Modelling the Emergence of Group Decisions Based on Mirroring and Somatic Marking

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Abstract. This paper introduces a neurologically inspired computational model for the emergence of group decisions. The model combines an individual decision making model based on Damasio's Somatic Marker Hypothesis with mutual effects of group members on each other via mirroring of emotions and intentions. The obtained model shows how this combination of assumed neural mechanisms can form an adequate basis for the emergence of common group decisions, while, in addition, there is a feeling of wellness with these common decisions amongst the group members.

1 Introduction

To express the impossibility of a task, sometimes the expression 'like managing a herd of cats' is used, for example, in relation to managing a group of researchers. This is meant to indicate that no single direction or decision will come out of such a group, no matter how hard it is tried. As an alternative, sometimes a reference is made to 'riding a garden-cart with frogs'. It seems that such a lack of coherence-directed tendency in a group is considered as something exceptional, a kind of surprising, and in a way unfair. However, as each group member is an autonomous agent with his or her own neurological structures, patterns and states, carrying for example, their own emotions, desires, preferences, and intentions, it would be more reasonable to expect that the surprise concerns the opposite side: how is it possible that so often, groups – even those of researchers – develop coherent directions and decisions, and, moreover, why do the group members in some miraculous manner even seem to feel good with these?

This paper presents a neurologically inspired computational modelling approach for the emergence of group decisions. It incorporates the ideas of somatic marking as a basis for individual decision making, see [1], [3], [5], [6] and mirroring of emotions and intentions as a basis for mutual influences between group members, see [7], [11], [12], [14], [15], 16], [18]. The model shows how for many cases indeed, the combination of these two neural mechanisms is sufficient to obtain the emergence of common group decisions on the one hand, and, on the other hand, to achieve that the group members have a feeling of wellness with these decisions.

The paper is organised as follows. In Section 2 a brief introduction of the neurological ideas underlying the approach is presented: mirroring and somatic marking. Next, in Section 3 the computational model is described in detail. Section 4 presents a number of simulation results. Section 5 addresses verification of the model against formally specified properties describing expected emerging patterns. Finally, Section 6 is a discussion.

2 Somatic Marking and Mirroring

Cognitive states of a person, such as sensory or other representations often induce emotions felt within this person, as described by neurologist Damasio, [4], [5]; for example:

> 'Even when we somewhat misuse the notion of feeling – as in "I feel I am right about this" or "I feel I cannot agree with you" – we are referring, at least vaguely, to the feeling that accompanies the idea of believing a certain fact or endorsing a certain view. This is because believing and endorsing *cause* a certain emotion to happen.' ([5], p. 93)

Damasio's *Somatic Marker Hypothesis*; cf. [1], [3], [5], [6], is a theory on decision making which provides a central role to emotions felt. Within a given context, each represented decision option induces (via an emotional response) a feeling which is used to mark the option. For example, a strongly negative somatic marker linked to a particular option occurs as a strongly negative feeling for that option. Similarly, a positive somatic marker occurs as a positive feeling for that option. Damasio describes the use of somatic markers in the following way:

> 'the somatic marker (..) forces attention on the negative outcome to which a given action may lead, and functions as an automated alarm signal which says: beware of danger ahead if you choose the option which leads to this outcome. The signal may lead you to reject, *immediately*, the negative course of action and thus make you choose among other alternatives. (…) When a positive somatic marker is juxtaposed instead, it becomes a beacon of incentive.' ([3], pp. 173-174)

Usually the Somatic Marker Hypothesis is applied to provide endorsements or valuations for options for a person's actions, thus shaping a decision process. Somatic markers may be innate, but may also by adaptive, related to experiences:

> 'Somatic markers are thus acquired through experience, under the control of an internal preference system and under the influence of an external set of circumstances which include not only entities and events with which the organism must interact, but also social conventions and ethical rules. ([3], p. 179)

In a social context, the idea of somatic marking can be combined with recent neurological findings on the *mirroring function* of certain neurons (e.g., [7], [11], [12], [14], [15], [16], [17], [18]. Mirror neurons are neurons which, in the context of the neural circuits in which they are embedded, show both a function to prepare for certain actions or bodily changes and a function to mirror states of other persons. They are active not only when a person intends to perform a specific action or body change, but also when the person observes somebody else intending or performing this action or body change. This includes expressing emotions in body states, such as facial expressions. For example, there is strong evidence that (already from an age of just 1 hour) sensing somebody else's face expression leads (within about 300 milliseconds) to preparing for and showing the same face expression ([10], p. 129-130). The idea is that these neurons and the neural circuits in which they are embedded play an important role in social functioning and in (empathic) understanding of others; (e.g., [7], [11], [17], [18]). The discovery of mirror neurons is often considered a crucial step for the further development of the discipline of social cognition, comparable to the role the discovery of DNA has played for biology, as it provides a biological basis for many social phenomena; cf. [11]. Indeed, when states of other persons are mirrored by some of the person's own states that at the same time are connected via neural circuits to states that are crucial for the own feelings and actions, then this provides an effective basic mechanism for how in a social context persons fundamentally affect each other's actions and feelings.

Given the general principles described above, the mirroring function relates to decision making in two different ways. In the first place mirroring of emotions indicates how emotions felt in different individuals about a certain considered decision option mutually affect each other, and, assuming a context of somatic marking, in this way affect how by individuals decision options are valuated in relation to how they feel about them. A second way in which a mirroring function relates to decision making is by applying it to the mirroring of intentions or action tendencies of individuals for the respective decision options. This may work when by verbal and/or nonverbal behaviour, individuals show in how far they tend to choose for a certain option. For example, in ([9], p.70) action tendencies are described as 'states of readiness to execute a given kind of action, [which] is defined by its end result aimed at or achieved'. In the computational model introduced below both of these (emotion and intention) mirroring effects are incorporated in the proposed model.

3 The Computational Model for Group Decision Making

In this section, based on the neurological principles of somatic marking and mirroring discussed in the previous section, the computational model for group decision making is introduced. To design such a model a choice has to be made for the grain-size: for example, it has to be decided in which level of detail the internal neurological processes of individuals are described. Such a choice depends on the aim of the model. In this case the aim was more to be able to simulate emerging patterns in groups of individuals, than to obtain a more detailed account of the intermediate neurological patterns and states involved. Therefore the choice was made to abstract to a certain extent from the latter types of intermediate processes. For example, the process of mirroring is described in an abstract manner by a direct causal relation from the emotional state shown by an individual to the emotional state shown by another individual, and the process of somatic marking is described by a direct causal relation from the emotional state shown for a certain option to the intention shown for this option (see Figure 1). These choices provide a model that is easier to handle for larger numbers of individuals. However, the model can easily be refined into a model that also incorporates more detailed intermediate internal processes, for example, based on recursive as-if body loops involving preparation and sensory neuron activations and the states of feeling the emotion, as shown in [13].

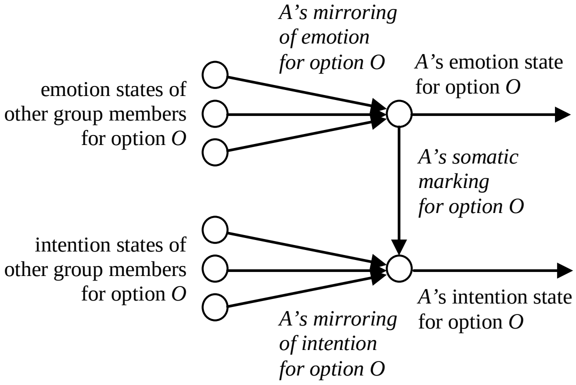

Fig. 1. Abstract causal relations induced by mirroring and somatic marking by person *A*

First for a given state *S* of a person (for example, an emotion or an intention) the impact due to the person's mirroring function is described. This is done by a basic building block called the contagion strength for any particular state *S* between two individuals within a group. This contagion strength from person *B* to person *A* for state *S* is defined as follows:

$$\gamma_{SBA} = \quad \varepsilon_{SB} \cdot \alpha_{SBA} \cdot \delta_{SA} \qquad \textbf{(1)}$$

Here ε_{SB} is the personal characteristic *expressiveness* of the sender (person *B*) for *S*, δ_{SA} the personal characteristic *openness* of the receiver (person *A*) for *S*, and α_{SBA} the interaction characteristic *channel strength* for *S* from sender *B* to receiver *A*. The expressiveness describes the strength of expression of given internal states by verbal and/or nonverbal behaviour (e.g., body states). The openness describes how strong stimuli from outside are propagated internally. The channel strength depends on the type of connection between the two persons, for example their closeness.

To determine the level $q_{SA}(t)$ of an agent *A* for a specific state *S* the following model is used. First, the overall contagion strength γ_{SA} from the group towards agent *A* is calculated:

$$\gamma_{SA} = \Sigma_{B \neq A}\, \gamma_{SBA} \qquad \textbf{(2)}$$

This value is used to determine the weighed impact $q_{SA}^*(t)$ of all the other agents upon state *S* of agent *A*:

$$q_{SA}^*(t) \;=\; \Sigma_{B \neq A}\, \gamma_{SBA} \cdot q_{SB}(t) \;/\; \gamma_{SA} \qquad \textbf{(3)}$$

How much this external influence actually changes state *S* of the agent *A* is determined by two additional personal characteristics of the agent, namely the tendency η_{SA} to absorb or to amplify the level of a state and the bias β_{SA} towards positive or negative impact for the value of the state. The model to update the value of $q_{SA}(t)$ over time is then expressed as follows:

$$q_{SA}(t + \Delta t) = q_{SA}(t) + \gamma_{SA} \cdot [\eta_{SA} \cdot [\beta_{SA} \cdot (1 - (1-q_{SA}*(t)) \cdot (1-q_{SA}(t))) + (1 - \beta_{SA}) \cdot q_{SA}*(t) \cdot q_{SA}(t)] + (1 - \eta_{SA}) \cdot q_{SA}*(t) - q_{SA}(t)] \Delta t \quad (4)$$

Here the new value of the state is the old value, plus the change of the value based on the contagion. This change is defined as the multiplication of the contagion strength times a factor for the amplification of information plus a factor for the absorption of information. The absorption part (after $1 - \eta_{SA}$) simply considers the difference between the incoming contagion and the current level for S. The amplification part (after η_{SA}) depends on the tendency or bias of the agent towards more positive (part of equation multiplied by β_{SA}) or negative (part of equation multiplied by $1 - \beta_{SA}$) level for S. Table 1 summarizes the most important parameters and state variables within the model (note that the last two parameters will be explained below).

Table 1. Parameters and state variables

$q_{SA}(t)$	level for state S of agent A at time t
ε_{SA}	extent to which agent A expresses state S
δ_{SA}	extent to which agent A is open to state S
η_{SA}	tendency of agent A to absorb or amplify state S
β_{SA}	positive or negative bias of agent A on state S
α_{SBA}	channel strenght for state S from sender B to receiver A
γ_{SBA}	contagion strength for S from sender B to receiver A
ω_{OIA}	weigth for group intention impact on agent A 's intention for O
ω_{OEA}	weigth for own emotion impact on agent A 's intention for O

The abstract model for mirroring described above applies to both emotion and intention states S or an option O, but does not describe any interplay between them yet. Taking the Somatic Marker Hypothesis on decision making as a point of departure, not only intentions of others, but also one's own emotions affect one's own intentions. To incorporate such an interaction, the basic model is extended as follows: to update $q_{SA}(t)$ for an intention state S relating to an option O, both the intention states of others for O and the $q_{S'A}(t)$ values for the emotion state S' for O are taken into account. These intention and emotion states S and S' for option O are denoted by OI and OE, respectively:

Level of emotion for option O of person A: $q_{OEA}(t)$
Level of intention indication for O of person A: $q_{OIA}(t)$

The combination of the own (positive) emotion level and the rest of the group's aggregated intention is made by a weighted average of the two:

$$q_{OIA}**(t) = (\omega_{OIA}/\omega_{OA})\, q_{OIA}*(t) + (\omega_{OEA}/\omega_{OA})\, q_{OEA}(t)$$
$$\gamma_{OIA}* = \omega\, \gamma_{OIA} \quad (5)$$

where ω_{OIA} and ω_{OEA} are the weights for the contributions of the group intention impact (by mirroring) and the own emotion impact (by somatic marking) on the intention of A for O, respectively, and $\omega_{OA} = \omega_{OIA} + \omega_{OEA}$. Then the model for the intention and emotion contagion based on mirroring and somatic marking becomes:

$$q_{OEA}(t + \Delta t) = q_{OEA}(t) + \gamma_{OEA}[\eta_{OEA}(\beta_{OEA} (1 - (1-q_{OEA}^*(t))(1-q_{OEA}(t))) + (1-\beta_{OEA})\, q_{OEA}^*(t)\; q_{OEA}(t)) + (1 - \eta_{OEA})\, q_{OEA}^*(t) - q_{OEA}(t)\;] \cdot \Delta t \quad (6)$$

$$q_{OIA}(t + \Delta t) = q_{OIA}(t) + \gamma_{OIA}^* [\eta_{OIA} (\beta_{OIA} (1 - (1-q_{OIA}^{**}(t))(1-q_{OIA}(t))) + (1-\beta_{OIA})\, q_{OIA}^{**}(t)\; q_{OIA}(t)) + (1 - \eta_{OIA})\, q_{OIA}^{**}(t) - q_{OIA}(t)] \cdot \Delta t \quad (7)$$

4 Simulation Results

The model has been studied in several scenarios in order to examine whether the proposed approach indeed exhibits the patterns that can be expected from literature. The investigated domain consists of a group of four agents who have to make a choice between four different options: A, B, C or D. The model has been implemented in Matlab by constructing three different scenarios which are characterized by different relationships (i.e., channel strength) between the agents. The scenarios used, involve two more specific types of agents: leaders and followers. Some agents have strong leadership abilities while others play a more timid role within the group. The general characteristics of leaders and followers as they were used in the experiments, which can be manifested differently within all agents, can be found in Table 2.

Table 2. Parameters and state variables for leaders and followers

	Leader *A*	**Follower *B***
emotion level	q_{OEA} high for particular O	-
intention level	q_{OIA} high for particular O	-
expressivity	ε_{SA} high	ε_{SB} low
channel strength	α_{SAB} high	α_{SAB} high
	α_{SBA} low	α_{SBA} low

The different scenarios are depicted in Figure 2. Scenario 1 consists of a group of agents in which agent1 has strong leadership abilities and high channel strengths with all other agents. His initial levels of emotion and intention for option A, are very high. Scenario 2 depicts a situation where there are two agents with leadership abilities in the group, agent1 and agent4. Agent1 has strong channel strength to agent2, while agent4 has a strong connection to agent3. Agent1 has an initial state of high (positive) emotion and intention for option A, while agent4 has strong emotion and intention states for option D. Agent2 and agent3 have show no strong intentions and emotions for any of the options in their initial emotion and intention states. In Scenario 3 there are no evident leaders. Instead, all agents have moderate channel strengths with each other. A majority of the agents (agent3 and agent4) prefers option C, i.e., initially they have high intention and emotions states for option C. For both scenarios two variants have been created, one with similar agent characteristics within the group (besides the difference between leader and follower characteristics), and the second with a greater variety of agent personalities. In this section, only the main results using the greater variety in agent characteristics are shown for the sake of brevity. For the formal verification (Section 6) both have been used.

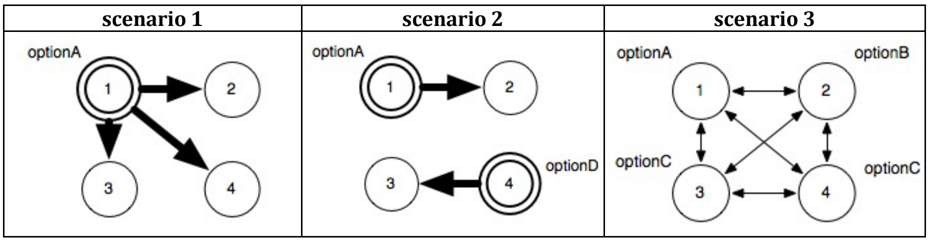

Fig. 2. Scenarios for the presented simulation experiments

The results of scenario 1 clearly show how one influential leader can influence the emotions and intention in a group. This is shown in the left graph of Figure 3, here the z-axis shows the value for the respective states, and the x-and y-axes represent time and the various agents. The emotion and intention of the leader (in this case agent1) spread through the network of agents, while the emotions and intentions of other agents hardly spread. Consequently, the emotions and intentions for option A, which is the preferred option of the leader, develop to be high in all agents. As can be seen in the figure, there are small differences between the developments of emotions and intentions of the agents. This is because they have different personality characteristics, which are reflected in the settings for the scenario[1]. Depending on their openness, agents are more or less influenced by the states of others. Those agents with low openness (such as agent4) are hardly influenced by intentions and emotions of others.

In scenario 2 (as shown in the right graph of Figure 3), the leader has somewhat

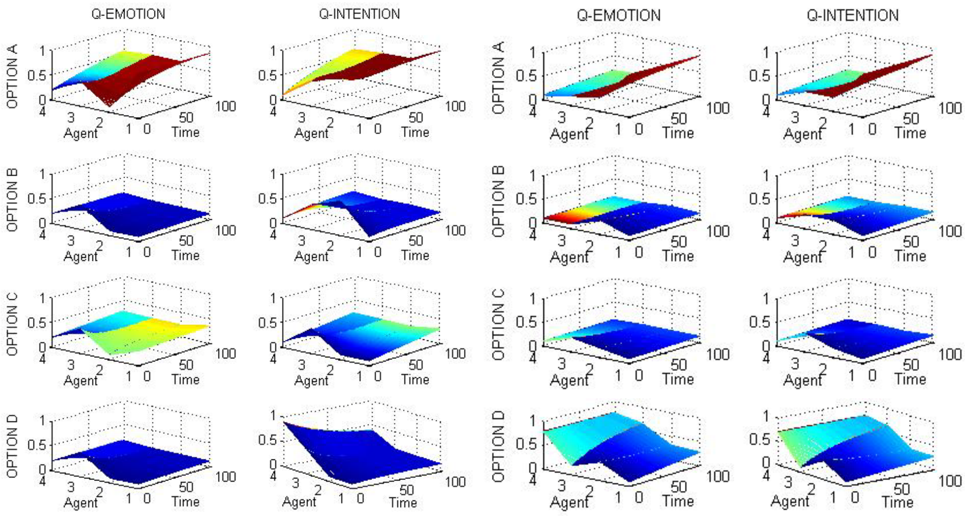

Fig. 3. Simulation results for scenario 1 (left) and scenario 2 (right)

[1] A full description of the characteristics and different parameter setting of the agents can be found in Appendix A: http://www.cs.vu.nl/~wai/Papers/group_decisions_appendix1.pdf

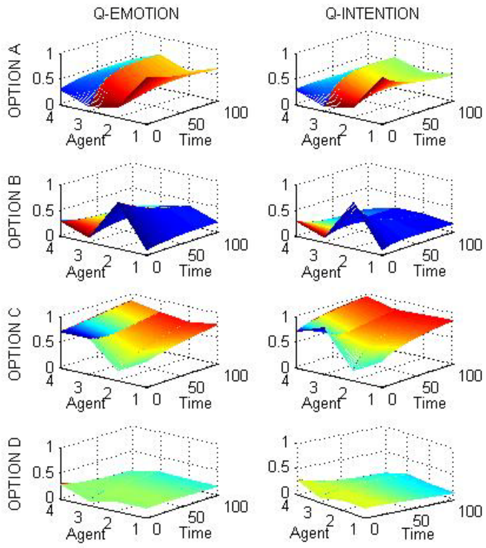

Fig. 4. Simulation results for scenario 3

positive emotions about option C as well, which explains the small but increasing spread of emotions (and after a while also intentions) concerning option C through the social network. Even though agent3 and agent2 both have a moderate intention for option B, their only strong channel strength is with each other, causing only some contagion between the two of them. Their intention does not spread because of a low expressive nature and low amplification rate of both agents. The patterns found in the simulation of scenario 2 are similar to the ones of scenario 1, with the addition that both leaders highly dominate the spread of the emotions and intentions. The figure shows that the emotions and intentions of agent2 turn out to depend highly on the emotions and intentions of agent1, whereas the emotions and intentions of agent3 highly depend on those of agent4. As can be seen in the figure, any preferences for option D and C by agent2 and agent3 quickly grow silent.

Scenario 3 shows how a group converges to the same high emotions and intentions for an option when there is no authority. In general, the graphs show that when there is no clear leadership, the majority determines the option with highest emotion and intentions in all agents. Option C, initially preferred by agent4 and agent3, eventually is the preferred option for all. However, the emotions and intentions for option A also spread and increase, though to a lesser extent. This is due to the fact that agent1 has strong feelings and intentions for option A and a high amplification level for these states. Furthermore, he has a significant channel strength with agent3, explaining why agent3 has the most increasing emotions and intentions for option A. However, the majority has the most important vote in this scenario.

Furthermore, some general statements can be made about the behaviour of the model. In case a leader has high emotions but low intentions for a particular option, both the intentions and emotions of all followers will increase for that option. On the other hand, if a leader has high intentions for a particular option, but not high emotions for that option, this intention will not spread to other agents.

5 Mathematical Analysis of Equilibria

During simulations it turns out that eventually equilibria are reached: all variables approximate values for which no change occurs anymore. Such equilibrium values can also be determined by mathematical analysis of the differential equations for the model:

$$dq_{OEA}(t)/dt = \gamma_{OEA}[\eta_{OEA}(\beta_{OEA}(1 - (1-q_{OEA}^*(t))(1-q_{OEA}(t))) + (1-\beta_{OEA})\, q_{OEA}^*(t)\; q_{OEA}(t)) + (1 - \eta_{OEA})\, q_{OEA}^*(t) - q_{OEA}(t)\;] \cdot \Delta t \quad \textbf{(8)}$$

$$dq_{OIA}(t)/dt = \gamma_{OIA}^* [\eta_{OIA}(\beta_{OIA}(1 - (1-q_{OIA}^{**}(t))(1-q_{OIA}(t))) + (1-\beta_{OIA})\, q_{OIA}^{**}(t)\; q_{OIA}(t)) + (1 - \eta_{OIA})\, q_{OIA}^{**}(t) - q_{OIA}(t)] \cdot \Delta t \quad \textbf{(9)}$$

Putting $dq_{OEA}(t)/dt = 0$ and $dq_{OIA}(t)/dt = 0$ and assuming γ_{OEA} and γ_{OIA}^* nonzero, provides the following equilibrium equations for each agent *A*.

$$\eta_{OEA}(\beta_{OEA}(1-(1-q_{OEA}^*)(1-q_{OEA})) + (1-\beta_{OEA})\, q_{OEA}^*\, q_{OEA}) + (1 - \eta_{OEA})\, q_{OEA}^* - q_{OEA} = 0 \quad \textbf{(10)}$$

$$\eta_{OIA}(\beta_{OIA}(1-(1-q_{OIA}^{**})(1-q_{OIA})) + (1-\beta_{OIA})\, q_{OIA}^{**}\, q_{OIA}) + (1 - \eta_{OIA})\, q_{OIA}^{**} - q_{OIA} = 0 \quad \textbf{(11)}$$

For given values of the parameters η_{OEA}, β_{OEA}, η_{OIA}, and β_{OIA} , these equations may be solved analytically or by standard numerical approximation procedures. Moreover, by considering when $dq_{OEA}(t)/dt > 0$ or $dq_{OEA}(t)/dt < 0$ one can find out when $q_{OEA}(t)$ is strictly increasing and when strictly decreasing, and similarly for $q_{OIA}(t)$. For example, for equation (2), one of the cases considered is the following.

Case $\eta_{OIA} = 1$ and $\beta_{OIA} = 1$

For this case, equation (2) reduces to $(1-(1-q_{OIA}^{**})(1-q_{OIA})) - q_{OIA} = 0$. This can easily be rewritten via $(1- q_{OIA}) -(1-q_{OIA}^{**})(1-q_{OIA}) = 0$ into $q_{OIA}^{**}(1-q_{OIA}) = 0$. From this, it can be concluded that equilibrium values satisfy $q_{OIA}^{**}= 0$ or $q_{OIA} = 1$, and q_{OIA} is never strictly decreasing, and is strictly increasing when $q_{OIA}^{**} > 0$ and $q_{OIA} < 1$. Now the condition $q_{OIA}^{**} = 0$ is equivalent to

$$(\omega_{OIA}/\omega_{OA})\, q_{OIA}^* + (\omega_{OEA}/\omega_{OA})\, q_{OEA} = 0 \;\Leftrightarrow$$
$$q_{OIA}^* = 0 \text{ if } \omega_{OIA} > 0 \text{ and } q_{OEA} = 0 \text{ if } \omega_{OEA} > 0$$

where $q_{OIA}^* = 0$ is equivalent to $\sum_{B\neq A} \gamma_{OIBA} \cdot q_{OIB} / \gamma_{OIA} = 0 \;\Leftrightarrow\; q_{OIB} = 0$ for all $B\neq A$ with $\gamma_{OIBA} > 0$. Assuming both ω_{OIA} and ω_{OEA} nonzero, this results in the following:

equilibrium: $q_{OIA} = 1$ or $q_{OIA} < 1$ and $q_{OEA} = 0$ and $q_{OIB} = 0$ for all $B\neq A$ with $\gamma_{OIBA} > 0$
strictly increasing: $q_{OIA} < 1$ and $q_{OEA} > 0$ or $q_{OIB} > 0$ for some $B\neq A$ with $\gamma_{OIBA} > 0$

For a number of cases such results have been found, as summarised in Table 3. This table considers any agent *A* in the group. Suppose *A* is the agent in the group with highest q_{OEA}, i.e., $q_{OEB} \leq q_{OEA}$ for all $B\neq A$. This implies that $q_{OEA}^* = \sum_{B\neq A} \gamma_{OEBA} \cdot q_{OEB} / \gamma_{OEA} \leq \sum_{B\neq A} \gamma_{OEBA} \cdot q_{OEA} / \gamma_{OEA} = q_{OEA} \sum_{B\neq A} \gamma_{OEBA} / \gamma_{OEA} = q_{OEA}$. So in this case always $q_{OEA}^* \leq q_{OEA}$. Note that when $q_{OEB} < q_{OEA}$ for some $B\neq A$ with $\gamma_{OEBA} > 0$, then $q_{OEA}^* = \sum_{B\neq A} \gamma_{OEBA} \cdot q_{OEB} / \gamma_{OEA} < \sum_{B\neq A} \gamma_{OEBA} \cdot q_{OEA} / \gamma_{OEA} = q_{OEA} \sum_{B\neq A} \gamma_{OEBA} \cdot / \gamma_{OEA} = q_{OEA}$. Therefore $q_{OEA}^* = q_{OEA}$ implies $q_{OEB} = q_{OEA}$ for all $B \neq A$ with $\gamma_{OEBA} > 0$. Similarly, when *A* has the lowest q_{OEA} of the group, then always $q_{OEA}^* \geq q_{OEA}$ and again $q_{OEA}^* = q_{OEA}$ implies

$q_{OEB} = q_{OEA}$ for all $B \neq A$ with $\gamma_{OEBA} > 0$. This implies, for example, for $\eta_{OEA} = 1$ and $\beta_{OEA} = 0.5$, assuming nonzero γ_{OEBA}, that always for each option the members' emotion levels for option *O* will converge to one value in the group (everybody will feel the same about option *O*).

Table 3. Equilibria cases for an agent A with both $\omega_{OEA} > 0$, $\omega_{OIA} > 0$, and $\gamma_{OEBA} > 0$ for all *B*

		$\boldsymbol{\eta_{OIA} = 1}$ $\boldsymbol{\beta_{OIA} = 1}$		$\boldsymbol{\eta_{OIA} = 1}$ $\boldsymbol{\beta_{OIA} = 0.5}$	$\boldsymbol{\eta_{OIA} = 1}$ $\boldsymbol{\beta_{OIA} = 0}$	
		$q_{OIA} = 1$	$q_{OIA} < 1$ $q_{OEA} = 0$ $q_{OIB} = 0$ for all $B \neq A$	$q_{OIA}^{**} = q_{OIA}$	$q_{OIA} = 0$	$q_{OIA} > 0$ $q_{OEA} = 1$ $q_{OIB} = 1$ for all $B \neq A$
$\boldsymbol{\eta_{OEA} = 1}$ $\boldsymbol{\beta_{OEA} = 1}$	$q_{OEA} = 1$	$q_{OEA} = 1$ $q_{OIA} = 1$	none	$q_{OEA} = 1$ $q_{OIA}^{**} = q_{OIA}$	$q_{OEA} = 1$ $q_{OIA} = 0$	$q_{OEA} = 1$ $q_{OIA} > 0$ $q_{OIB} = 1$ for all $B \neq A$
	$q_{OEA} < 1$ $q_{OEB} = 0$ for all $B \neq A$	$q_{OEA} < 1$ $q_{OIA} = 1$ $q_{OEB} = 0$ for all $B \neq A$	$q_{OEC} = 0$ for all *C* $q_{OIA} < 1$ $q_{OIB} = 0$ for all $B \neq A$	$q_{OEA} < 1$ $q_{OIA}^{**} = q_{OIA}$ $q_{OEB} = 0$ for all $B \neq A$	$q_{OEA} < 1$ $q_{OIA} = 0$ $q_{OEB} = 0$ for all $B \neq A$	none
$\boldsymbol{\eta_{OEA} = 1}$ $\boldsymbol{\beta_{OEA} = 0.5}$	$q_{OEA}^{*} = q_{OEA}$	$q_{OEA}^{*} = q_{OEA}$ $q_{OIA} = 1$	$q_{OEC} = 0$ for all *C* $q_{OIA} < 1$ $q_{OIB} = 0$ for all $B \neq A$	$q_{OEA}^{*} = q_{OEA}$ $q_{OIA}^{**} = q_{OIA}$	$q_{OEA}^{*} = q_{OEA}$ $q_{OIA} = 0$	$q_{OEC} = 1$ for all *C* $q_{OIA} > 0$ $q_{OIB} = 1$ for all $B \neq A$
$\boldsymbol{\eta_{OEA} = 1}$ $\boldsymbol{\beta_{OEA} = 0}$	$q_{OEA} = 0$	$q_{OEA} = 0$ $q_{OIA} = 1$	$q_{OEA} = 0$ $q_{OIA} < 1$ $q_{OIB} = 0$ for all $B \neq A$	$q_{OEA} = 0$ $q_{OIA}^{**} = q_{OIA}$	$q_{OEA} = 0$ $q_{OIA} = 0$	none
	$q_{OEA} > 0$ $q_{OEB} = 1$ for all $B \neq A$	$q_{OEA} > 0$ $q_{OIA} = 1$ $q_{OEB} = 1$ for all $B \neq A$	none	$q_{OEA} > 0$ $q_{OIA}^{**} = q_{OIA}$ $q_{OEB} = 1$ for all $B \neq A$	$q_{OEA} > 0$ $q_{OIA} = 0$ $q_{OEB} = 1$ for all $B \neq A$	$q_{OIA} > 0$ $q_{OEC} = 1$ for all *C* $q_{OIB} = 1$ for all $B \neq A$

6 Verifying Properties Specifying Emerging Patterns

This section addresses the analysis of the group decision making model by specification and verification of properties expressing dynamic patterns that emerge. The purpose of this type of verification is to check whether the model behaves as it should, by automatically verifying such properties against the simulation traces for the various scenarios. In this way the modeller can easily detect inappropriate behaviours and locate sources of errors in the model. A typical example of a property that may be checked, is whether no unexpected situations occur, such as a variable running out of its bounds (e.g., $q_A(t) > 1$, for some time point t and agent *A*), or whether eventually an equilibrium value is reached, but also more detailed expected properties of the model such as compliance to the theories found in literature.

A number of dynamic properties have been identified, formalized in the Temporal Trace Language (TTL), cf. [2] and automatically checked. The TTL software environment includes a dedicated editor supporting specification of dynamic properties to obtain a formally represented temporal predicate logical language TTL formula. In addition, an automated checker is included that takes such a formula and a set of traces as input, and verifies automatically whether the formula holds for the traces. The language TTL is built on atoms referring to *states* of the world, *time points* and *traces*, i.e. trajectories of states over time. In addition, *dynamic properties* are temporal predicate logic statements that can be formulated with respect to traces based on a state ontology.

Below, a number of the dynamic properties that were identified for the group decision making model are introduced, both in semi-formal and in informal notation (where state(γ, t) |= p denotes that p holds in trace γ at time *t*). The first property counts the number of subgroups that are present. Here, a subgroup is defined as a group of agents having the same highest intention. Each agent has 4 intention values (namely one for each of the four options that exist), therefore the number of subgroups that can emerge are always: 1, 2, 3 or 4 subgroups.

P1 –number of subgroups

The number of subgroups in a trace γ is the number of options for which there exists at least one agent that has an intention for this option as its highest valued intention.

P1_number_of_subgroups(γ:TRACE) ≡ sum(I:INTENTION, case(highest_intention(γ, I), 1, 0)

where

highest_intention(γ:TRACE, I:INTENTION) ≡
∃A:AGENT [∀R1:REAL state(γ, te) |= has_value(A, I, R1)
⇒ ∀I2:INTENTION≠I, ∀R2:REAL [state(γ, te) |= has_value(A, I2, R2) ⇒ R2 < R1]]

In this property, the expression case(p, 1, 0) in TTL functions such that if property p holds it is evaluated to the second argument (*1* in this example), and to the third argument (*0* in this example) if the property does not hold. The sum operator simply adds these over the number of elements in the sort over which the sum is calculated (the intentions in this case). Furthermore, when tb or te are used in the property, they denote the begin or end time of the simulation, whereby in te an equilibrium is often reached. Property P1 can be used to count the number of subgroups that emerge. A subgroup is defined as a group of agents that each have the same intention as their intention with highest value. This property was checked on multiple traces that each belong to one of the three scenario's discussed in the simulation results section. For the traces for both variants of scenario 1: , a single subgroup was found, for scenario 2: two subgroups were found, and for scenario 3, a single subgroup was found, which is precisely according to the expectations.

The second property counts the number of agents in each of the subgroups, using a similar construct.

P2– subgroup size

The number of agents in a subgroup for intention I is the number of agents that have this intention as their highest intention.

P2_subgroup_size(γ:TRACE, I:INTENTION) ≡ sum(A:AGENT, case(highest_intention_for(γ, I, A), 1, 0))

where

highest_intention_for(γ:TRACE, I:INTENTION, A:AGENT) ≡
∀R1:REAL [state(γ, te) |= has_level(A, I, R1)
⇒ ∀I2:OPTION≠I, ∀R2:REAL [state(γ, te) |= has_level(A, I2, R2) ⇒ R2 < R1]]

In the traces for scenario1 the size of the single subgroup that occurred was 4 agents. For scenario 2 two subgroups of 2 agents were found. Finally, in scenario 3 only a single subgroup combining 4 agents has been found. These findings are correct; they indeed correspond to the simulation results.

The final property, P3, expresses that an agent is a leader in case its intention values have changed the least over the whole simulation trace, as seen from his initial intention values and compared to the other agents (thereby assuming that these agents moved towards the intention of the leader that managed to convince them of this intention).

P3–leader

An agent is considered a leader in a trace if the number of intentions for which it has the lowest change is at least as high as all other agents.

P3_leader (γ:TRACE, A:AGENT) ≡
∀A2:AGENT ≠A
sum(I:INTENTION, case(leader_for_intention(γ, A, I),1,0)) ≥
sum(I:INTENTION, case(leader_for_intention(γ, A2, I),1,0))

where

leader_for_intention(M:TRACE, A:AGENT, I:INTENTION) ≡
∀R1, R2: REAL [[state(γ, tb) |= has_value(A,I, R1) & state(γ, te) |= has_value(A, I, R2)]
⇒ ∀R3, R4: REAL, ∀A2:AGENT ≠A
[state(γ, tb) |= has_value (A2, I, R4) & state(γ, te) |= has_value (A2, I, R3)
⇒ |R2-R1|< |R3-R4|]]

Using this definition, only agent 1 qualifies as a leader in scenario 1. For scenario 2 only agent 4 is a leader. Finally, in scenario 3 both agent 1 and agent 3 are found to be leaders as they both have equal intentions for which they change the least.

7 Discussion

In this paper, an approach has been presented, to model the emergence of group decisions. The current model has been based on the neurological concept of mirroring (see e.g. [12], [18]) in combination with the Somatic Marker Hypothesis of Damasio (cf. [1], [3], [5], [6]). An existing model of emotion contagion (cf. [8]) was taken as inspiration, and has been generalised to contagion of both emotions and intentions, and extended with interaction between the two, in the form of influences of emotions upon intentions. Several scenarios have been simulated by the model to investigate the emerging patterns, and also to look at leadership of agents within groups. The results of these simulation experiments show patterns as desired and expected. In order to be able to make this claim more solid, both a mathematical analysis as well as a formal verification of the simulation traces have been performed, showing that the model indeed behaves properly.

For future work, an interesting element would be to scale up the simulations and investigate the behaviour of agents in larger scale simulations. Furthermore, modelling a more detailed neurological model is also part of future work, thereby defining an abstraction relation mapping between this detailed level model and the current model.

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