Displaying and Regulating Different Social Response Patterns: a Computational Agent Model[1]

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Abstract

Differences in social responses of individuals can often be related to differences in functioning of certain neurological mechanisms. This paper presents a computational agent model capable of showing different types of social response patterns based on such mechanisms, adopted from theories on mirror neuron systems, emotion integration, emotion regulation, and empathy. The presented agent model provides a basis for human-like social response patterns of virtual agents in the context of simulation-based training (e.g., for training of physicians or therapists), gaming, or for agent-based generation of virtual stories.

Keywords: social response, ASD, regulation, computational agent model

1 Introduction

Human social interaction often goes beyond verbal exchange of information. For example, to obtain and display forms of mutual empathic understanding, both verbal and nonverbal interaction play a role. Such forms of understanding have been recognized not only to be important to maintain personal relationships, but also in professional relationships, for example, between a teacher and a student, between a counselor and a client, or between a physician and a patient. To monitor such social interactions of professionals, and, when desired, to improve their capabilities in these interactions, specific means and training facilities have been or are being developed. Examples from the medical area are (Bonvicini et al., 2009; Hojat, 2007; 2009; Suchman, Markakis, Beckman, Frankel, 1997; Tulsky et al., 2011; Zimmermann et al., 2011). As, for example, discussed in (Turkey et al., 2011) computer support environments for training purposes may provide a useful contribution to this field. However, to be able to develop environments of good quality, insight in the mechanisms underlying such social interaction is important.

In recent years neurological mechanisms have been discovered that describe how, for example, direct nonverbal contagion of emotions (e.g., responding to a smile) may take place between agents. Within neuroscience the study of mechanisms behind social interaction has led to a fast developing new discipline called Social Neuroscience (e.g., Cacioppo and Berntson, 2005; Cacioppo, Visser, and Pickett, 2006; Decety and Cacioppo, 2010; Harmon-Jones and Winkielman, 2007). Examples of processes and mechanisms identified as important for social interaction are mirror neuron systems, self-other distinction, emotion integration, emotion regulation and

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empathy. Such mechanisms provide a useful point of departure to design biologically plausible computational models that offer a wide human-like social interaction repertoire. Here the concept of mirror neuron is a central concept relating to the other mechanisms as well. Mirror neurons are neurons with both a function of preparing, and of mirroring a similar state of another person; e.g., (Iacoboni, 2008; Rizzolatti and Sinigaglia, 2008; Pineda, 2009).

The collection of mechanisms considered in this paper has resulted from in-depth neurological investigations of deficits in social interaction. In the neurological literature these are put forward as the mechanisms that show impairments for persons with such deficits in social interaction. The contribution of such mechanisms to social functioning is usually studied by comparing a group persons that do not show adequate social interaction with a control group of persons with typical social functioning. Within the natural, human population, substantial differences in social behaviour between different persons occur. Some of the specific types of social interaction are considered to be ‘autistic’ to a certain extent, and the persons displaying them are sometimes diagnosed as having some form of an Autism Spectrum Disorder (ASD); e.g., (Richer and Coates, 2001; Frith, 2003).

The computational agent model presented here integrates computational formalisations of mechanisms for mirroring, self-other distinction, emotion integration, emotion regulation, and empathy put forward in the recent neurological literature as crucial for adequate social interaction. These mechanisms have been incorporated in the computational model in an abstracted form, so that the model can be considered a computational model inspired by these neurological mechanisms. Given the use of neurological mechanisms as a point of departure, a biologically plausible agent model results that can be used as a basis for the development of applications, for example, in the context of simulation-based training, gaming or virtual stories. Such applications can concern software environments using virtual agents based on the model presented here with built-in parameters representing personal characteristics. This does not only allow settings for human-like agents that model an idealised, perfect form of social interaction, but also settings that model different forms of imperfection in social interaction as occurring in the natural human population. In particular, such environments can be helpful in training professionals such as physicians in their social interaction.

In this paper, after some background in neurological mechanisms in the literature is discussed in Section 2, the design of the computational agent model is presented in Section 3. In Section 4 an exploration is presented illustrated by a number of simulation results and (emerging) properties shown by the simulated patterns. Finally, Section 5 is a discussion.

2 Neurological Background

In this section a review is presented of theories in the social-neurological literature about mechanisms relevant to social interaction. Each subsection describes one of the mechanisms and indicates a different hypothesis about causes of deficits in social interaction due to malfunctioning of that mechanism.

2.1 Mirror Neurons

It has been found that certain preparation states for actions or for expressing body states (at the neural level related to *mirror neurons*) have multiple functions, not only the function of preparing, but also the function of *mirroring* a similar state of another person; e.g., (Iacoboni, 2008; Rizzolatti and Sinigaglia, 2008; Pineda, 2009; Fried et al., 2011; Keysers and Gazzola, 2010;

Mukamel et al., 2010). Neurological evidence for specific impairments due to reduced activation of mirror neurons in persons with ASD is reported in, e.g., (Dapretto et al., 2006; Iacoboni, 2008; Williams et al., 2001). For example, in (Dapretto et al., 2006, p. 30) it is reported that children with ASD show reduced mirror neuron activity when observing emotional expressions, compared to typically developing children, and the hypothesis is put forward that early dysfunction in the mirror neuron system is at the core of social deficits observed in persons with ASD. This points at the mirror neuron system as a first mechanism which is important for social interaction. Reduced functioning of the mirror neuron system is a first hypothesis about causes of deficits in social interaction.

The functional meaning of activation of mirror neurons (e.g., preparing or mirroring or both) may be strongly context-dependent: in which cases is their activation meant to lead to actual execution of the action, and in which cases it is not. A specific subset of mirror neurons has been found that seem to be able to provide such a context; this is discussed next.

2.2 Super Mirror Neurons, Control, and Self-Other Distinction

Suitable forms of context can be defined at the neurological level based on what are called *super mirror neurons* (Iacoboni, 2008a, pp. 196-203; Iacoboni, 2008b; Brass and Spengler, 2009). These are neurons which were suggested to have a function in control (allowing or suppressing) action execution after preparation has taken place. In single cell recording experiments with epileptic patients, cells were found that are active when the person prepares an own action that is executed, but shut down when the action is only observed, which leads to the hypothesis that these cells may be involved in the functional distinction between preparation state generated in order to actually perform the action, and a preparation state generated to interpret an observed action (or both, in case of imitation). More specifically, this has been shown in work reported in (Mukamel et al., 2010; Fried, Mukamel, Kreiman, 2011); see also (Keysers and Gazzola, 2010; Iacoboni, 2008a; Iacoboni, 2008b; Iacoboni and Dapretto, 2006). For example, Iacoboni (2008b) describes these experiments in 14 patients with epilepsy undergoing pre-surgical evaluation of the foci of epilepsy; see also (Iacoboni, 2008a, pp. 201-203). Some of the main findings are that neurons with mirror neuron properties were found in all sites in the mesial frontal cortex where recording took place (approximately 12% of all recorded neurons); half of them related to hand-grasping, and the other half to emotional face expressions. A subset of neurons was found that show behaviour that relate to execution of the action: they have excitatory responses during action execution and inhibitory responses during action observation (Iacoboni, 2008b, p. 30). In (Iacoboni, 2008a, 2008b; Iacoboni and Dapretto, 2006) such types of neurons have been termed *super mirror neurons*, to indicate the control function they may have with respect to the execution of an action. In (Iacoboni, 2008, pp. 201-202) it is also described that some of such cells are sensitive to a specific person, so that an observed action can also be attributed to the person that was observed (self-other distinction). In (Brass and Spengler, 2009) and (Hamilton et al., 2007) it is suggested that the types of social interaction seen in persons with ASD can be related to reduced self-other distinction and control of imitation.

2.3 Emotion Integration

The integration of affective processes in cognitive processes (e.g., Pessoa, 2008; Phelps, 2006) is another type of mechanism that is assumed to play an important role in social interaction. According to Damasio (1999) sensory representations of stimuli usually induce emotional responses in the form of preparations for modified body states. Activation of such preparation states lead to further mental processing via an *as-if body loop* from preparation state to emotions felt based on sensory representation of body states associated to the prepared action. Conversely, it is assumed that the preparation for the response is also affected by the level of feeling the emotion in the form of the sensory representation of the body state. Thus reciprocal causation relations exist between emotions felt and preparations for actions, which realises *integration of emotion* in preparation of actions; see also (Damasio, 2003; Bosse et al., 2012). In (Grezes and de Gelder, 2009; Grezes et al., 2009) the role of emotion integration is emphasized, referring to brain areas such as STS (Superior Temporal Sulcus) and AMG (Amygdala) and their connectivity. In (Grezes and de Gelder, 2009, pp. 73-74) it is put forward that studies provide evidence that in autistic subjects this reduced connectivity may result in the mirror mechanism (although by itself well functioning) being dissociated from socio-affective capabilities.

2.4 Enhanced Sensory Processing Sensitivity and Emotion Regulation

A fourth mechanism affecting social interaction is regulation to compensate for enhanced *sensory processing (SP) sensitivity*. For example, in (Baker et al., 2008, pp. 867-868) it is put forward that dysfunction in processing sensory information results in deviant behaviours to (down)regulate stimulation from the environment; see also (Hofsten and Gredebäck, 2009). This hypothesis has a long history, going back, for example, to (Hutt et al., 1964) and (Tinbergen, and Tinbergen, 1972), who compared ASD-related behaviours to stereotyped and avoidance behaviours shown by animals when placed in stressful circumstances. During this long history not all of the several claims made in this direction have been confirmed. Specific difficulties are not only the many different ways and degrees in which ASD-related phenomena occur in different persons, but also the adaptation by internal emotion regulation mechanisms employed to compensate for deviations in sensory processing sensitivity.

In (Gross, 1998; 2001; 2007; Goldin et al., 2008) a process model of *emotion regulation* is described. Emotion regulation is taken as including all of the conscious and nonconscious strategies used to increase, maintain, or decrease one or more components of an emotional response; see also (Bosse, Pontier, and Treur, 2010). When an emotional response is increased, this is called *up-regulation*, and when it is decreased it is called *down-regulation*. The considered emotional responses have *experiential* (subjective feeling of the emotion), *behavioral*, and *physiological* components (responses such as heart rate and respiration). To prevent a person from having a too high emotional or too low emotional response level, regulation strategies are used, differentiated as antecedent-focused strategies and response-focused strategies. *Antecedent-focused strategies* are applied in the process preparing for responses before they are fully activated. *Response-focused strategies* are applied to the actual emotional response, when a response which is already underway is modulated. Gross distinguishes four different types of antecedent-focused emotion regulation strategies: *situation selection*, *situation modification*, *attentional deployment* and *cognitive change*.

Situation selection occurs when a person chooses for a situation that is expected to generate the emotional response level the person wants to have for a certain emotion. For example, a person can go to a party instead of staying home instead, because at the party someone will be met with a positive effect on feeling happy. This is an example of up-regulating one’s emotion (happiness). An example of situation selection to down-regulate one’s emotion (anger) is avoiding some annoying person. Situation modification means that a person modifies an existing situation so as to obtain a different level of emotion. For instance, when watching a thriller on television, one may zap to another channel when the ‘thrill’ becomes too strong. Attentional deployment is shifting attention to a certain aspect, for example, closing your eyes when watching an exciting penalty shoot-out. Cognitive change is selecting a specific cognitive meaning to an event. A specific type of cognitive change, which is aimed at down-regulating emotion, is *reappraisal*: the individual reappraises or cognitively re-evaluates a potentially emotion-eliciting situation in terms that decrease its emotional impact (Gross, 2001). An example of reappraisal is a case when a person performs bad and blames other circumstances, instead of his own efforts. Response modulation is applied after the emotion response tendencies have been generated: a person tries to affect the response tendencies becoming a behavioral response. A specific type of response modulation, aimed at down-regulating, is *suppression* which means that an individual inhibits ongoing expressive behavior (Gross, 2001).

In the specific case of enhanced sensitivity for certain types of stimuli, compensation can take place by forms of emotion regulation by avoiding situations or aspects of situations in which these stimuli occur, or focus attention differently, and/or by suppressing the own bodily response. Such regulation may not only diminish or even eliminate or overcompensate phenomena, which makes them hard to observe in experiments, but as it typically is a cyclic adaptive process it also makes it difficult to attribute causality.

In recent years the perspective of enhanced sensory processing sensitivity has become a quite active area of research; see for example, (Baker et al., 2008; Crane et al., 2009; Gepner and Féron, 2009; Lane et al., 2010; Smith, 2009). Using eye trackers that have become widely available, much work focuses on gaze fixation or gaze aversion behaviour in relation to over-arousal due to enhanced sensitivity for sensory processing of face expressions, in particular in the region of the eyes; e.g., (Corden et al., 2008; Kirchner et al., 2010; Kylliäinen and Hietanen, 2006; Neumann et al., 2006; Spezio et al., 2007). To get rid of arousal which is experienced as too strong, as a form of antecedent-focused regulation (in particular, attentional deployment) the gaze can be taken away from the observed face or eyes (gaze aversion). According to this perspective, gaze aversion and showing an expressionless face and (monotonous) voice, as often occur in persons with ASD, can be viewed as forms of regulation of the level of arousal, which otherwise would be experienced as too overwhelming, and disturbing for the other mental processes.

2.5 Empathic Responses

Developing empathy is an important process as a basis for social interaction. In (De Vignemont and Singer, 2006; Singer and Leiberg, 2009) the following four elements of the process to develop empathy are formulated:

(1) Presence of an affective state in a person
(2) Isomorphism of the person’s own and the other person’s affective state
(3) Elicitation of the person’s affective state upon observation or imagination of the other person’s affective state
(4) Knowledge of the person that the other person’s affective state is the source of the person’s own affective state

The neurological mechanisms to obtain empathy involve mirror neurons, self-other distinction and emotion integration (as described in Sections 2.1, 2.2 and 2.3 above). Given an affective state in another person (1), mirror neurons (see Section 2.1) and emotion integration by as-if body loops (Section 2.3) form a mechanism that generates an own affective state isomorphic with the other person’s affective state (2), thereby using observation or imagination of the other person’s expressions (3). Moreover, by self-other distinction (see Section 2.2), knowledge is obtained that the other person is the source of this affective state (4).

These elements and underlying mechanisms can be considered as a basis of developing an internal state of 'having empathy'. However, within social interaction, it is not only important that this occurs as an internal state, but also that this is displayed to the other person. Such an interaction does not only involve displaying the emotion felt ('showing feeling') but also displaying the fact of knowing that it concerns the emotion of the other person ('showing knowing'). Therefore, such a 'displayed empathy' or an 'empathic response', may involve:

(a) Showing the same emotion as the other agent
(b) Telling that the other agent has this emotion

Assuming true, faithful bodily and verbal expression, these two criteria (a) and (b) are entailed by the four criteria of empathy formulated in (De Vignemont and Singer, 2006; Singer and Leiberg, 2009). For example, if it is assumed that the affective state in (1) is shown to the other person by expressing it nonverbally and/or verbally, then (1) and (2) entail (a). Moreover, if it is assumed that the knowledge in (4) is communicated, then (4) entails (b).

It is generally acknowledged that showing empathy is important in professional relations, for example for physicians; e.g., (Bonvicini et al., 2009; Hojat, 2007; 2009; Suchman, Markakis, Beckman, Frankel, 1997; Tulsky et al., 2011; Zimmermann et al., 2011). The items (a) and (b) will be illustrated for this context. In (Suchman et al., 1997, p. 679) the following is one of the example dialogues discussed:

Example 1
PHYSICIAN: How do you feel about the cancer — about the possibility of it coming back?
PATIENT: Well, it bothers me sometimes but I don't dwell on it. But I'm not as cheerful about it as I was when I first had it. I just had very good feelings that everything was going to be all right, you know. But now I dread another operation. [empathic opportunity]
PHYSICIAN: You seem a little upset; you seem a little teary-eyed talking about it. [empathic response]

Note that this is only a partial representation of the social interaction: it is only a linguistic representation of the interaction that does not show the nonverbal expressions of the physician that may have been there accordingly. Such positive example dialogues are contrasted to dialogues where the physician misses the opportunity to show an empathic response, such as the following one (Suchman et al., 1997, p. 679):

Example 2
PHYSICIAN: Does anybody in your family have breast cancer?
PATIENT: No.
PHYSICIAN: No?
PATIENT: Now I just start [unintelligible] after I had my hysterectomy. I was taking estrogen, right?
PHYSICIAN: Yeah?
PATIENT: You know how your breast get real hard and everything? You know how you get sorta scared? [empathic opportunity]
PHYSICIAN: How long were you on the estrogen? [empathic opportunity terminator, missed empathic opportunity]
PATIENT: Oh, maybe about 6 months.

In Example 1 the response at least satisfies (b), and when nonverbal expressions are assumed accordingly it satisfies both (a) and (b). When in Example 1 it would be assumed that the physician keeps a nonexpressive pokerface, it does not satisfy (a). The response in Example 2 does not satisfy (b) and when nonverbal expressions are assumed absent accordingly also not (a). When in Example 2 it would be assumed that the physician still expresses the emotion, it would satisfy (a).

3 The Computational Agent Model

In this section the computational agent model will be described in detail. First an overview will be given, and subsequently the different parts of the model will be addressed: sensory representations, preparations, mirroring and super mirroring, expressing body states, communication and gaze, maintaining body state and gaze, and generating sensor states.

3.1 Overview of the Model

The theories described in Section 2 above each point at a different mechanism that is important for social interaction. To obtain adequate social interaction, all of these mechanisms have to function well in conjunction. More specifically, the following theories described in Section 2 were taken into account in designing the computational model:

- mirror neuron systems; e.g., (Dapretto *et al.*, 2006; Iacoboni, 2008)
- super mirror neurons for self-other distinctions and control; e.g., (Iacoboni, 2008; Brass and Spengler, 2009)
- emotion integration; e.g., (Grèzes and de Gelder, 2009; Grèzes *et al.*, 2009)
- regulation of enhanced sensory processing sensitivity, in particular for face expressions; e.g., (Neumann *et al.*, 2006; Spezio *et al.*, 2007; Baker *et al.*, 2008; Corden *et al.*, 2008)
- empathic responding using mirror neurons, self-other distinction and emotion integration; e.g., (De Vignemont and Singer, 2006; Singer and Leiberg, 2009)

A reasonable perspective is that all of the mechanisms as put forward play their role in social interaction in an integrative manner, and if one of them is not functioning well, this may lead to specific deficits in social functioning. Based on this view, in the design of the computational model below an integrative approach has been followed where for each of the mechanisms a computational formalisation was included in the model, and integrated with the computational formalisations of the other mechanisms. When all of the mechanisms work well, this results in adequate social functioning, but when one or more of them do not work well this easily leads to deficits in social interaction. For each of the computational formalisations of the mechanisms such malfunctioning can be specified by specific parameter settings.

So, the elements described above have been exploited in an integrative manner in the presented computational agent model. Thus a human-like agent model is obtained that, depending on its settings is able to show different types of social response patterns, for example, the type of responses of the physician discussed in Section 2.5 for the social interaction between a physician and a patient (see Example 1). More specifically, the computational agent model designed incorporates mirroring, super mirroring (for self-other distinction and control), emotion integration, gaze adaptation as a form of emotion regulation to compensate for enhanced sensory processing sensitivity, and empathic responding; see Figure 1 for an overview. Here WS is used to denote world states, SS for sensor states, SR sensory representation states and ES for effector states. Moreover, PB indicates a preparation for a body state and PS a super mirroring state for control. Furthermore, PC indicates a preparation for a communication, and EC the actually performed (expression of) communication. The connections between the states have weights indicated by ω_i. Furthermore, labels LPi refer to the corresponding detailed dynamic property specification presented below. States that relate to the physical world such as body states, sensor states and effector states are modelled in an abstract form. They may be related to any specific physical mechanisms of choice.

Note that in the causal graph of the model three loops occur: the body loop to adapt the body, the as-if body loop to adapt the internal body map, and the gaze adaptation loop to regulate the enhanced arousal. The effect of these loops is that for any new external situation encountered, in principle, a (numerical) approximation process may take place until the internal states reach an equilibrium (assuming that the situation does not change too fast). However, as will be discussed in Section 4, it is also possible that a (static) external situation does not lead to an equilibrium, but to periodic oscillations.

Modeling causal relations discussed in neurological literature in the manner as presented here does not take specific neurons into consideration but uses more abstract cognitive or mental states. In this way abstraction takes place by lifting neurological knowledge to a mental (cognitive/affective) modelling level. The type of computational model that results shows some technical elements from the neural modelling area. More specifically, it takes states as having a certain activation level (as opposed to binary states), thus making reciprocal loops possible. To achieve this, the modelling approach exploits techniques used in continuous-time recurrent neural networks, in line with what is proposed by Beer (1995), adopting elements from (Hopfield 1982, 1984). In particular, for a state causally depending on multiple other states, values for incoming activation levels are combined, using a combination function.

The computational agent model has been computationally formalised using the hybrid modeling language LEADSTO (cf. Bosse et al., 2007), and in differential equation format. Within LEADSTO a dynamic property or temporal causal relation $a \twoheadrightarrow b$ denotes that when a state property a (or conjunction thereof) occurs, then after a certain time delay, state property b will occur. Below, this delay will be taken as a uniform time step Δt. Being hybrid LEADSTO subsumes numerical dynamical systems (e.g., Port and van Gelder, 1995).

In the model s denotes a stimulus (e.g., a smiling face of another agent B, or the tears of the patient in Example 1 in Section 2.5), b a body state (e.g., a responsive smile or sad face) and B an agent (another agent or the agent self). A super mirroring state can either refer to an agent B, or to enhanced sensory processing sensitivity, indicated by sens. Note that, following [Damasio, 1999], a body state b is used as a label to indicate an emotion, and SR(b) the feeling of the emotion. Communication of b to B means communication that the agent self knows that B feels b (e.g., the last line of Example 1 in Section 2.5: 'You seem a little upset; you seem a little teary-eyed talking about it.'). This has been modelled using the notion g(s̲) for gaze direction in relation to s. Note that for the sake of simplicity g(s̲) denotes a specific gaze direction in an area *avoiding* s.

Connections between states (the arrows in Figure 1) have weights, as indicated in Table 1 and in Fig. 1. A weight ω_k may depend on a specific stimulus s, and body state b involved, and on an agent B (self or another agent), when this is indicated by an index B. It usually has a value between *0* and *1*, but for suppressing effects it can also be negative. In the column indicated by LP a reference is made to the (temporally) Local Property (LP) that specifies the update dynamics of the activation value of the 'to state' based on the activation levels of the 'from states'; see below.

By varying the connection strengths, different possibilities for the social interaction repertoire offered by the model can be realised. Emotion integration takes place by using a connection from SR(b): in LP4 (mirroring), LP6 (super mirroring), and LP7 (preparing communication).

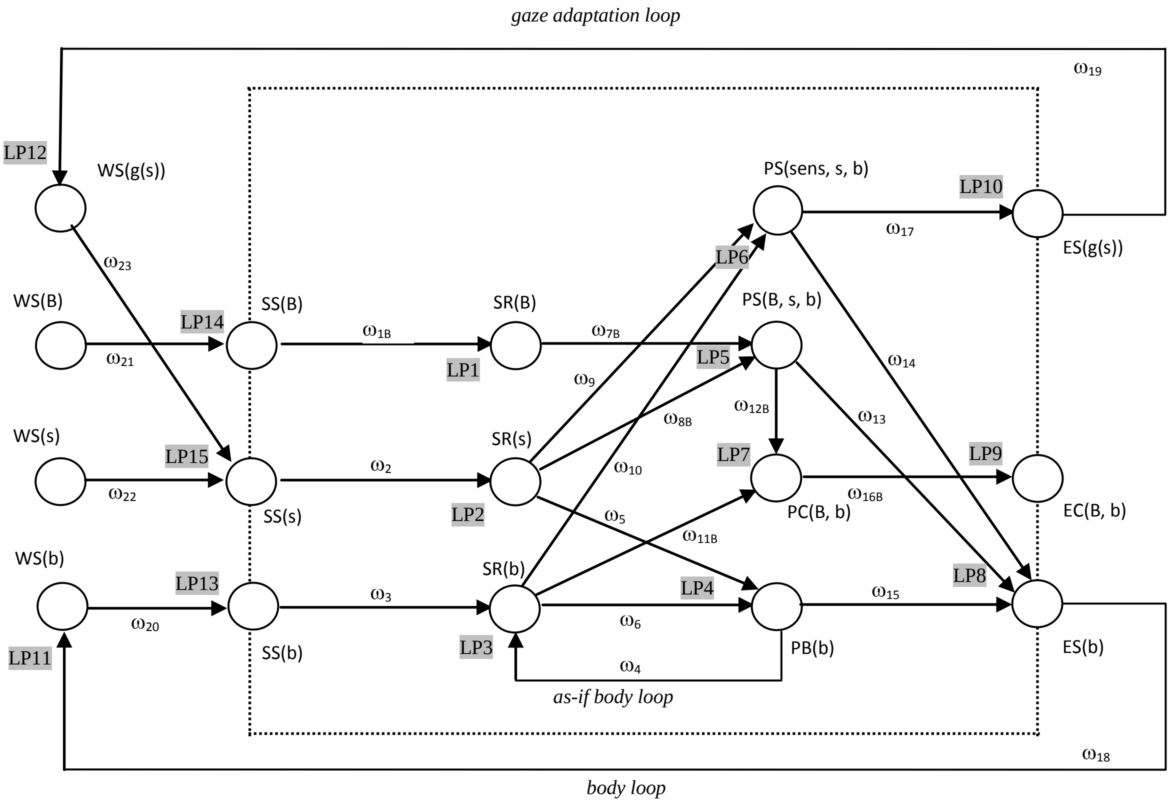


Figure 1 Overview of the computational agent model; see also Table 1

Reduced emotion integration can be expressed by low weights ω_6, ω_{10}, ω_{11B} for these connections. Similarly, low values for ω_5 in LP4, resp. ω_{7B}, ω_{8B} in LP5 can be used to achieve reduced mirroring, resp. super mirroring, and higher values for ω_9, ω_{10} in LP6 indicate enhanced sensory processing sensitivity. Below, each of the dynamic properties is described in more detail as a semiformal description. Formal specifications in the hybrid LEADSTO format are shown in Box 1. As an alternative representation, for readers more familiar with that format, in Box 2 a formal specification of the model in differential equation format is shown. Note that in the LEADSTO specification capitals are used, as in Figure 1 and Table 1, but as a distinction in the differential equations small letters are used to indicate the related values.

During processing, each state property has a strength represented by a real number between *0* and *1*; variables *V* (possibly with subscripts) run over these values. In dynamic property specifications, this is added as a last argument to the state property expressions (an alternative notation activation(a, V) with a a state property has not been used for the sake of notational simplicity). Parameter γ is a speed factor, which determines how fast a state is changing, based on input received from other states connecting to it.

3.2 Generating sensory representations

The properties LP1 to LP3 describe how sensory representations are generated for an agent B, stimulus, and body state.

LP1 Sensory representation of an external agent B

If an agent B is sensed with level V_1,
and the sensory representation of agent B has level V_2.
then after duration Δt the sensory representation of agent B will have level $V_2 + \gamma\, [\, f(\omega_{1B} V_1) - V_2\,]\ \Delta t$.

Here *f* is a function for which different choices can be made, for example, the identity function $f(W) = W$, or a continuous logistic threshold function of the form

$$th(\sigma, \tau, W) = \left(\frac{1}{1+e^{-\sigma(W-\tau)}} - \frac{1}{1+e^{\sigma\tau}}\right)(1+e^{-\sigma\tau})$$

with σ a steepness and τ a threshold value. Note that for higher values of στ (e.g., σ higher than $20/\tau$) this threshold function can be approximated by the simpler expression:

$$th(\sigma, \tau, W) = \frac{1}{1+e^{-\sigma(W-\tau)}}$$

In the simulations for the sake of simplicity for properties LP1, LP2, and LP11 to LP14 the function $f(W) = W$ was chosen for *f*; this easily could be changed to a logistic threshold function. For properties LP3 to LP10 *f* is based on the logistic threshold function: $f(W_1, W_2) = th(\sigma, \tau, W_1+W_2)$; similarly for more arguments. Property LP2 is similar to LP1 but applied to stimulus s instead of agent B (for example, a face expression).

	from states	**to state**	**ω**	**LP**	**explanation**
Representing	SS(B)	SR(B)	ω_{1B}	LP1	Representing an agent B from sensing B
	SS(s)	SR(s)	ω_2	LP2	Representing a stimulus s (e.g., another agent B's smile or tears)
		SR(b)		LP3	Representing a *body map* for b: emotion b felt (e.g., own smile)
	SS(b)		ω_3		- from sensing own body state b
	PB(b)		ω_4		- via *as-if body loop* from preparation for body state b
Preparing, Super mirroring		PB(b)		LP4	Preparing for *body state* b: emotional response b (e.g., own smile or sad face)
	SR(s)		ω_5		- via *mirroring* from represented stimulus s (e.g., smile of B)
	SR(b)		ω_6		- via *emotion integration* from emotion b felt
		PS(B, s, b)		LP5	*Super mirroring* for *self-other distinction*
	SR(B)		ω_{7B}		- from represented agent B
	SR(s)		ω_{8B}		- from represented stimulus s (e.g., smile or tears of B)
		PS(sens, s, b)		LP6	*Super mirroring* for *enhanced sensitivity*
	SR(s)		ω_9		- from represented stimulus s (e.g., smile or tears of B)
	SR(b)		ω_{10}		- from emotion b felt
		PC(B, b)		LP7	Preparing *communication* (e.g., 'you feel b')
	SR(b)		ω_{11B}		- via *emotion integration* from emotion b felt
	PS(B, s, b)		ω_{12B}		- *controlled* by *super mirroring state* for B
Expressing		ES(b)		LP8	Expressing *body state* b (e.g., own smile)
	PS(self, s, b)		ω_{13}		- *controlled* by *super mirroring state* for self
	PS(sens, s, b)		ω_{14}		- *controlled* by *super mirroring state* for enhanced sensitivity
	PB(b)		ω_{15}		- from preparation state for b
	PC(B, b)	EC(B, b)	ω_{16B}	LP9	Expressing *communication* (e.g., 'you feel sad')
	PS(sens, s, b)	ES(g(s))	ω_{17}	LP10	Expressing *gaze, controlled* by *super mirroring state* for enhanced sensitivity
Maintaining	ES(b)	WS(b)	ω_{18}	LP11	Maintaining actual *body state*
	ES(g(s))	WS(g(s))	ω_{19}	LP12	Maintaining actual *gaze*

Sensing	WS(b)	SS(b)	ω_{20}	LP13	Sensing body state b
	WS(B)	SS(B)	ω_{21}	LP14	Sensing an agent B
	WS(s) WS(g(<u>s</u>))	SS(s)	ω_{22} ω_{23}	LP15	Sensing stimulus s - from world state s - *regulated* by *gaze state* g(<u>s</u>)

Table 1 Overview of the connections, their weights, and their explanations; see also Figure 1

LP2 Sensory representation of stimulus s
If a stimulus s is sensed with level V_1,
and the sensory representation of s has level V_2.
then after duration Δt the sensory representation of s will have level $V_2 + \gamma\, [\, f(\omega_2 V_1) - V_2\,]\ \Delta t$.

The sensory representation of a body state as described by property LP3 is not only affected by a corresponding sensor state (which in turn is affected by the body loop), but also via the as-if body loop by the preparation for this body state. Note that the as-if body loop provides effects on the sensory representation in a shorter time than via the body loop: bodily change usually is a factor slower than neurological change (e.g., one or two seconds vs. *300* to *500* milliseconds).

LP3 Sensory representation of a body state
If the sensor state for body state b has level V_1
and the preparation state for body state b has level V_2
and the sensory representation of body state b has level V_3
then after Δt the sensory representation of body state b will have level $V_3 + \gamma [f(\omega_3 V_1, \omega_4 V_2) - V_3]\ \Delta t$.

3.3 Generating preparation, mirroring and super mirroring states

Preparation for a bodily change triggered by s (e.g., an observed face expression leading to preparation for a similar expression) is modelled as follows.

LP4 Preparing for or mirroring a body state
If the sensory representation of s has level V_1,
and the sensory representation of b has level V_2,
and the preparation for body state b has level V_3
then after duration Δt the preparation state for body state b will have level $V_3 + \gamma [f(\omega_5 V_1, \omega_6 V_2) - V_3]\ \Delta t$.

Super mirroring for an agent B generates a state indicating on which agent (self-other distinction for B another agent) the focus is, and whether or not to act (the case of self); this is modelled in LP5.

LP5 Super mirroring for another agent or self
If the sensory representation of agent B (another agent or self) has level V_1,
and the sensory representation of s has level V_2,
and the super mirroring state for B, s and b has level V_3
then after duration Δt the super mirroring for B, s and b will have level $V_3 + \gamma [f(\omega_{7B} V_1, \omega_{8B} V_2) - V_3]\ \Delta t$.

Super mirroring for sensory processing sensitivity, modelled in LP6, generates a state indicating in how far the stimulus induces an inadequately high sensory body representation level. This state is the basis for two possible regulations (modelled in LP8 and LP10 below): of the expressed body state, and of the gaze.

LP6 Super mirroring for enhanced sensitivity
If the sensory representation of s has level V_1,

and the sensory representation of b has level V_2
and the sensitivity super mirroring state for s and b has level V_3
then after duration Δt sensitivity super mirroring for s and b will have level $V_3 + \gamma [f(\omega_9 V_1, \omega_{10} V_2) - V_3] \Delta t$.

The preparation of a verbal empathic reaction to another agent depends on feeling a similar emotion, and on adequate self-other distinction, as modelled in LP7.

LP7 Preparing for communication
If the sensory representation of body state b has level V_1,
and the super mirroring for agent B≠self, s and b has level V_2,
and the preparation of communication of b to B has level V_3
then after Δt the preparation of communication of b to B will have level $V_3 + \gamma [f(\omega_{11B} V_1, \omega_{12B} V_2) - V_3] \Delta t$.

3.4 Expressing prepared states

Expressing a (prepared) body state depends on whether a super mirroring state for self is available. However, to cover regulative behaviour to compensate for enhanced sensory processing sensitivity, also the sensitivity super mirroring state is involved, with an inhibiting effect on expressing the prepared body state (ω_{14} is taken to be negative). Such an effect can achieve that although the agent feels the same as the other agent, the face remains expressionless. In this way LP8 models a mechanism for *response-focused regulation* (suppression of the own response) to compensate for an undesired level of arousal; cf. [Gross, 1998; Goldin *et al.*, 2008].

LP8 Expressing a body state
If the super mirroring state for self, s and b has level V_1,
and the super mirroring state for sensitivity, s and b has level V_2,
and the preparation for body state b has level V_3
and expressing body state b has level V_4
then after duration Δt body state b will be expressed with level $V_4 + \gamma [f(\omega_{13} V_1, \omega_{14} V_2, \omega_{15} V_3) - V_4] \Delta t$.

Note that expression states ES are the agent's effector states (e.g., the muscle states); body and gaze states result from these expression states (via LP11 and LP12 below). A preparation for a verbal empathic reaction leads to expressing this communication in a straightforward manner.

LP9 Expressing communication
If the preparation of communication of b to B has level V_1,
and the expressed communication for b to B has level V_2
then after Δt the agent will express communication of b to B with level $V_2 + \gamma [f(\omega_{16B} V_1) - V_2] \Delta t$.

Dynamic property LP10 models *antecedent-focused regulation* (*attentional deployment*) as described in [Gross, 1998; Goldin *et al.*, 2008]: directing the own gaze away from the stimulus that feels too overwhelming. Note that the gaze direction g(s) for s is taken to be *1* for total avoidance of stimulus s, and *0* for no avoidance (it indicates the extent of avoidance).

LP10 Expressing gaze for avoidance of s
If super mirroring for sensitivity, s and b has level V_1,
and the expressed gaze for avoidance of s has level V_2
then after Δt the expressed gaze avoidance for s will have level $V_2 + \gamma [f(\omega_{17} V_1) - V_2] \Delta t$.

3.5 Maintaining body and gaze states

Properties LP11 and LP12 describe how the expression states affect the body and gaze in a straightforward manner.

LP11 From body expression to body state
If the expression state for body state b has level V_1,
and the body state b has level V_2
then after Δt body state b will have level $V_2 + \gamma [f(\omega_{18}V_1) - V_2] \Delta t$.

LP 12 is similar to LP11 with gaze instead of body.

LP12 From gaze expression to gaze state
If the expression state for gaze for s has level V_1,
and the gaze for s has level V_2
then after Δt the gaze for s will have level $V_2 + \gamma [f(\omega_{19}V_1) - V_2] \Delta t$.

3.6 Generating sensor states

Sensing a body state and agent B also happen in a straightforward manner, as described by LP13 and LP14.

LP13 Generating a sensor state for a body state
If the body state b has level V_1,
and the sensor state for body state b has level V_2
then after Δt the sensor state for body state b will have level $V_2 + \gamma [f(\omega_{20}V_1) - V_2] \Delta t$

LP14 is similar to LP13 with agent B instead of body.

LP14 Generating a sensor state for an agent B
If the agent B is present with level V_1,
and the sensor state for agent B has level V_2
then after Δt the sensor state for agent B will have level $V_2 + \gamma [f(\omega_{21}V_1) - V_2] \Delta t$

Within the external world, to generate a sensor state for a stimulus *s*, the gaze state with respect to *s* is taken into account. As the gaze state indicates the extent of avoidance of *s*, it has an inhibiting effect on sensing *s* (ω_{23} is taken to be negative); here *f* has been modelled by $f(W_1, W_2) = W_1(1+W_2)$ with $-1 \leq W_2 \leq 0$.

LP15 Generating a sensor state for a stimulus
If stimulus s is present with level V_1,
and gaze state for avoidance of s has level V_2,
and the sensor state for s has level V_3,
then after Δt the sensor state for s will have level $V_3 + \gamma [f(\omega_{22}V_1, \omega_{23}V_2) - V_3] \Delta t$

LP1 Sensory representation of an external agent B
$SS(B,V_1)$ & $SR(B, V_2) \twoheadrightarrow SR(B, V_2 + \gamma [f(\omega_{1B}V_1) - V_2] \Delta t$

LP2 Sensory representation of a stimulus s
$SS(s,V_1)$ & $SR(s, V_2) \twoheadrightarrow SR(s, V_2 + \gamma [f(\omega_2V_1) - V_2] \Delta t$

LP3 Sensory representation of a body state
$SS(b, V_1)$ & $PB(b, V_2)$ & $SR(b, V_3) \twoheadrightarrow SR(b, V_3 + \gamma [f(\omega_3V_1, \omega_4V_2) - V_3] \Delta t)$

LP4 Preparing for or mirroring a body state
$SR(s,V_1)$ & $SR(b,V_2)$ & $PB(b, V_3) \twoheadrightarrow PB(b, V_3 + \gamma [f(\omega_5V_1, \omega_6V_2) - V_3] \Delta t)$

LP5 Super mirroring for another agent or self
$SR(B,V_1)$ & $SR(s,V_2)$ & $PS(B, s, b, V_3) \twoheadrightarrow PS(B, s, b, V_3 + \gamma [f(\omega_{7B}V_1, \omega_{8B}V_2) - V_3] \Delta t)$

LP6 Super mirroring for enhanced sensitivity
$SR(s,V_1)$ & $SR(b,V_2)$ & $PS(sens, s, b, V_3) \twoheadrightarrow PS(sens, s, b, V_3 + \gamma [f(\omega_9V_1, \omega_{10}V_2) - V_3] \Delta t))$

LP7 Preparing for communication
$SR(b, V_1)$ & $PS(B, s, b, V_2)$ & $B \neq self$ & $PC(B, b, V_3) \twoheadrightarrow PC(B, b, V_3 + \gamma [f(\omega_{11B}V_1, \omega_{12B}V_2) - V_3] \Delta t)$

LP8 Expressing a body state
$PS(self, s, b, V_1)$ & $PS(sens, s, b, V_2)$ & $PB(b, V_3)$ & $ES(b, V_4) \twoheadrightarrow ES(b, V_4 + \gamma [f(\omega_{13}V_1, \omega_{14}V_2, \omega_{15}V_3) - V_4] \Delta t)$

LP9 Expressing communication
$PC(B, b, V_1)$ & $EC(B, b, V_2) \twoheadrightarrow EC(B, b, V_2 + \gamma [f(\omega_{16B}V_1) - V_2] \Delta t)$

LP10 Expressing gaze for avoidance of s
$PS(sens, s, b, V)$ & $ES(g(s), V_2) \twoheadrightarrow ES(g(s), V_2 + \gamma [f(\omega_{17}V_1) - V_2] \Delta t)$

LP11 From body expression to body state
$ES(b, V_1)$ & $WS(b, V_2) \twoheadrightarrow WS(b, V_2 + \gamma [f(\omega_{18}V_1) - V_2] \Delta t)$

LP12 From gaze expression to gaze state
$ES(g(s), V_1)$ & $WS(g(s), V_2) \twoheadrightarrow WS(g(s), V_2 + \gamma [f(\omega_{19}V_1) - V_2] \Delta t)$

LP13 Generating a sensor state for a body state b
$WS(b, V_1)$ & $SS(b, V_2) \twoheadrightarrow SS(b, V_2 + \gamma [f(\omega_{20}V_1) - V_2] \Delta t)$

LP14 Generating a sensor state for an agent B
$WS(B, V_1)$ & $SS(B, V_2) \twoheadrightarrow SS(B, V_2 + \gamma [f(\omega_{21}V_1) - V_2] \Delta t)$

LP15 Generating a sensor state for a stimulus
$WS(s, V_1)$ & $WS(g(s), V_2)$ & $SS(s, V_3) \twoheadrightarrow SS(s, V_3 + \gamma [f(\omega_{22}V_1, \omega_{23}V_2) - V_3] \Delta t$

Box 1 Formalisation of the Local Properties in the hybrid language LEADSTO

LP1 Sensory representation of an external agent B

$$\frac{d\,sr(B)(t)}{dt} = \gamma\ [f(\omega_{1B} ss(B)(t)) - sr(B)(t)]$$

LP2 Sensory representation of a stimulus s

$$\frac{dsr(s)(t)}{dt} = \gamma\ [f(\omega_2 ss(s)(t)) - sr(s)(t)]$$

LP3 Sensory representation of a body state

$$\frac{d\,sr(b)(t)}{dt} = \gamma\ [f(\omega_3 ss(b)(t), \omega_4 pb(b)(t)) - sr(b)(t)]$$

LP4 Preparing for or mirroring a body state

$$\frac{dpb(b)(t)}{dt} = \gamma\ [f(\omega_5 sr(s)(t), \omega_6 sr(b)(t)) - pb(b)(t)]$$

LP5 Super mirroring for another agent or self

$$\frac{d\,ps(B,s,b)(t)}{dt} = \gamma\ [f(\omega_{7B} sr(B)(t), \omega_{8B} sr(s)(t)) - ps(B, s, b)(t)]$$

LP6 Super mirroring for enhanced sensitivity

$$\frac{dps(sens,s,b)(t)}{dt} = \gamma\ [f(\omega_9 sr(s)(t), \omega_{10} sr(b)(t)) - ps(sens, s, b)(t)]$$

LP7 Preparing for communication

$$\frac{d\,pc(B,b)(t)}{dt} = \gamma\ [f(\omega_{11B} sr(b)(t), \omega_{12B} ps(B, s, b)(t)) - pc(B, b)(t)]$$

LP8 Expressing a body state

$$\frac{des(b)(t)}{dt} = \gamma\ [f(\omega_{13} ps(self, s, b)(t), \omega_{14} ps(sens, s, b)(t), \omega_{15} pb(b)(t)) - es(b)(t)]$$

LP9 Expressing communication

$$\frac{d\,ec(B,b)(t)}{dt} = \gamma\ [f(\omega_{16B} pc(B, b)(t)) - ec(B, b)(t)]$$

LP10 Expressing gaze for avoidance of s

$$\frac{d\,es(g(s))(t)}{dt} = \gamma\,[f(\omega_{17} ps(sens, s, b)(t)) - es(g(s))(t)]$$

LP11 From body expression to body state

$$\frac{d\,ws(b)(t)}{dt} = \gamma\,[f(\omega_{18} es(b)(t)) - ws(b)(t)]$$

LP12 From gaze expression to gaze state

$$\frac{d\,ws(g(s))(t)}{dt} = \gamma\,[f(\omega_{19} es(g(s))(t)) - ws(g(s))(t)]$$

LP13 Generating a sensor state for a body state b

$$\frac{d\,ss(B)(t)}{dt} = \gamma\,[f(\omega_{21} ws(B)(t)) - ss(B)(t)]$$

LP14 Generating a sensor state for an agent B

$$\frac{d\,ss(B)(t)}{dt} = \gamma\,[f(\omega_{21} ws(B)(t)) - ss(B)(t)]$$

LP15 Generating a sensor state for a stimulus

$$\frac{d\,ss(s)(t)}{dt} = \gamma\ [f(\omega_{22} ws(s)(t), \omega_{23} ws(g(s))(t)) - ss(s)(t)]$$

Box 2 Formalisation of the Local Properties in differential equation format

4 Types of Social Response Patterns Shown

To analyse the different types of response patterns shown by the computational agent model, some dynamic properties were identified and formally specified in a hybrid reified temporal predicate logic (e.g., Galton, 2006). Here at(a, T) means that state property a holds at time T, and s(B, b) denotes the stimulus for self consisting of the expression of body state b by agent B. By automated verification they have been checked for generated simulation traces, allowing to evaluate easily the patterns for a variety of parameter values. Below the dynamic properties are introduced in an informally expressed manner; their formalisations are shown in Box 3.

4.1 Overview

The simulations discussed first, have been performed with $\gamma = 1$, $\Delta t = 0.5$, and settings for threshold and steepness values as shown in Table 2. In the graphs in Figures 2 and 3, and further, time is at the horizontal axis and activation levels are at the vertical axis.

	LP3	LP4	LP5self	LP5sens	LP6	LP7	LP8	LP9	LP10
τ	*0.8*	*1*	*1*	*1*	*2.5*	*1.5*	*1.5*	*0.5*	*0.5*
σ	*8*	*8*	*40*	*40*	*40*	*8*	*40*	*40*	*40*

Table 2 Setting for threshold and steepness values used

The first property expresses that when an agent B is met, showing a certain emotion, then within a certain time a response occurs, which can consist of:

(1) agent self feels the same as agent B,
(2) this feeling is bodily expressed by self, and
(3) it is communicated by agent self to agent B that B feels this.

An example of this is the response described for Example 1 in Section 2.5.

SBP1(M_1, M_2, R(b, V)) Response occurrence
When agent B≠self is present expressing a certain feeling b from some point in time on, then after some time agent self will have a response R (generating the feeling of b, resp. bodily expression, resp. communication).

By combination 8 different types of response are possible; see Table 3. Some of them are not likely to occur (types 5, 6, and 7): when the agent self does not feel the emotion, it is probably hard to communicate or show it. The way in which different connections relate to different types of processes, as depicted in Table 1, provides an indication of which deviant connection strengths may lead to which phenomena. For example, when ω_5 (connecting SR(s) to PB(b); see Figure 1 and Table 1) is low, mirroring is reduced, and as a consequence a low social response (type 8) occurs, which is in accordance with what is reported, for example, in (Dapretto *et al.*, 2006). This may correspond to the missed empathic response in Section 2.5, Example 2.

	1	2	3	4	5	6	7	8
feeling	+	+	+	+	-	-	-	-
body	+	+	-	-	+	+	-	-
communication	+	-	+	-	+	-	+	-
type of response	full empathic response	feeling and body expression without communication	feeling and communication without body expression	feeling without body expression and communication				no feeling, no body expression, no communication
example conditions	fully adequate conditions	inadequate self-other distinction	inadequate emotion integration	both inadequate emotion integration and self-other distinction				inadequate mirroring
example parameter settings	none of ω_k low	ω_{7B}, ω_{8B} low or ω_{11B}, ω_{12B} low	ω_{7self}, ω_{8self} low	ω_6 , ω_{11} low				ω_5 low

Table 3 Different types of possible social responses:
+ means that the response occurs, - means that it does not occur (or is very weak)

An example of type 1 is shown in Figure 2 displaying the feeling (rep body), mirroring (prep body), expression of body (expr body), and communication (expr comm). Here, $\omega_k = 1$ for all k, except for the suppressing connections (from PS(sens, s, b) to ES(b), and from WS(g(s)) to SS(s), respectively): $\omega_{14} = \omega_{23} = -1$. The pattern shows an increase of mirroring, followed by bodily expression and feeling, and communication. This corresponds to a type of response as shown by the physician in Section 2.5, Example 1.

Response type 4 in Table 3 only concerns the feeling (not externally observable). For response type 2, the feeling is expressed: it is externally observable, but no verbal communication takes place. Response type 2 with low ω_{7B} or ω_{8B} (from SR(B), resp. SR(s) to PS(B, s, b)) displays that no adequate self-other distinction is made (reduced super mirroring); e.g., (Iacoboni, 2008; Brass and Spengler, 2009).

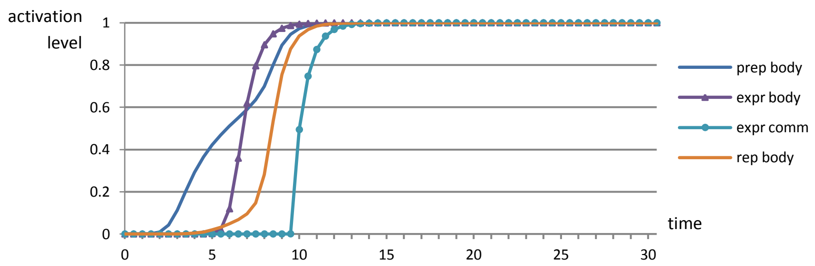


Figure 2 Example simulations: full empathic response

Response type 4 with low ω_6 (from SR(b) to PB(b)) can be viewed as a form of emotion contagion without integrating the emotion in responses; cf (Grèzes and de Gelder, 2009; Grèzes *et al.*, 2009). In contrast, in response type 3 the emotion felt is attributed to the other agent, but no bodily expression is shown. Figure 3 shows an example of response type 4. The level of emotion felt is becoming high, but due to lack of emotion integration ($\omega_6 = \omega_{11B} = 0$ and the other ω_k the same as for the upper graph), the bodily and verbal expression are reduced.

activation
level

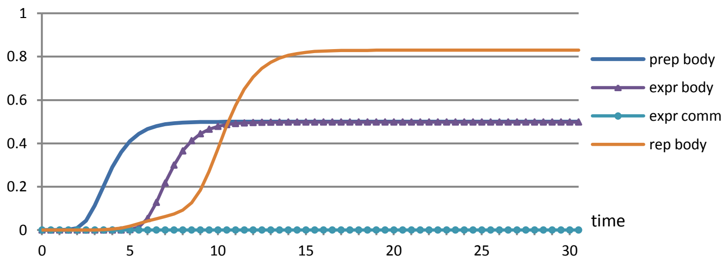


Figure 3 Example simulations: reduced emotion integration

In case of regulation due to enhanced sensory sensitivity (e.g., Baker *et al.*, 2008; Corden *et al.*, 2008), patterns occur when a response only lasts for a short time, expressed as:

SBP2(M_1, M_2, D, R(b, V)) Response withdrawal
When agent B≠self is present expressing a certain feeling b from some point in time on, and the agent self has response R, then within time duration D this response will disappear.

4.2 Oscillation patterns

The combination SBP1 & ¬SBP2 expresses a persistent response, whereas SBP1 & SBP2 specifies only a short occurrence of a response. However, after withdrawal of the response due to regulation, also the arousal level for b will become low, which brings the agent in practically the same state as initially. An oscillatory pattern results, while the environment is fully static. Such oscillatory social response patterns indeed can be observed in persons with some forms of ASD, who let their gaze go back and forth to another person's eyes during a contact, as a way of regulation of enhanced sensitivity. Figure 4 shows an example of such a response pattern, specified as follows.

SBP3(M_1, M_2, M_3, R(b, V)) Response oscillation
When an agent B bodily expressing a certain feeling is present from some point in time on, then:
(1) for every time point there is a later time point for which response R occurs
(2) for every time point there is a later time point for which response R does not occur

The agent model shows this type of social response when the threshold for sensory sensitivity is set between *1* and *2*; for example, for Figure 4, it was set to *1.2.* Moreover, as for the upper graph $\omega_k = 1$ for all *k*, except for the suppressing connections: $\omega_{14} = \omega_{23} = -1$. It is shown that body expression and communication last only for short time periods, but recur. If the threshold value is set *1* or lower, no response occurs (type 8); if it is *2* or higher a persistent response occurs (type 1).

Note that instead of varying the threshold for sensory sensitivity, similar patterns are generated when the connection strength ω_{17} (from PS(sens, s, b) to ES(g(s))) is varied. The oscillatory patterns due to regulation for enhanced sensitivity occur for all response types in Table 3.

activation
level

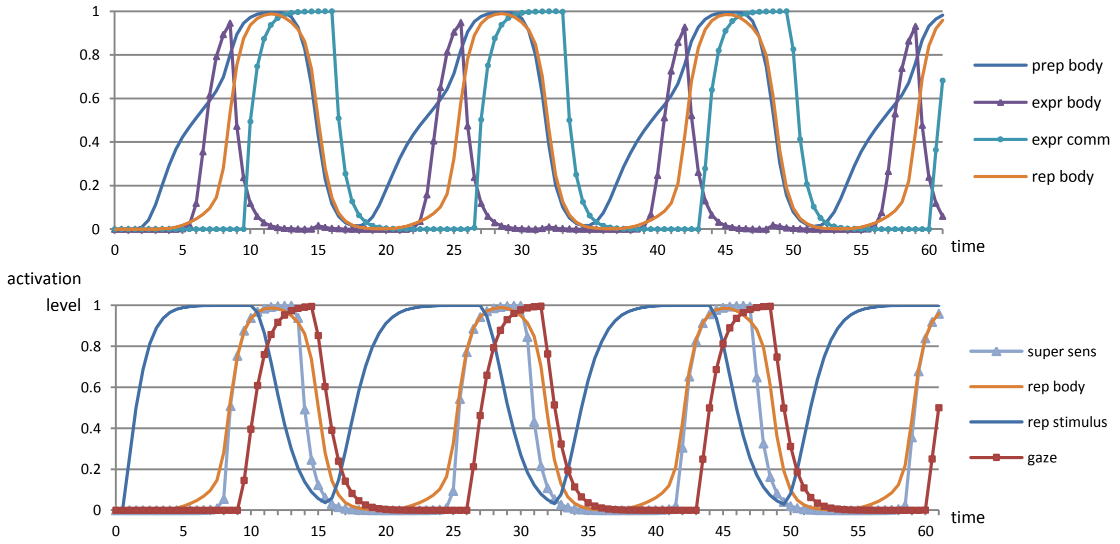


Figure 4 Example simulation: enhanced sensitivity

Note that the oscillatory patterns shown by the model have a regular periodicity. For example, in Figure 4 the pattern repeats itself about every *18* time units. This period reflects the time needed to calm down the too high arousal.

4.3 Comparison to empirical gaze data

From human experiments empirical data of gaze patterns are known. These can be used to have a (quite modest) validation of the model. For example, in (Neumann et al., 2006) it was found that for a group of persons with ASD the average fixation time of the gaze was about *85 ms* at the eyes and *215 ms* at the mouth (for the control group this was *190 ms* at the eyes vs *50 ms* at the mouth); cf. (Neumann et al., 2006, p. 198, Fig. 4), see also Figure 5 below.

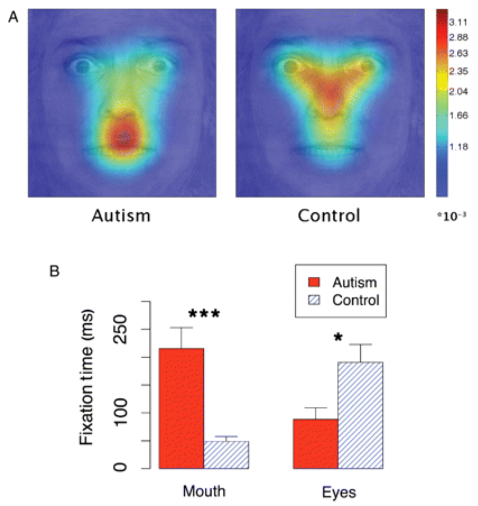
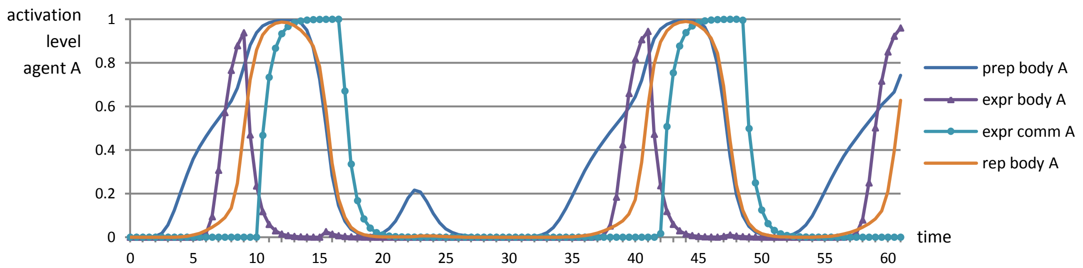


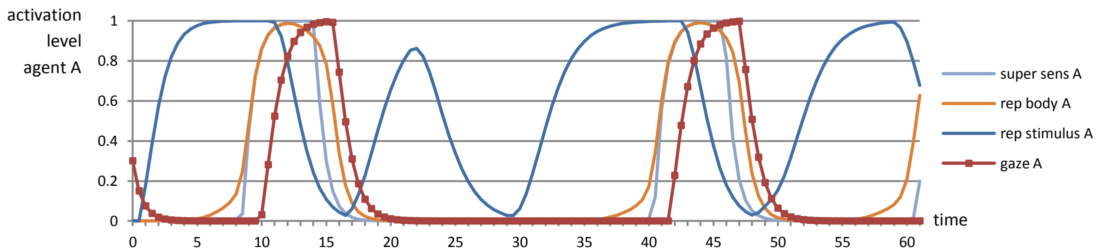
Figure 5 Fixations made in an experiment, adopted from (Neumann et al., 2006, Fig. 4)

This gives an estimated average period of *300 ms* for the ASD group in that experiment. It was possible to mimic this average period quite accurately by choosing $\gamma = 0.06$ and keeping all other parameter value the same as for the case depicted in Figure 4. So, for these settings the model describes an average of this group of persons with ASD. Note, however, that individuals will deviate from this average, and one individual will also show differences over time. In realistic situations eye movements do not only depend on the regulation mechanism, but also on other events that may happen, for example, a gesture or an eye-blink of the other person, or some interpunction in the talking of the other person.

4.4 Interaction of two persons displaying regulation of enhanced sensory sensitivity

In the scenarios discussed above and shown in Figures 2 to 4 the other agent B and the stimulus were assumed static. However, the agent model can be applied to agent B as well. In this case it is assumed that the eyes of one agent are the stimulus for the other agent, so that in a mutual manner an avoiding gaze regulation of one agent affects the stimulus for the other agent as well. This might describe a situation when a physician with reduced social interaction capabilities (due to enhanced sensory processing sensitivity) has an interaction with a patient who also has such reduced capabilities. For this situation, it turns out that the interaction often starts in an asynchronous and irregular way, as shown in Figure 6. This is an example where the values for one parameter, namely the update speed parameter γ were taken different. This can be considered as expressing an individual difference in neurological response time: for agent A it is *1* as for self before, and for agent B it is *0.7*, which means that agent B responds *30*% slower than agent A. Also when differences in values of other parameters or in initial values are made, the pattern starts in an asynchronous and irregular manner. In Figure 6 the upper half of the figure shows activation levels of agent A over time, the lower half the same for agent B. For example, in Figure 6, first both gazes are on the eyes, but after time point 10 agent a takes the gaze way from the eyes (until time point 17). Agent b also starts to take away the gaze from the eyes at time 15, but soon comes back again (around time 20), since in the meantime the other agent's gaze has gone elsewhere. But after time 20 agent A's gaze comes on the eyes again and then agent B takes the gaze from the eyes for a longer time (until time 30). Such social interaction patterns may occur as a bit chaotic and weird (the pattern shown will in fact later on end up in a periodic oscillating pattern: a limit cycle), but the introduced agent model shows the logic and rationality behind such patterns.





activation
level
agent B

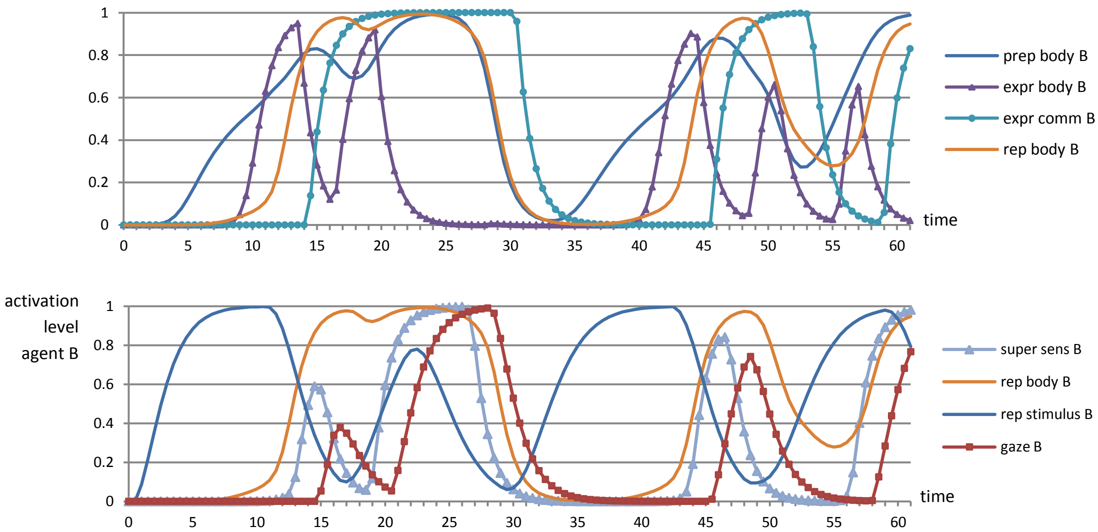


Figure 6 Bidirectional enhanced sensitivity pattern

SBP1(M_1, M_2, R(b, V)) Response occurrence

$\forall T_1\ [\forall V_1, V_2, T_2 \geq T_1\ [\ at(WS(B, V_1), T_2)\ \ \&\ \ at(WS(s(B, b), V_2), T_2)\ \Rightarrow\ V_1 \geq M_1\ \&\ V_2 \geq M_1\ ]$

$\Rightarrow\ \exists V, T_3 \geq T_1\ at(R(b, V), T_3)\ \ \&\ V \geq M_2\ ]$

with R(b, V) one of SR(b, V), ES(b, V), EC(B, b, V).

SBP2(M_1, M_2, D, R(b, V)) Response withdrawal

$\forall V, T_1, T_3 \geq T_1\ [$

$\forall V_1, V_2, T_2 \geq T_1\ \ [\ at(WC(B, V_1), T_2)\ \ \&\ \ at(WS(s(B, b), V_2), T_2)\ \Rightarrow\ V_1 \geq M_1\ \&\ V_2 \geq M_1\ ]\ \&\ at(R(b, V), T_3)\ \&\ V \geq M_2\ ]$

$\Rightarrow \exists V, T_4 \geq T_3\ [T_4 \leq T_3 + D\ \&\ at(R(b, V), T_4)\ \&\ V < M_2\ ]\ ]$

SBP3(M_1, M_2, M_3, R(b, V)) Response oscillation

$\forall T_1\ [\ [\forall V_1, V_2, T_2 \geq T_1\ [\ at(WC(B, V_1), T_2)\ \ \&\ \ at(WS(s(B, b), V_2), T_2)\ \Rightarrow\ V_1 \geq M_1\ \&\ V_2 \geq M_1\ ]$

$\Rightarrow\ \forall T_3 \geq T_1\ \ [\ \exists V, T_4 \geq T_3\ [\ at(R(b, V), T_4)\ \ \&\ V > M_2\ ]\ \ \&\ \ \exists V, T_4 \geq T_3\ [\ at(R(b, V), T_4)\ \ \&\ V < M_3]\ \ ]$

Box 3 Formalisation of the response patterns

5 Discussion

The presented computational agent model for regulated social response patterns uses theories from Social Neuroscience as a point of departure: theories on mirror neuron systems, self-other distinction, emotion integration, emotion regulation, and empathy. It was shown how a wide variety of realistic social response patterns can be obtained by varying the agent's makeup of mental structures, inspired by relevant literature on autism spectrum disorders. In contrast to work as discussed in (Hendriks and Treur, 2010; Laan and Treur, 2011; Bosse *et al.*, 2012), the presented agent model addresses regulation of enhanced sensory processing sensitivity by super mirroring to control body, face expression and gaze, based on the emotion regulation theory presented in (Gross, 1998; 2007; Goldin *et al.*, 2008). The current model does not cover how the types of behaviour shown by the model can be acquired by some forms of learning. In future work this will also be addressed. Some initial steps in this direction can be found in (Treur, 2011a). In the current paper only a quite modest step towards validation that has been taken has been discussed. In future research more extensive types of validation are planned, in which a more specific link with empirical gaze data over time (and if possible also empirical neurological data) are to be considered. Such validation research should show in more detail how the abstract states in the model relate, for example, to actual gaze responses, sensory and motor body states, and communication actions.

The model provides a basis for human-like behaviour of virtual agents in the context of simulation-based training or gaming. For example, it may provide a basis for the implementation of virtual agents for training of professionals such as teachers, psychotherapists or physicians, or in applications of human-like virtual characters with realistic body and face expression and gaze. For example, in (Suchman, 1997; Tulsky, 2011) the need for such training of physicians and computer assistance for such training is emphasized. The presented model provides a basis to easily generate different types of example interaction scenarios varying from prefect ones to instances with some aspect(s) of imperfection, and use these to deepen insight in such responses and their possible imperfections. For example, an environment can be developed offering a virtual agent which is able to show face expressions and communication, which is driven by the computational model presented here. Interaction with a second virtual agent can be shown within this environment. Such an environment can have possibilities to easily adapt parameters (e.g., the ω's) and see what the effect is on the social interaction between the two virtual agents. This environment can be used as a tool during the education of psychotherapists, to obtain (virtual) experiences with different forms and deviations in social interaction in relation to these parameter settings.

In a wide literature, the role of emotions in virtual agents in general is addressed; e.g., (Bates *et al.*, 1994; Yang *et al.*, 2008; Gratch *et al.*, 2009). Usually these approaches are not specifically related to empathic responses, and often use body or face expressions as a way of presentation, and not as a more biologically grounded basis for the emotion as in the neurological perspective of (Damasio, 1999), which was adopted in the current paper. The importance of computational models for 'caring' agents in a virtual context showing empathy has also been recognized in the literature; see, for example (Klein *et al.*, 2002; Bickmore and Picard, 2004; McQuiggan *et al.*, 2008; Bickmore *et al.*, 2010). Moreover, in (Ochs, Pelachaud, and Sadek 2008; Rodrigues, Mascarenhas, Dias, and Paiva, 2009; Boukricha and Wachsmuth, 2011; Paiva, 2011; Leite, Pereira, Castellano, Mascarenhas, Martinho, and Paiva, 2012) virtual agents are developed that have or show empathy. In this literature the aim is to realize perfect empathy. The basis is usually chosen in appraisal theories for emotion generation. The computational agent model presented in the current paper differs from such existing models in that it is grounded in recent insights from neuroscience and emotion regulation, and reflects these theories. Moreover, the presented model is able to display social responses in a realistic human-like manner, not only of ideal empathic humans, but also of socially less perfect humans. Therefore using the current model it is possible, for example, in simulation-based training to generate example scenarios showing certain forms of imperfection in social interaction which are realistic in the sense that they directly relate to differences in the human population as described by the neurological theories used as a basis.

In (McQuiggan *et al.*, 2008) the CARE framework for experiments with humans and empathic virtual agents is described. A possibility for future research is to integrate the presented agent model in an environment such as, for example the CARE environment, and conduct experiments with different types of (imperfect) empathic agents. As another example, based on the presented model a social interaction pattern between two agents as shown in Figure 3 can be easily implemented within a displayed agent-based virtual story context. The expressed emotions can be displayed on the faces of the two agents, and gaze regulation can be displayed as eyes or faces turning away from each other. When the agent model described is used as an engine to generate the states and behaviour for each of the two virtual agents, the interactive pattern will automatically be generated.

Modeling causal relations discussed in neurological literature in the manner as presented here does not need to take specific neurons into consideration but can use more abstract mental states, relating, for example, to groups of neurons. This is a way to exploit within the agent modelling area results from the large and more and more growing amount of neurological literature. This can be considered as lifting neurological knowledge to a mental (cognitive/affective) level. Nevertheless, the type of agent model that results inherits some technical characteristics from the neurological level, in particular the approach based on small continuous-time recurrent neural networks described by Beer (1995), which was inspired by (Hopfield, 1982, 1984). For example, it takes states as having a certain activation level, instead of binary, for example in order to make reciprocal cognitive/affective loops and gradual adaptation possible. As a consequence, for a state depending on multiple other states, values for such incoming activation levels have to be combined. Therefore combination functions *f* are needed, such as the one based on the continuous logistic threshold function used here, or an alternative function *f* can be considered, such as:

$f(W_1, W_2) = 1$	if $W_1 + W_2 \geq \tau$, and 0 otherwise
$f(W_1, W_2) = W_1 + W_2$	if $W_1 + W_2 \leq 1$, and 1 otherwise
$f(W_1, W_2) = min(W_1, W_2)$	
$f(W_1, W_2) = max(W_1, W_2)$	
$f(W_1, W_2) = \beta\, max(W_1, W_2) + (1-\beta)\, min(W_1, W_2)$	$(0 \leq \beta \leq 1)$
$f(W_1, W_2) = W_1W_2$	
$f(W_1, W_2) = 1- (1-W_1)(1-W_2)$	
$f(W_1, W_2) = \beta(1- (1-W_1)(1-W_2)) + (1 - \beta)W_1W_2$	$(0 \leq \beta \leq 1)$

So, in order to model such an agent at a cognitive/affective level abstracting from neurological detail, still some machinery is needed that usually may be associated to a neural modelling perspective. However, in order to successfully model agents with more complex and human-like behaviour, for example incorporating mutual cognitive/affective interactions, and adaptive behaviour, the toolset for the agent modeller has to include such numerical modelling techniques, enabling to model agents in a hybrid logical/numerical manner.

The adopted modelling approach is based on the hybrid language LEADSTO (Bosse et al., 2007). This language is hybrid in the sense that it allows to model in an integrative manner both qualitative, logical aspects and quantitative, numerical aspects. A number of modelling approaches in the literature exist have some similarities to this modelling approach. In the first place this holds for the family of approaches based on Dynamical Systems Theory using differential and difference equations (e.g., Ashby, 1952; Port and van Gelder, 1995). In these approaches, difference equations are used, for example, of the form: $\Delta x = f(x)\,\Delta t$ or $x(t + \Delta t) = x(t) + f(x(t))\,\Delta t$. Such difference equations can be modelled in LEADSTO as follows (here d is Δt): has_value(x, v) $\twoheadrightarrow_{d,\, d,\, d,\, d}$ has_value(x, v+f(v)*d). This shows how LEADSTO subsumes modelling approaches based on difference equations. In addition to those approaches the LEADSTO language allows to express qualitiative and logical aspects.

Another family of modelling approaches, indicated as Executable Temporal Logic (e.g., Barringer, Fisher, Gabbay, Owens, and Reynolds, 1996; Fisher, 2005), is based on temporal logic formulae of the form $\varphi\ \&\ \chi \Rightarrow \psi$, where φ is a past formula, χ a present formula and ψ a future formula. In comparison to this format, the LEADSTO format is more expressive in the sense that it allows order-sorted predicate logic for state properties, and allows one to express quantitative aspects. Moreover, the explicitly expressed timing parameters (by real numbers) go beyond

Executable Temporal Logic, which uses discrete time. On the other hand, within some of these approaches in Executable Temporal Logic it is allowed to refer to past states at different points in time, and thus to model more complex relationships over time, which is not directly possible in LEADSTO. For LEADSTO the choice has been made to model only the basic mechanisms of a process (e.g., the direct causal relations), like in modelling approaches based on difference equations and not the more complex ones, but still allowing to express the timing by real numbers.

Another family of modelling approaches is based on causal relations: the class of *qualitative reasoning* techniques (e.g., Forbus, 1984). The main idea of these approaches is to represent knowledge in terms of abstract, qualitative concepts. Like in LEADSTO, qualitative reasoning can be used to perform simulation. A difference with LEADSTO is that it is a purely qualitative approach, and that it is less expressive with respect to temporal and quantitative aspects. Also in the medical domain, modelling dynamics processes by means of causal relations is very common. According to Greenland and Brumback (2002), there are four major classes of causal models in the health-sciences literature: *causal diagrams*, *potential-outcome models*, *structural equation models*, and *sufficient-component cause models*. However, as opposed to the LEADSTO approach, these approaches only focus on analysis, not on simulation.

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