Modelling Joint Decision Making Processes Involving Emotion-Related Valuing and Mutual Empathic Understanding

Jan Treur
VU University Amsterdam, Agent Systems Research Group
De Boelelaan 1081, 1081 HV, Amsterdam, The Netherlands
treur@cs.vu.nl http://www.cs.vu.nl/~treur

Abstract. In this paper a social agent model for joint decision making is presented addressing the role of mutually acknowledged empathic understanding in the decision making. The model is based on principles from recent neurological theories on mirror neurons, internal simulation, and emotion-related valuing. Emotion-related valuing of decision options and mutual contagion of intentions and emotions between agents are used as a basis for mutual empathic understanding and convergence of decisions and their associated emotions.

1 Introduction

An important aspect in group functioning is the ability for joint decision making. Groups often develop coherent decisions, and group members usually share a good feeling with them. In recent years developments in neuroscience have clarified some of the mechanisms underlying such processes, in particular, in the new discipline called Social Neuroscience (e.g., [7], [15], [22]). Two interrelated core concepts in this discipline are mirror neurons and internal simulation. Mirror neurons are neurons that not only have the function to prepare for a certain action or body change, but are also activated upon observing somebody else who is performing or tending to perform this action or body change (e.g., [27], [37], [42]). Internal simulation is mental processing that copies processes that may take place externally, for example, in another individual (e.g., [9], [11], [18], [20], [24]). On the one hand, mirror neurons and internal simulation have been put forward as a basic mechanism for imitation and contagion of actions and emotions; on the other hand, they have been related to empathy; e.g., [27]. In this way mirror neurons and internal simulation provide a basis both to mutually tune individual intentions and emotions and to develop mutual empathic understanding between persons (e.g., [14], [18], [20], [32], [38], [43], [44]). Usually these two aspects are addressed separately, but in joint decision making processes they both play their roles in order to achieve solidly grounded joint decisions.

Empathic understanding can concern both cognitive (e.g., knowing or believing) and affective (e.g., feeling) aspects. An affective type of understanding provides a basis for experiencing in the understanding. Affective and cognitive understanding are often related to each other, as any cognitive state triggers an associated emotional response which is the basis of the related feeling (e.g., [9], [11], [12], [13]).

Usually in an individual decision making process, before a decision option is chosen an internal simulation takes place to predict the expected effects of the option (e.g., [2], [9], [11], [12], [13], [33]). Based on these predicted effects a valuation of the option takes place, which may involve or even be mainly based on the affective state associated to this effect, as, for example, described in [1], [9], [10], [12], [34], [36]. To achieve a solid joint decision, a shared feeling and valuation for the chosen option are important, and also mutual recognition of this sharedness. When this is achieved, a common decision has a strong shared emotional grounding as the group members do not only intend to follow that option, but they also share a good feeling about it, and they have (mutually acknowledged) empathic understanding of how other persons feel about the options. The latter may be important as well for those cases that no common option is reached, as a basis for acceptance of non-joint decisions.

In this paper, first in Section 2 some core concepts from Social Neuroscience are briefly reviewed. Next, in Section 3 the neurologically inspired social agent model is presented. In Section 4 some of the explored simulation scenarios are discussed. Finally, Section 5 is a discussion.

2 Mirror Neurons, Internal Simulation and Emotion-Related Valuing

In this section two core concepts in the discipline of Social Neuroscience are briefly discussed: mirror neurons and internal simulation. Together they realise an individual's mental function of mirroring mental processes of another individual. The discovery of mirror neurons originates from single cell recording experiments with monkeys in Parma in the 1990s. In particular, the focus was on an area in the premotor cortex (F5) known to be involved in the preparation of grasp actions. It was discovered that some of the recorded cells were not only firing when the monkey was preparing a grasp action, but also when somebody in the lab was grasping something and the monkey just observed that; cf. [17], [39]; see also [27], [41], [42]. It turned out that in the premotor area F5 about *20%* of the neurons are both active when preparing and when observing the action. After the discovery of mirror neurons in monkeys it has been hypothesized that similar types of neurons also occur in humans. Indeed, for humans from the usual imaging methods it can be found that in certain premotor areas activity occurs both when an action is observed and when the action is prepared; e.g., [8], [19] based on EEG data; [21], [40] based on PET data, [29] based on fMRI. Recently the existence of mirror neurons in humans has found support in single cell experiments with epilepsy patients undergoing pre-surgical evaluation of the foci of epilepsy; cf. [16], [35]; see also [27], pp. 201-203; [28], [31].

Due to the multiple functions of mirror neurons, the functional meaning of activation of them (e.g., preparing or observing an action, or both) in principle is context-dependent. The context determines in which cases their activation is meant to lead to actual execution of the action (e.g., in self-initiated action performance, or imitation), and in which cases it is not (e.g., in action observation). A specific type of mirror neurons, called *super mirror neurons* has been suggested to be able to indicate such a context and play a role in the control of actual execution of a prepared action. These neurons are assumed to indicate self-other distinction and exert control by allowing or suppressing action execution, and/or by suppressing preparation states. More details on such neurons and the role they play can be found in [6], [23], [28], and [27], pp. 196-203.

Activation states of mirror neurons are important not by themselves, but because they play a crucial role in an important mental function: *mirroring* mental processes of other persons by *internal simulation*. In [30] the following causal chain is suggested (see also [13], pp. 114-116):

> sensory representation → preparation for bodily changes → expressed bodily changes →
> emotion felt = based on sensory representation of (sensed) bodily changes

Damasio made a further step by introducing an *as-if body loop* bypassing actually expressed bodily changes (cf. [9], pp. 155-158; see also [11], pp. 79-80; [12], [13]):

sensory representation → preparation for bodily changes = emotional response →
emotion felt = based on sensory representation of (simulated) bodily changes

An as-if body loop describes an *internal simulation* of the bodily processes, without actually affecting the body, comparable to simulation in order to perform, for example, prediction, mindreading or imagination; e.g., [2], [18], [20], [24], [33]. The feelings generated in this way play an important role in valuing predicted or imagined effects of actions, in relation to amygdala activations; see, e.g., [34], [36]. The emotional response and feeling mutually affect each other in a bidirectional manner: an as-if body loop usually occurs in a cyclic form; see, for example, in ([12], pp. 91-92; [13], pp. 119-122):

emotion felt = based on sensory representation of (simulated) bodily changes →
preparation for bodily changes = emotional response

This provides a cyclic process that (for a constant environment) can lead to equilibrium states for both, as shown, for example, in [5] by a computational model. As mirror neurons make that some specific sensory input (an observed person) directly links to related preparation states, it fits quite well in the perspective based on as-if body loops. In this way mirroring is a process that fully integrates mirror neuron activation states in the ongoing internal simulation processes based on as-if loops; see also [13], pp. 102-104.

Above it has been pointed out how states of other persons lead to activation of some of a person's coresponding own states that at the same time play a crucial role in the person's own feelings and decisions for actions. This provides an effective mechanism for how observed (tendencies for) actions and feelings and own actions and feelings are tuned to each other. This mechanism explains how in a social context persons fundamentally affect each other's individual decisions and states, including feelings. Moreover, it is also the basis for empathic understanding of other persons' preferences and feelings. The mutually acknowledged empathic understanding modelled in Section 3 is based on the following criteria:

(a) Showing the same state as the other agent (nonverbal part of the empathic response)
(b) Telling that the other agent has this state (verbal part of the empathic response)

Assuming true, faithful nonverbal and verbal expression, these two criteria are in line with the four criteria of empathy for emotion states formulated in [14], [44]:

(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

An empathic response is modelled both for emotions and action tendencies. In the latter case this means nonverbally showing the same tendency, and communicating the other person that he or she has this tendency. Both the tuning and convergence of action tendencies and the mutual empathic understanding (even when finally no common option is decided for) play a crucial role in joint decision making processes.

3 The Social Agent Model

The issues and perspectives briefly reviewed in the introduction and Section 2 have been used as a basis for the neurologically inspired cognitive agent model presented below (for an overview, see Fig. 1); in summary:

- Decision making is based on *emotion-related valuing* of the *predicted effects* of each action option

- Both the tendency to go for an action and the associated emotion are transferred between agents via *mirroring processes* using *internal simulation*
- These mirroring processes at the same time induce a gradual process of mutually *tuning* the considered actions and their emotion-related valuations, and the development of mutual *empathic understanding*
- The outcome of such a joint decision process in principle involves three elements:
    - a *common action* option
    - a *shared positive feeling* and valuation for the effect of this action option
    - mutually *acknowledged empathic understanding* for both the action option and the feeling
- In case of an outcome without a common choice for an action option, the process results in mutually *acknowledged empathic understanding*

In the model s denotes a *stimulus*, a an *option* for an *action* to be decided about, and e a world state which is an *effect* of the action. The effect state e is *valued* by associating a *feeling* state b to it, which is considered to be positive for the agent (e.g., in accordance with a goal).

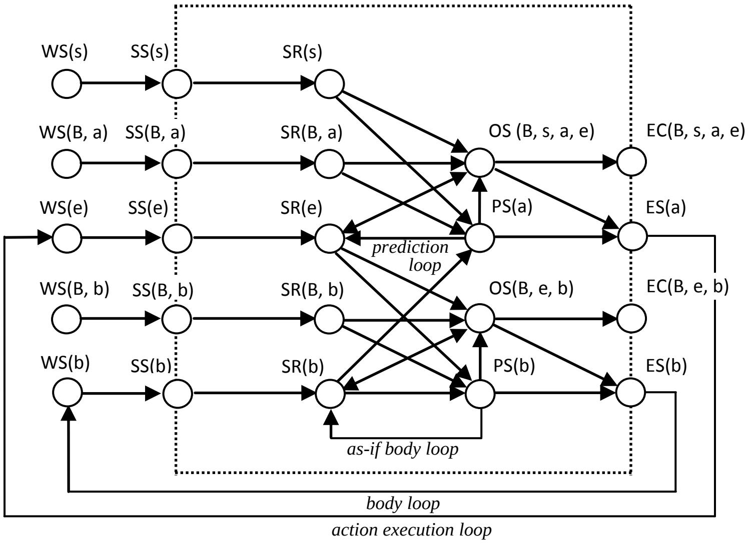

Fig. 1. Overview of the social agent model

The state properties used in the model are summarised in Table 1. The social agent model uses ownership states for actions a and their effects e, both for self and other agents, specified by OS(B, s, a, e) with B another agent or self, respectively (see Figure 1). Similarly, ownership states are used for emotions indicated by body state b, both for self and other agents, specified by OS(B, e, b) with B another agent or self. As an example, the four arrows to OS(B, s, a, e) in Figure 1 show that an ownership state OS(B, s, a, e) is affected by the preparation state PS(a) for the action a, the sensory representation SR(b) of the emotion-related value b for the (predicted) effect e, the sensory representation SR(s) of the stimulus s, and the sensory representation SR(B) of the agent B.

Table 1. State properties used

notation	description
WS(W)	world state W: an action a of agent B, a feeling b of agent B, a stimulus s, effect e, or emotion indicated by body state b
SS(W)	sensor state for W
SR(W)	sensory representation of W
PS(X)	preparation state for X: action a or expressing emotion by body state b
ES(X)	execution state for X: action a or expressing emotion by body state b
OS(B, s, a, e)	ownership state for B of action a with effect e and stimulus s
OS(B, e, b)	ownership state for B of emotion indicated by body state b and effect e
EC(B, s, a, e)	communication to B of ownership for B of action a with effect e and stimulus s
EC(B, e, b)	communication to B of ownership for B of emotion indicated by body state b and effect e

Action prediction is modelled by the connection from the action preparation PS(a) to the sensory representation SR(e) of the effect e. Suppression of the sensory representation of a predicted effect (according to, e.g., [3], [4], [33]) is modelled by the (inhibiting) connection from the ownership state OS(B, s, a, e) to sensory representation SR(e). The control exerted by the ownership state for action a is modelled by the connection from OS(B, s, a, e) to ES(a). Communicating ownership for an action (a way of expressing recognition of the other person's states, as a verbal part of showing empathic understanding) is modelled by the connection from the ownership state OS(B, s, a, e) to the communication effector state EC(B, s, a, e). Similarly, communicating of ownership for an emotion for effect e indicated by b is modelled by the connection from the ownership state OS(B, e, b) to the communication effector state EC(B, e, b).

Connections between state properties (the arrows in Figure 1) have weights, as indicated in Table 2.

Table 2. Overview of the connections and their weights

from states	to state	weights	LP
SS(W)	SR(W)	ω_{1W}	LP1
PS(a), OS(B, s, a, e), SS(e)	SR(e)	ω_{21e}, ω_{22e}, ω_{23e}	LP2
PS(b), OS(B, e, b), SS(b)	SR(b)	ω_{21b}, ω_{22b}, ω_{23b}	
SR(s), SR(b), SR(B, a)	PS(a)	ω_{31a}, ω_{32a}, ω_{33a}	LP3
SR(e), SR(b), SR(B, b)	PS(b)	ω_{31b}, ω_{32b}, ω_{33b}	
SR(B, a), SR(s), PS(a), SR(e)	OS(B, s, a, e)	ω_{41a}, ω_{42a}, ω_{43a}, ω_{44a}	LP4
SR(B, b), SR(e), PS(b), SR(b)	OS(B, e, b)	ω_{41b}, ω_{42b}, ω_{43b}, ω_{44b}	
OS(B, s, a, e), PS(a)	ES(a)	ω_{51a}, ω_{52a}	LP5
OS(B, e, b), PS(b)	ES(b)	ω_{51b}, ω_{52b}	
ES(a)	WS(e)	ω_{6e}	LP6
ES(b)	WS(b)	ω_{6b}	
WS(W)	SS(W)	ω_{7W}	LP7
OS(B, s, a, e)	EC(B, s, a, e)	ω_{8a}	LP8
OS(B, e, b)	EC(B, e, b)	ω_{8b}	

In this table the column LP refers to the (temporally) Local Properties LP1 to LP9 presented below. A weight usually has a value between *-1* and *1* and may depend on the specific agent B, stimulus s, action a and/or effect state b involved. Note that in general weights are assumed non-negative, except for inhibiting connections, such as ω_{22e} which models suppression of the sensory representation of effect e, and ω_{22b} which models suppression of the sensory representation of body state b.

Below, the dynamics following the connections between the states in Figure 1 are described in more detail. This is done for each state by a dynamic property specifying how the activation value for this state is updated based on the activation values of the states connected to it (the incoming arrows in Figure 1).

The cognitive agent model has been computationally formalised in this way using the hybrid modeling language LEADSTO; cf. [5]. 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. Each time first a semiformal description is given, and next a formal specification in the hybrid LEADSTO format. Parameter γ indicates the speed by which an activation level is updated based on received input from other states.

During processing, each state property has an activation level 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(p, V) with p a state property has not been used for the sake of notational simplicity).

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

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

with σ a steepness and τ a threshold value, when $X \geq 0$, and 0 when $X < 0$. Note that for higher values of $\sigma\tau$ (e.g., $\sigma > 20/\tau$) this threshold function can be approximated by:

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

In the example simulations, in LP1, LP6, and LP7, f is taken the identity function $f(W) = W$, and for the other states f is a combination function based on the logistic threshold function: $f(X_1, X_2) = th(\sigma, \tau, X_1+X_2)$, and similarly for other numbers of arguments; in this choice common practice is followed, but other types of combination functions might be used as well. For example values for τ and σ, see Table 3 in Section 4.

The first property LP1 describes how sensory representations are generated for any state W, indicating a stimulus s, an action a of an agent B, or a feeling b of an agent B.

LP1 Sensory representation of w based on a sensor state for w
If the sensor state for W has level V_1
and the sensory representation of W has level V_2
then after duration Δt the sensory representation of W will have level $V_2 + \gamma\, [\, f(\omega_{1W}V_1) - V_2\,]\ \Delta t$.
$SS(W, V_1)\ \&\ SR(W, V_2) \twoheadrightarrow SR(W, V_2 + \gamma\, [\, f(\omega_{1W}V_1) - V_2\,]\, \Delta t$

The sensory representation of an effect state e as described by property LP2 is not only affected by a corresponding sensor state for e (which in turn is affected by the world state), as in LP1, but also by two action-related states:

- via the *predictive loop* by a preparation state, as a way of *internal simulation* to predict the effect e of a prepared action a
- by an inhibiting connection from the self-ownership state, to *suppress* the sensory representation of the *effect* e of the action a, once it is going to be initiated

This is expressed in dynamic property LP2. Note that for this suppressing effect the connection weight ω_{22e} from ownership state for action a to sensory representation for effect e is taken negative, for example $\omega_{22e} = -0.2$. Dynamic property LP2b specifies a similar temporal relationship for update of the sensory representation of a body state, and thus models *internal simulation* by an *as-if body loop*.

LP2e Sensory representation for an effect state e
If the preparation state for action a has level V_1
and the ownership of action a for B and s has level V_2
and the sensor state for state e has level V_3
and the sensory representation state of e has level V_4
then after Δt the sensory representation state of e will have
level $V_4 + \gamma [\, f(\omega_{21e}V_1, \omega_{22e}V_2, \omega_{23e}V_3) - V_4 \,] \Delta t$.

$\mathrm{PS}(a, V_1)\ \&\ \mathrm{OS}(B, s, a, e, V_2)\ \&\ \mathrm{SS}(b, V_3)\ \&\ \mathrm{SR}(b, V_4) \twoheadrightarrow \mathrm{SR}(b, V_4 + \gamma [\, f(\omega_{21e}V_1, \omega_{22e}V_2, \omega_{23e}V_3) - V_4 \,] \Delta t)$

LP2b Sensory representation for a body state b
If the preparation state for body state b has level V_1
and the ownership of body state b for B and b, and e has level V_2
and the sensor state for state b has level V_3
and the sensory representation of state b has level V_4
then after Δt the sensory representation state of b will have
level $V_4 + \gamma [\, f(\omega_{21b}V_1, \omega_{22b}V_2, \omega_{23b}V_3) - V_4 \,] \Delta t$.

$\mathrm{PS}(a, V_1)\ \&\ \mathrm{OS}(B, e, b, V_2)\ \&\ \mathrm{SS}(b, V_3)\ \&\ \mathrm{SR}(b, V_4) \twoheadrightarrow \mathrm{SR}(b, V_4 + \gamma [\, f(\omega_{21b}V_1, \omega_{22ob}V_2, \omega_{23b}V_3) - V_4 \,] \Delta t)$

Preparation for action a is affected by

- the sensory representation of stimulus s
- the body state b associated to the predicted effect e of the action,
- observation of the action (tendency) in another agent

The first bullet can be considered as an external trigger for the action. The second bullet models the impact of the result b of the *emotion-related valuing* of the action effect e. The third bullet models the *mirroring* effect for the action as observed as a tendency in another agent. Similarly for the preparation for a body state b; here the sensory representation of the effect e serves as a trigger, and the emotion state of another agent is mirrored.

LP3a Preparing for an action a
If sensory representation of s has level V_1
and sensory representation of body state b has level V_2
and sensory representation of B for a has level V_3
and the preparation for action a has level V_4
then after Δt the preparation state for action a will have
level $V_4 + \gamma [\, f(\omega_{31a}V_1, \omega_{32a}V_2, \omega_{33Ba}V_3) - V_4 \,] \Delta t$.

$\mathrm{SR}(s,V_1)\ \&\ \mathrm{SR}(b,V_2)\ \&\ \mathrm{SR}(B, a)\ \&\ \mathrm{PS}(a, V_4) \twoheadrightarrow \mathrm{PS}(a, V_4 + \gamma [\, f(\omega_{31a}V_1, \omega_{32a}V_2, \omega_{33Ba}V_3) - V_4 \,] \Delta t)$

LP3b Preparing for a body state b
If sensory representation of e has level V_1
and sensory representation of b has level V_2
and sensory representation of B for b has level V_3
and the preparation for action a has level V_4
then after Δt the preparation state for action a will have
level $V_4 + \gamma [\, f(\omega_{31b}V_1, \omega_{32b}V_2, \omega_{33Bb}V_3) - V_4 \,] \Delta t$.

$\mathrm{SR}(e,V_1)\ \&\ \mathrm{SR}(b,V_2)\ \&\ \mathrm{SR}(B, b)\ \&\ \mathrm{PS}(b, V_4) \twoheadrightarrow \mathrm{PS}(b, V_4 + \gamma [\, f(\omega_{31b}V_1, \omega_{32b}V_2, \omega_{33Bb}V_3) - V_4 \,] \Delta t)$

Ownership states for an action a or body state b are generated by LP4. They can be considered as a way of keeping track of the agent's context with respect to the action or body state. This context concerns both the agent self and the other agents and their extent of ownership of the action or body change; in this sense it is a basis for attribution to an agent, and includes self-other distinction. Moreover, a self-ownership is used to control execution of prepared actions or body states, like *super mirror neurons* are assumed to do. For example, in case the agent B is self, the ownership state for action a strengthens the initiative to perform a as a self-generated action: executing a prepared action depends on whether a certain activation level of the ownership state for the agent self is available for this action. This is how control over the actual execution of the action (go/no-go decision) is exerted, and can, for example, be used to veto the action in a late stage of preparation.

LP4a Generating an ownership state for B and a
If the sensory representation of (tendency for) action a in agent B has level V_1
and the sensory representation of s has level V_2
and the preparation for action a has level V_3
and the sensory representation of e has level V_4
and ownership of a for B, s and e has level V_5
then after Δt ownership of a for B, s and e will have
level $V_5 + \gamma\ [\ f(\omega_{41a}V_1, \omega_{42a}V_2, \omega_{43a}V_3, \omega_{44a}V_4) - V_5]\ \Delta t$.
$\mathrm{SR}(\mathrm{B}, \mathrm{a}, V_1)\ \&\ \mathrm{SR}(\mathrm{s}, V_2)\ \&\ \mathrm{PS}(\mathrm{a}, V_3)\ \&\ \mathrm{SR}(\mathrm{e}, V_4)\ \&\ \mathrm{OS}(\mathrm{B}, \mathrm{s}, \mathrm{a}, \mathrm{e}, V_5)$
$\twoheadrightarrow \mathrm{OS}(\mathrm{B}, \mathrm{s}, \mathrm{a}, \mathrm{e}, V_5 + \gamma\ [\ \mathrm{f}(\omega_{41a}V_1, \omega_{42a}V_2, \omega_{43a}V_3, \omega_{44a}V_4) - V_5\ ]\ \Delta t)$

LP4b Generating an ownership state for B and b
If the sensory representation of B with body state b has level V_1
and the sensory representation of e has level V_2
and the preparation for body state b has level V_3
and the sensory representation of b has level V_4
and ownership of b for B and e has level V_5
then after Δt ownership of b for B and e will have
level $V_5 + \gamma\ [\ f(\omega_{41b}V_1, \omega_{42b}V_2, \omega_{43b}V_3, \omega_{44b}V_4) - V_5]\ \Delta t$.
$\mathrm{SR}(\mathrm{B}, \mathrm{b}, V_1)\ \&\ \mathrm{SR}(\mathrm{e}, V_2)\ \&\ \mathrm{PS}(\mathrm{b}, V_3)\ \&\ \mathrm{SR}(\mathrm{b}, V_4)\ \&\ \mathrm{OS}(\mathrm{B}, \mathrm{e}, \mathrm{b}, V_5)$
$\twoheadrightarrow \mathrm{OS}(\mathrm{B}, \mathrm{e}, \mathrm{b}, V_5 + \gamma\ [\ \mathrm{f}(\omega_{41b}V_1, \omega_{42b}V_2, \omega_{43b}V_3, \omega_{44b}V_4) - V_5\ ]\ \Delta t)$

Note that in case of the agent self, the first condition in LP4 is meant to indicate a *self-context* for in how far the agent has a certain willingness to come to an action or expression. For example, when no other agent is present the willingness to explicitly express emotions may be less, or when the agent is in a passive mood, willingness to come to an action a may be low. The use of ownership states in control of execution is modelled by LP5:

LP5a Action a execution
If ownership of a for B and s and e has level V_1
and preparation for action a has level V_2
and the action execution state for a has level V_3
then after Δt the action execution state for a will have level $V_3 + \gamma\ [\ f(\omega_{51a}V_1, \omega_{52a}V_2) - V_3\ ]\ \Delta t$.
$\mathrm{OS}(\mathrm{B}, \mathrm{s}, \mathrm{a}, \mathrm{e}, V_1)\ \&\ \mathrm{PS}(\mathrm{a}, V_2)\ \&\ \mathrm{ES}(\mathrm{a}, V_3)$
$\twoheadrightarrow \mathrm{ES}(\mathrm{a}, V_3 + \gamma\ [\ \mathrm{f}(\omega_{51a}V_1, \omega_{52a}V_2) - V_3\ ]\ \Delta t)$

LP5b Body change b execution
If ownership of b for B and e has level V_1
and preparation for body state b has level V_2
and the execution state for b has level V_3
then after Δt the execution state for b will have level $V_3 + \gamma\ [\ f(\omega_{51b}V_1, \omega_{52b}V_2) - V_3\ ]\ \Delta t$.
$\mathrm{OS}(\mathrm{B}, \mathrm{e}, \mathrm{b}, V_1)\ \&\ \mathrm{PS}(\mathrm{b}, V_2)\ \&\ \mathrm{ES}(\mathrm{b}, V_3)$
$\twoheadrightarrow \mathrm{ES}(\mathrm{b}, V_3 + \gamma\ [\ \mathrm{f}(\omega_{51b}V_1, \omega_{52b}V_2) - V_3\ ]\ \Delta t)$

Note that these executions also function as the *nonverbal part of the empathic response*; for example, showing a face expression with the same emotion as the other person.

Property LP6 describes in a straightforward manner how execution of action a or body change b affects the world state for effect e or body state b.

LP6e From action execution to effect state
If the execution state for action a has level V_1,
and world state e has level V_2
then after Δt world state e will have level $V_2 + \gamma\ [\ f(\omega_{6e}V_1) - V_2\ ]\ \Delta t$.
$\mathrm{ES}(\mathrm{a}, V_1)\ \&\ \mathrm{WS}(\mathrm{e}, V_2) \twoheadrightarrow \mathrm{WS}(\mathrm{e}, V_2 + \gamma\ [\ \mathrm{f}(\omega_{6e}V_1) - V_2\ ]\ \Delta t)$

LP6b From body change execution to body state
If the execution state for body state b has level V_1,
and body state b has level V_2
then after Δt body state b will have level $V_2 + \gamma\ [\ f(\omega_{6b}V_1) - V_2\ ]\ \Delta t$.
ES(a, V_1) & WS(b, V_2) $\twoheadrightarrow$ WS(b, $V_2 + \gamma\ [\ f(\omega_{6b}V_1) - V_2\ ]\ \Delta t$)

The following property models how sensor states are updated. It applies to an action a of agent B, a feeling b of agent B, a stimulus s, effect e, or emotion indicated by body state b (covered by variable W).

LP7 Generating a sensor state for a world or body state W
If world state W has level V_1
and the sensor state for W has level V_2
then after Δt the sensor state for W will have
level $V_2 + \gamma [\ f(\omega_{7W}V_1) - V_2]\ \Delta t$.
WS(W, V_1) & SS(W, V_2) $\twoheadrightarrow$ SS(W, $V_2 + \gamma\ [\ f(\omega_{7W}V_1) - V_2\ ]\ \Delta t$)

Communication of ownership of the other agent to the other agent represents acknowledgement of an agent that it has noticed the state of the other agent: a *verbal part* of the *empathic response*. These communications depends on the ownership states as specified in LP8.

LP8a Communication of the other agent B's intention a and e for s
If the ownership state of a and e for B and s has level V_1,
and communication of a and e for B and s has level V_2
then after Δt communication of a and e for B and s will have level $V_2 + \gamma\ [\ f(\omega_{8a}V_1) - V_2\ ]\ \Delta t$.
OS(B, s, a, e, V_1) & EO(B, s, a, V_2) $\twoheadrightarrow$ EO(B, s, a, e, $V_2 + \gamma\ [\ f(\omega_{8a}V_1) - V_2\ ]\ \Delta t$)

LP8b Communication of the other agent B's emotion b for e
If the ownership state of b for B and e has level V_1,
and communication of b for B and e has level V_2
then after Δt communication of b for B and e will have level $V_2 + \gamma\ [\ f(\omega_{8b}V_1) - V_2\ ]\ \Delta t$.
OS(B, e, b, V_1) & EO(B, e, b, V_2) $\twoheadrightarrow$ EO(B, e, b, $V_2 + \gamma\ [\ f(\omega_{8b}V_1) - V_2\ ]\ \Delta t$)

4 Simulation Results

In this section simulation results are presented for some of the scenarios that have been explored. Three scenarios for two agents will be discussed. In the first two of them mutual empathic understanding and convergence to a joint decision are achieved (for two different situations), and in the third scenario mutual empathic understanding is achieved but no convergence to a joint decision. In all of the scenarios all connection strengths were taken *1*, except the inhibiting connections, which were taken *-0.2*, and the connection to the action effect in the world which was taken *0* as the focus here is on the process of decision making prior to the actual execution of the decision. The values for the threshold τ and steepnees σ parameters were taken as shown in Table 3. The speed factor γ was taken *0.5* and $\Delta t = 0.2$. In the graphs shown in Figs 2 to 4 time is on the horizontal axis and activation levels as indicated are on the vertical axis. Each time the upper graph shows agent A and the lower graph agent B.

Table 3. Threshold and steepness values used

to state	τ	σ	LP
SR(e)	*0.2*	*4*	LP2
SR(b)	*0.7*	*4*	
PS(a)	*1*	*4*	LP3
PS(b)	*0.7*	*4*	
OS(B, s, a, e)	*3.2*	*8*	LP4
OS(B, e, b)	*3.2*	*8*	
ES(a)	*1.6*	*20*	LP5
ES(b)	*1*	*20*	
EC(B, s, a, e)	*0.6*	*20*	LP8
EC(B, e, b)	*0.6*	*20*	

Scenario 1: Mutual empathic understanding and joint decision: different self-contexts In the first scenario both agents get stimulus s as input with level *1*. The only difference is that agent A has level *1* for the self-context factor which indicates willingness to come to action and for agent B this is *0.5*. In Fig. 2 the activation levels over time are shown.

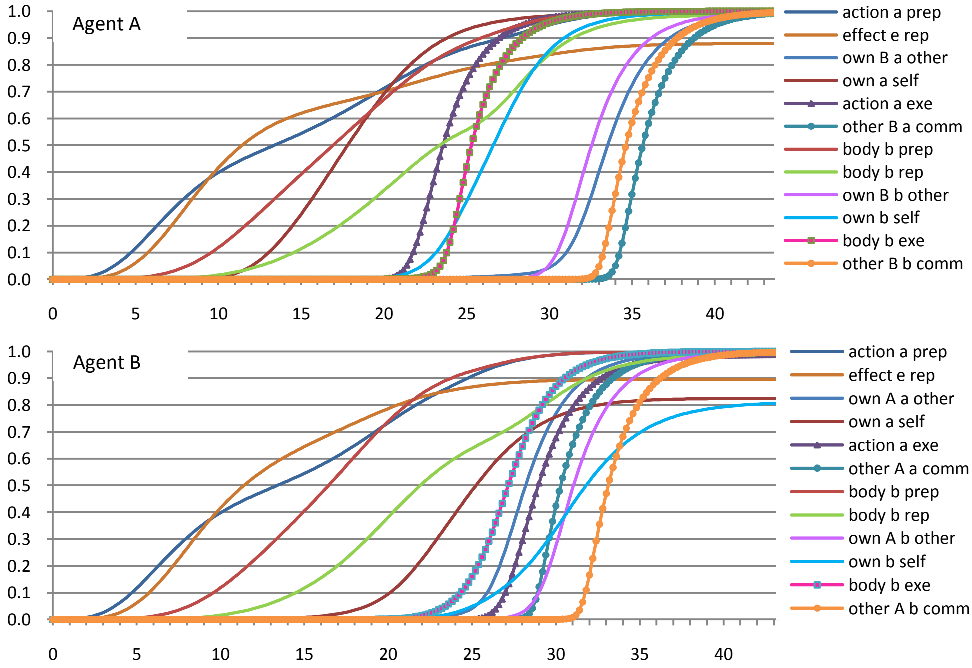

Fig. 2. Reaching a joint decision and mutual understanding for different self-contexts

It is shown that triggered by the stimulus s, from time point 3 on both agents develop a preparation for action option a, which is immediately followed by activation of predicted effect e. Next, around time point 6 both agents start to develop an emotional response preparation for b on the predicted effect e, and as a consequence (by the as-if body loop) the feeling of this emotion from time point 9 on. Around time point 10 agent A starts to activate the self ownership state for action option a, whereas for agent B this only happens later, after time point 16, due to its lower self-context value. Due to this, agent A expresses (the tendency for) action option a from time point 20 on. Moreover, from time point 22 on agent A expresses the emotion felt, after an ownership state for this was activated from time point 20 on. Note that at this point in time point agent B does not show such reactions, due to the lower self-context for agent B.

However, agent A's responses will affect agent B. More specifically, by B's mirroring of the two types (action tendency and body state) of expression from agent A, agent B is affected in its preparation levels for both the action option and the bodily response. Due to this, agent B also expresses the feeling from time point 21 and the tendency for action option a from time point 26 on. This actually creates a joint decision for action option a, accompanied by a good feeling b for it. Moreover, this also provides the nonverbal part of B's empathic response on agent A's action tendency and feeling. Furthermore, agent B shows a verbal empathic response to A for both the action and the feeling starting at time points 28 and 30, respectively. Note that the verbal empathic response from agent A comes later, at time points 32 and 33 respectively, which reflects the fact that some time was needed to get agent B in the proper state (due to mirroring) to show support for action option a and feeling b.

Scenario 2: Mutual empathic understanding and joint decision; different levels of s
The second scenario addresses a case in which agent B and A both have self-context level *1*, and A has stimulus level *1*, but for agent B the stimulus s is only present with level *0.5*; see Fig. 3. Also in this case after some time a joint decision comes out, but the pattern is a bit different, as now agent B depends on agent A for its activation of preparation for action option a and the associated emotional response and feeling. Therefore during the period from time point 5 to time point 25 the activation levels of action preparation, effect prediction, emotional response and feeling stay low. After time point 25 they move up due to the influence of agent A's expression starting at time points 20 and 21.

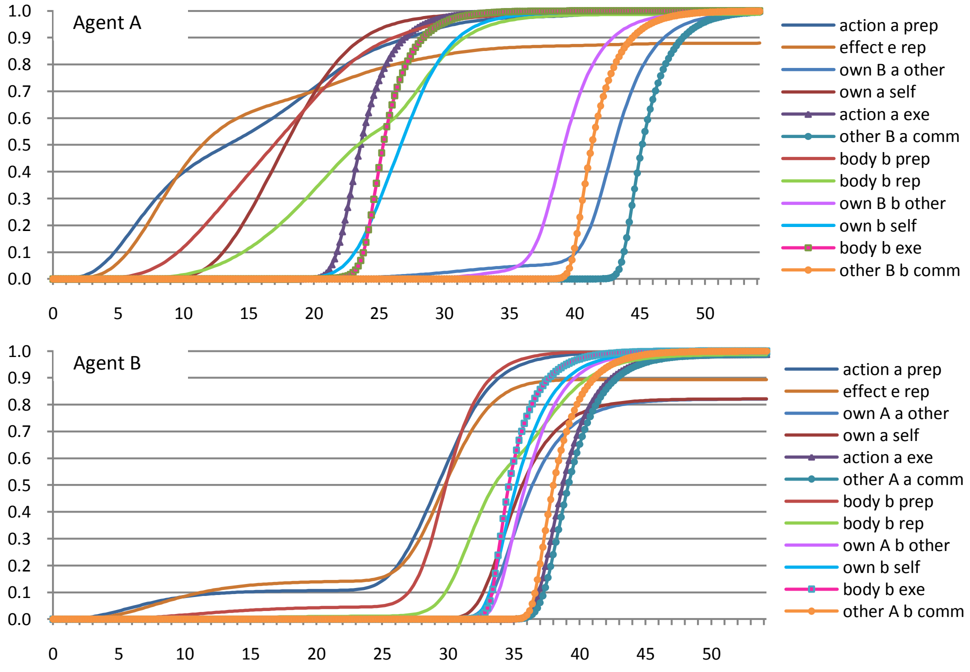

Fig. 3. Reaching a joint decision and mutual understanding for different stimulus levels

Scenario 3: Mutual empathic understanding and no joint decision
The third scenario addresses a case in which agent A has self-context level *1*, but for agent B this level is *0*; see Fig. 4. The stimulus s for both has level *1*. In this case after no joint decision comes out, as agent B does not follow A in the action option a, but still empathic responses are shown. In Fig. 4 it is shown that as in scenario 1 agent B develops expressed states for the action a and feeling b, from time point 20 on. Also agent B shows the same pattern as in scenario 1, up to time point 20. However, then a main difference is that in the current scenario the self ownership state of B for a does not develop; it becomes not much more than *0.1*. As a consequence no tendency for action a is developed. Note that due to the emotion contagion still the feeling level of agent B becomes higher and as a result this feeling is expressed (from time point 22 on), thus contributing a nonverbal empathic response. Moreover, also verbal empathic responses of agent B are developed after time points 27 and 30, respectively.

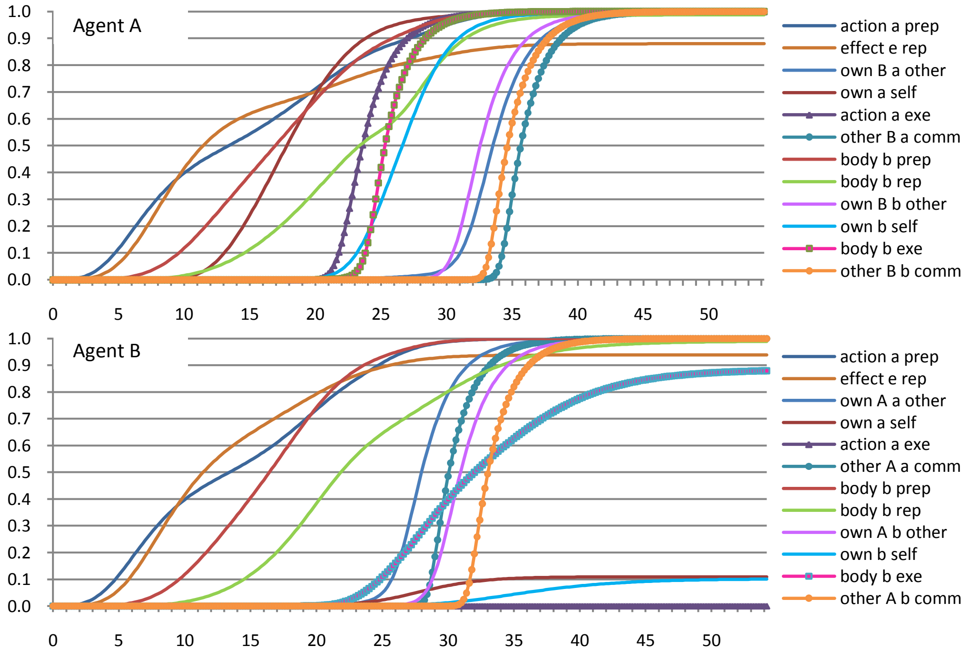

Fig. 4. Achieving mutual understanding but no joint decision

5 Discussion

In this paper a social agent model was presented based on mechanisms from Social Neuroscience. The model addresses the emergence of joint decisions, accompanied by shared emotions and mutually acknowledged empathic understanding. To this end it covers both cognitive and affective processes and their interaction in decision making, and social contagion. Core mechanisms adopted are mirror neurons (e.g., [27], [37], [42]), internal simulation (e.g., [9], [11], [18], [20], [24]), and emotion-related valuing of predicted effects of action options (e.g., [1], [9], [10], [12], [34], [36]). It was shown how such social agent models can be used to perform simulation and analysis of the emergence of joint decisions grounded in shared emotion-related valuing, and together with mutual empathic understanding of agents. As the approach combines cognitive and affective aspects not only the group members reach a joint decision, but they also share the experience of a good feeling about it, which gives the joint decision a solid emotional grounding, and they have a mutually acknowledged empathic understanding of this.

The social agent model uses elements from the model presented in [45] for the empathic understanding, but in contrast to [45] where the empathic understanding was limited to emotions, in the current model it is applied to both (tendencies for) actions and emotions. Furthermore, the current model uses the idea of ownership states as in the model presented in [46]. However, in [46] ownership states are differentiated into prior and retrospective ownership states, which was not done in the current model. Moreover, in the current model the ownership states were used both for actions and for expressing emotions, whereas in [46] they were only focused on actions, and emotions were not addressed.

Another difference to both [45] and [46] is the use in the current model of social contagion to affect both action tendencies and associated feelings in order to come to joint decisions accompanied by shared associated emotions. This purpose was also addressed at an abstract level in [25] and [26], but the models in these references do not address the underlying internal neurological mechanisms within the agents, and the mutually acknowledged empathic understanding as addressed in the model presented in the current paper.

The obtained social agent model can be used as a basis for the design of human-like virtual agents for simulation-based training or in gaming, or for virtual stories. For the first type of application the idea is to develop a number of virtual agents cooperating with a human trainee as a team in an decision making task. For the second type of application the idea is to design a system for agent-based virtual stories in which, for example, persons play a role which can be based on the presented model.

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