 0.7, contextual stress = 0.1, fatigue = 0.1. The evaluation-decision system for valence of response by the doctor functions very similarly to the evaluation-decision system for speaking up of the nurse. State $\mathbf{D5}_{N\_SPU}$ activates at $t = 138.5$, right after the nurse speaks up in the world, which depicts the sensory information to the doctor that the nurse spoke up. This activation prompts activation the eval-states. Because of the high receptivity for speaking up, $\mathbf{D10}_{srs\_POS}$ activity amplifies, whilst $\mathbf{D11}_{srs\_NEG}$ decreases. In like manner to the srs-eval loop previously described for the evaluation-decision system for speaking up, $\mathbf{D10}_{srs\_POS}$ activity receives more activation than $\mathbf{D11}_{srs\_NEG}$. In turn, the eval-state activates the related ps-state subsequently. The ps-state obtains additional activation due to the relatively high perceived patient harm ($t = 164$; $V = 0.79$) with slight repression through hesitancy by the cs-state. Due to the related ps-state, the es-state for the doctor responding positive $\mathbf{D6}_{res\_POS}$ activates. The states relating to choosing a negative response were suppressed in accordance with the literature. The doctor promptly responds positively in the world $\mathbf{WS9}_{res\_POS}$ causing the predicted decrease of fear of repercussion in the **N** model at $t = 206.5$. Because of $\mathbf{WS9}_{res\_POS}$ activity, team trust and the states related to psychological safety see an increase in activity given the expectation that a positive response by the doctor applies to an environment where individuals feel safe to take interpersonal risks. Team trust, however, decreases as $\mathbf{WS9}_{res\_POS}$ halts activity. An explanation for this lack of retention pertains to model design as the activity of this state is not persistent but can in the future be addressed by reification of the state persistence.

5.2.2. Speaking up with a negative response

Provided that receptivity to speaking up by the doctor largely depends on their physiological and mental state (i.e., fatigue and stress), the next simulation sets the initial values of contextual stress and fatigue at 0.65. In addition, contextual receptivity to speaking up is set to 0.2 to model initial low receptiveness. Fig. 7 shows low receptiveness to speaking up with a highly agitated mental state of the doctor (i.e., high stress and fatigue). Therefore, the srs-eval loop in the evaluation-decision system amplifies $\mathbf{D11}_{eval\_NEG}$ instead due to the negative connectivity between the contextual receptivity to speaking up and $\mathbf{D20}_{srs\_res\_NEG}$. This leads to choosing a negative response as the doctor chooses the ps-states for the negative response, causing activation of $\mathbf{WS10}_{res\_NEG}$. The doctor responding negatively leads to an inverse effect compared to the doctor responding positively. Specifically, fear for repercussion increases and related psychological safety states and team trust decreases. The comparison between the positive and negative response illustrates some interpersonal consequences, considering the

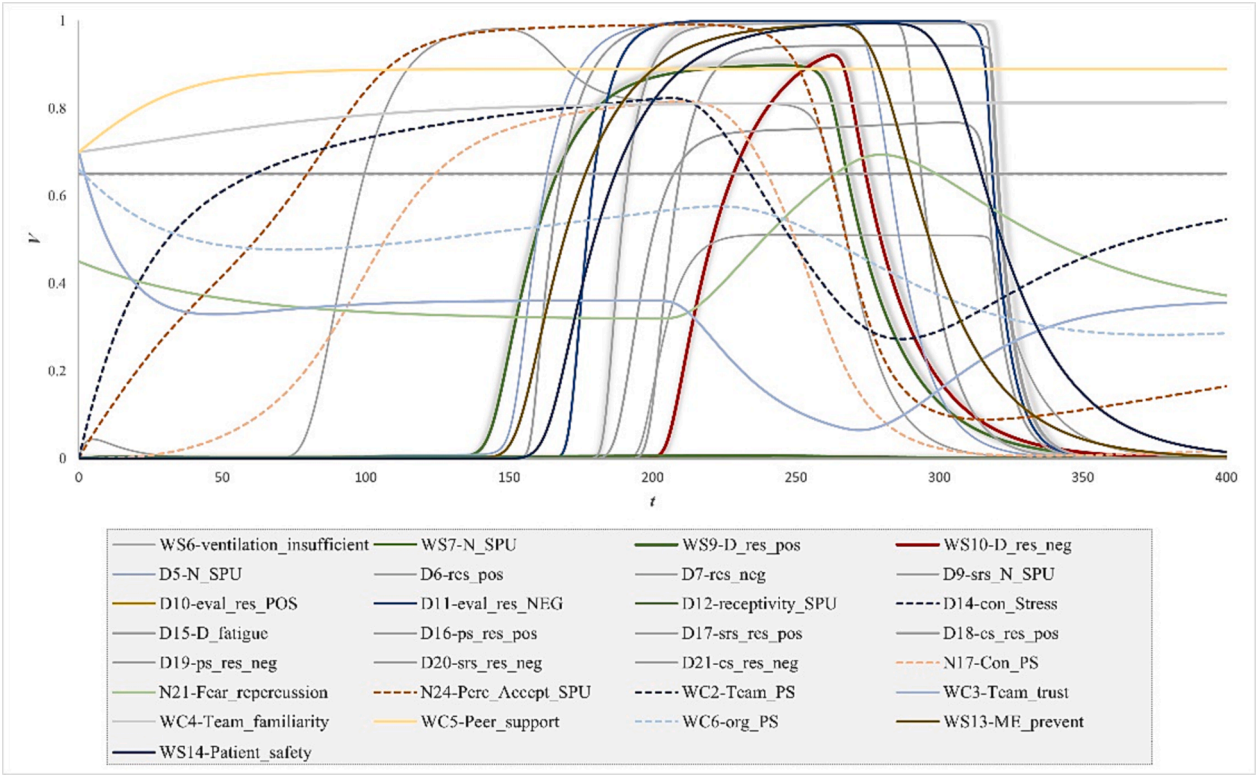

Fig. 7. Speaking up and an adverse response from the doctor.

importance of the attitude of the doctor.

5.3. Silence

The next simulation experiment shows silence behaviour. To model this behaviour, changes in initial values of the following states were made: certainty skills and knowledge = 0.01, experience in years = 0.2, prior training in communication = 0.01, contextual fear for repercussion = 0.7. Fig. 8 indicates the consequences of low contextual psychological safety on speaking up behaviour. Given that the mentioned states were low, with higher suppression of fear for repercussion, contextual psychological safety activates slightly. Due to this low activity, the **N15**$_{srs\_SL}$ state increases in activity given the negative connection between contextual psychological safety and the srs-state. Contrarily, low contextual psychological safety does not provide adequate activation for **N12**$_{srs\_SPU}$, despite the relatively high perceived patient harm. The evaluative decision-making system accordingly causes activation for the choice of silence. As expected, however, decision stress decreases once the nurse has made the choice to keep silent which solidifies that the stress felt is mainly due to the choice in the provided model. Because the nurse chose silence, there is no prompt from the doctor, as **WS8**$_{SL}$ is not connected to the doctor's individual model. Consequently, no preventative measures are taken to apprehend the possible medical error, which results in patient safety to be stagnant and low as depicted in Fig. 8.

6. Simulation experiments using the safety coach

The last simulation experiment discussed addresses the situation wherein the Safety Coach intervenes to prevent the medical event from occurring or deteriorating, leading to an increase in patient safety. The Safety Coach contains a copy of the 'perfect' nurse model for speaking up and will therefore always choose speaking up whenever relevant. Hence, contextual psychological safety and perceived acceptability to speaking up within the SFC individual model are high in activity, as illustrated in Fig. 9. In this situation, the nurse situation is not 'perfect', which is likely the case, and therefore chooses silence. For the **SFC** mental model to activate, it receives activation from **WS6**$_{intervention\_insufficient}$ to **SFC5**$_{intervention\_insufficient}$. To monitor behaviour of the nurse, the SFC model receives the same activity to the copied states. In Fig. 9 the activation of **SFC5**$_{intervention\_insufficient}$ after **WS6**$_{intervention\_insufficient}$ for this is illustrated with an amplification of this WS-state because of the inherent increased patient risk. The Safe Coach makes the choice to speak up in a similar sequence of state activation as the nurse if they choose to speak up. However, the simulation shows that only if the nurse chooses silence, then **SFC13**$_{cs\_SPU}$ receives adequate activation to intervene by speaking up itself, depicted by **WS11**$_{SFC\_SPU}$ in the simulation through activation of the cs-states. In Fig. 9 the consequences of the SFC intervention are displayed. Because of intervention the Safety Coach allows for an increase of patient safety on account of all healthcare professionals in the delivery room now being aware of the problem, hence leading the team to take measures against ME deterioration. With the Safety Coach controlling the situation and essentially modelling speaking up behaviour, the Safety Coach decreases fear of repercussion in the nurse as portrayed by the simulation.

7. Discussion

In this paper, we have proposed an initial controlled adaptive network model for speaking up behaviour during delivery room management. The aim was to identify and demonstrate the complexities of speaking up behaviour of healthcare professionals, specifically nurses, in healthcare systems using available literature and network modelling. The proposed model shows how speaking up behaviour in nurses or residents can be influenced and what the presence or absence of this behaviour may cause for patient safety in accordance with available literature. In addition, efforts were made to highlight the importance of the attitude of the doctor or person in charge on perceived psychological safety at individual and contextual level. Last, the simulation experiments demonstrated how a monitoring and controlling system may be

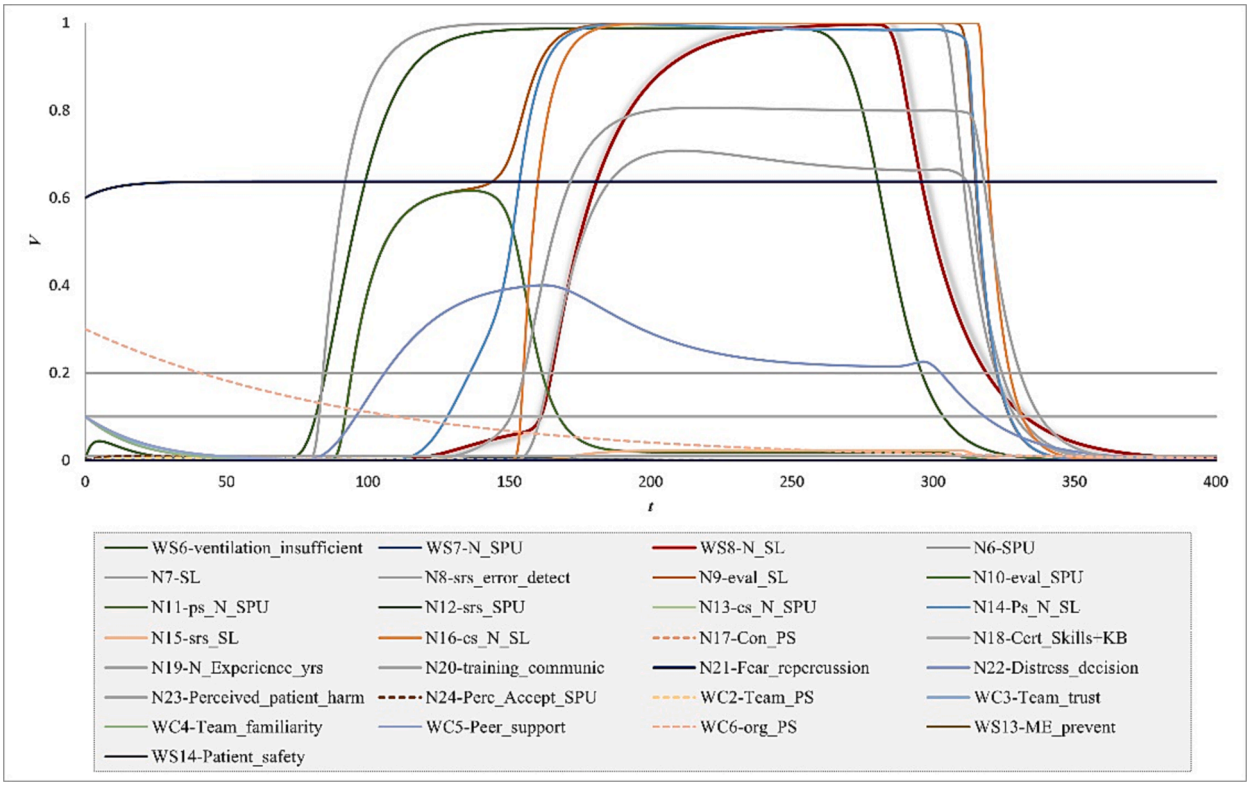

Fig. 8. Simulation experiment for silence by the nurse.

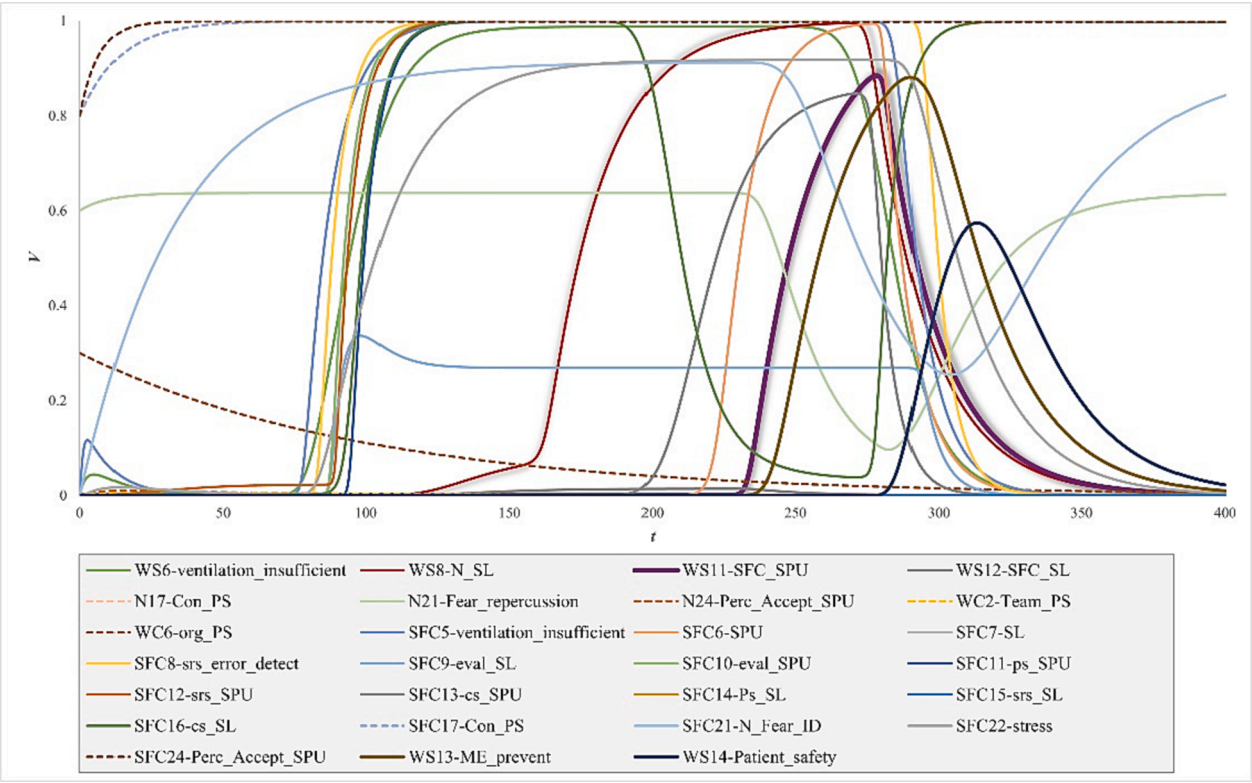

Fig. 9. Simulation experiment for silence by the nurse with intervention of the SFC.

beneficial as intervention when healthcare professionals hesitate to speak up to prevent the patient from deteriorating due to (preventable) medical errors.

The model was verified by using mathematical stationary point analysis. These points occur for state Y when $dY(t)/dt = 0$; by (1) and (2) of Section 3, in terms of the network characteristics, the criterion for $dY(t)/dt = 0$ is as follows:

$$\mathbf{aggimpact}_{X,Y}(t) = Y(\mathrm{t}) \text{ or } Y = 0 \tag{3}$$

where

$$\mathbf{aggimpact}_{X,Y}(t) = \mathbf{c}_Y(\omega_{X1,Y}X_1(t), \ldots, (\omega_{Xk,Y}X_k(t)) \tag{4}$$

For four states stationary points were verified; see Table 2. The deviations $|\mathbf{aggimpact}_Y(\mathrm{t}) - Y(\mathrm{t})|$ obtained were small, which provides an indication that the proposed model is correct in terms of design.

The proposed model includes psychological safety as a mediator for speaking up by the nurse. Whilst several factors were taken into consideration based on the literature, the model largely depends on fear of repercussion as determining input for psychological safety. This factor was chosen specifically due to direct associations made in the existing literature on psychological safety (Kish-Gephart et al., 2009). Future studies, however, may consider scrutinization of social contextual and group biases (Jones & Roelofsma, 2000), leadership (Bienefeld & Grote, 2014; Weiss, Kolbe, Grote, Spahn, & Grande, 2018), hierarchy and interpersonal relations (Beament & Mercer, 2016; Bould, Sutherland, Sydor, Naik, & Friedman, 2015; O'Donovan, van Dun, & McAuliffe, 2020; Peadon, 2020), influence of speaking up content and tone (Lemke et al., 2021). Leadership style relative to speaking up is one of the more well-studied topics in known literature. There are lines of evidence suggesting inclusive leadership to be a predictor for increased psychological safety of both the team and individual (Pattni et al., 2017; Weiss et al., 2018) and, subsequently, speaking up behaviour. A related predictor of speaking up to leadership in teams and the organisation on a larger scale is the hierarchical structure between team members (Hémon et al., 2020; Long et al., 2020). In other words, the impact of the doctor or team leader on the perceived acceptability to speak up is a valuable domain in understanding how a work culture can be cultivated that prompts speaking up instead of silence. It is worthwhile for future studies to extend the proposed initial model for speaking up, as addressing these topics was out of the scope of the current paper.

In addition, the paper briefly introduced the dyadic communication between doctor and nurse by including the doctor individual model for receptivity to speaking up. However, effective communication is reliant on a multitude of factors not included in the current model for it is out of the scope of the study. In the future studies related to speaking up can emphasise the complexity of this dyadic communication by addressing (e.g.) communication styles (Tan et al., 2017), the tone and content of speaking up and its consequences on doctor-nurse interactions (Lemke et al., 2021), and cultural and professional differences in norms (Long et al., 2020). These themes can be addressed specifically in terms of how the nurse-doctor relationship is affected as well as how this may consequently influence future speaking up behaviour.

Table 2
Mathematical verification using stationary point analysis results.

State Y	$WS6_{ventilation\_insufficient}$	$WS7_{N\_speaking\_up}$	$WS9_{D\_res\_POS}$	$N_{fear\_repercussion}$
time point	142.5	243.5	262	199.5
$Y(t)$	0.977839	0.899415	0.871426	0.310906
$aggimpact_Y(t)$	0.976556	0.899060	0.850113	0.309844903
deviation	−0.001283	−0.000356	−0.021313	−0.001061

Another proposition for future studies with the purpose of achieving completeness is the added dimension of organisational learning relative to psychological safety and its effects on speaking up among healthcare professionals. Organisational learning pertains to the collective learning by groups or teams within an organisation, which has a positive influence on organisational performance through shared knowledge between workers (Ratnapalan & Uleryk, 2014). Existing literature links healthcare professionals operating in a psychologically safe environment to, on average, being more inclined to engage in team and individual learning regarding taking initiatives for care optimisation (Newman et al., 2017). The prevention of medical errors, to be specific. Therefore, encouraging a psychologically safe climate of transparency about safety concerns allows for organisational learning (O'Donovan & McAuliffe, 2020a). Future models can address this dimension of organisational learning through the addition of adaptivity, which entails modelling complex and dynamic processes; processes that adaptively change over time (Treur, 2020a). Predictors introduced in this paper are familiarity and trust among team members, which also change over time and thus affect psychological safety dynamically. For future studies, it is therefore worthwhile to introduce this adaptivity level to the emergence of speaking up among healthcare professionals.

This paper addresses the complexity of speaking up within the healthcare setting by introducing an adaptive computational model. Despite considering fewer factors compared to the literature, the model illustrates in a causal and generic manner the following findings with the use of experimental simulations. The model demonstrates that high perceived psychological safety, affected by individual, contextual, and interpersonal factors, prompts the likelihood of speaking up behaviour of healthcare professionals. In like manner, the model predicts how the valence of response from the receiver affects the perceived psychological safety. Furthermore, the virtual coach within the model intervenes to speak up in order to optimize patient safety when it predicts silent behaviour from the healthcare professionals. In conclusion, we introduce the first computational model to predict speaking up behaviour regarding speaker and receiver, as well as an intervention to further optimize care in healthcare organisations.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cogsys.2023.02.002.

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