

A Multi-Agent Model for Emotion Contagion Spirals Integrated within a Supporting Ambient Agent Model

Tibor Bosse¹, Rob Duell², Zulfiqar A. Memon^{1,3},
Jan Treur¹, C. Natalie van der Wal^{1,2}

¹Vrije Universiteit Amsterdam, Department of Artificial Intelligence
De Boelelaan 1081, 1081 HV Amsterdam, The Netherlands

²Force Vision Lab, Barbara Strozilaan 362a, 1083 HN Amsterdam, The Netherlands

³Sukkur Institute of Business Administration (SIBA),
Airport Road Sukkur, Sindh, Pakistan
{tbosse, rduell, zamemon, treur, cw1210}@few.vu.nl

Abstract This paper uses an agent-based approach to formalize and simulate emotion contagion spirals within groups. The computational multi-agent model is integrated within an intelligent ambient agent to monitor and predict group emotion levels over time and propose group support actions based on that.

Keywords: multi-agent model, emotion contagion spirals, ambient agent model.

1 Introduction

The occurrence of emotion contagion spirals in groups is a social phenomenon, where levels of emotion occur that may substantially exceed the original emotion levels of group members. How to avoid such spirals for negative emotions and how to stimulate them for positive emotions can be a real challenge for both group members and group leaders. This paper first presents an analysis and a computational model for the occurrence of emotion contagion spirals in groups. Next, it is shown how this model has been integrated within an ambient agent model to support group leaders. The ambient agent can predict and analyze the team's emotional level for present and future time points. In case a team's emotional level is found (to become) deficient compared to a certain norm, the ambient agent proposes the team leader to take some measures.

Emotions allow humans to respond quickly and efficiently to events that affect their welfare [15]. In addition, they provide us with information about others' behavioral intentions, and script our social behavior. Research on the idea that emotion also has a strong social component, which can influence interactions, is found in, e.g. [12], [13]. The process of emotion contagion, in which a group member influences the emotions of another group member (and vice versa), through the conscious or unconscious induction of emotion states [21], is a primary mechanism through which individual emotions create a collective emotion. This process has been described as an inclination to mimic the gestural behavior of others, to "synchronize facial expression, utterances and attitudes" [13]. Emotion contagion has been shown to occur in many cases varying from emotions in small groups to panicking crowds; see [1], [23], [16]. The positive effects of the spread of emotions in groups have been investigated empirically in [9], where it is hypothesized that positive emotions trigger upward spirals toward enhanced emotional well-being. This prediction is based on Frederickson's broaden-and-build theory [10]. The broaden hypothesis states that positive emotions broaden people's mind-sets: the scopes of attention, cognition, action and the array of percepts, thoughts, and actions

presently in mind are widened. The complementary narrowing hypothesis predicts the reverse pattern: negative emotions shrink people’s thought-action repertoires. Support for the broaden and narrowing hypotheses can be found in [8]. The build hypothesis expresses that positive emotions encourage people to discover and explore new ways of thinking and action, by which they are building their personal resources such as socio-emotional and, intellectual skills. The broaden hypothesis can predict upward spirals in emotional well-being of a person, which the authors investigated in [9]. The authors demonstrated that initial experiences with positive affect can improve broad-minded-coping, which in turn can predict increases in positive affect over time, creating an upward spiral towards improved emotional well-being.

This paper first introduces a multi-agent model that formalizes and simulates emotion contagion spirals within groups. Next it is shown how this computational model can be used in applications within a teamwork context, supported by an intelligent ambient agent. Section 2 explains a formalized model of group emotion contagion spirals. Next, in Section 3, simulation results for this model are presented and in Section 4, the model is analyzed mathematically. Section 5 addresses formal verification of the emotion contagion spirals model and the simulation results. Section 6 describes how the model for emotion contagion spirals has been integrated within an existing ambient agent model. In Section 7 some simulation results are discussed for the resulting ambient agent model. Section 8 is a discussion.

2 The Emotion Contagion Spiral Model

The model introduced in this paper distinguishes multiple factors that influence emotion contagion spirals. In [1] (following [16]) Barsade describes an informal model of emotion contagion in which the emotion being expressed and transferred between group members is characterized by the valence (positive or negative) and the energy level with which the emotion is expressed. Furthermore Barsade [1] suggests two categories of contagion mechanisms: automatic subconscious contagion through mimicry and feedback and conscious transfer through social comparison of moods and appropriate responses in groups, mediated by attention. Regardless of the mechanisms employed, it is claimed that the type of emotion and the degree of emotion contagion in groups, is influenced by the emotional valence and the emotional energy.

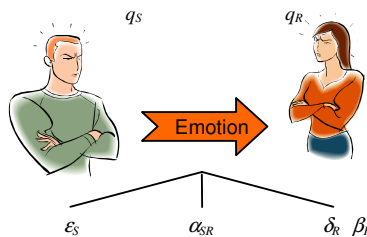


Figure 1: Aspects of Emotion Contagion Spirals

Inspired by these theories, in this section a computational model of emotion contagion spirals is proposed. First a number of aspects are distinguished that play a role in the contagion spirals, varying from aspects related to the sender, the channel between sender and receiver and the receiver of the transferred emotion. Accordingly, the model distinguishes three parts in the process of transfer of emotion and related parameters: a sender S , a receiver R , and the channel from S to R (see Fig. 1 and Table 1).

current level of the sender’s emotion	q_s	current level of the receiver’s emotion	q_r
extent to which the sender expresses the emotion	ε_s	openness or sensitivity for received emotion	δ_r
the strength of the channel from sender to receiver	α_{sR}	tendency to adapt emotions upward or downward	β_r

Table 1: Parameters for aspects of emotion contagion spirals

The aspect ε_s depends on how introvert or extravert, expressive, active and energetic the person is. It represents the degree to which a person transforms internal emotion into external expression. In this sense, an introvert person will induce a weaker contagion of an emotion than an extravert person. The aspect α_{sR} depends on the type and intensity of the contact between the

two persons (e.g., distance vs attachment). The aspect δ_R indicates the degree of susceptibility of the receiver: the extent to which the receiver allows the emotions received from others to affect his own emotion, and how flexible/persistent the receiver is emotionally. The aspect β_R describes the tendency to amplify or reduce emotions, when triggered by received emotions.

As a first step, all aspects have been formalized numerically by numbers in the interval $[0, 1]$. In addition, the parameter γ_{SR} is used to represent the strength of which an emotion is received by R from sender S , modeled as: $\gamma_{SR} = \epsilon_S \alpha_{SR} \delta_R$ (1). The stronger the channel, the higher α_{SR} and the more contagion will take place. The model works as follows: if gamma is set to 0 there will be no contagion, if γ_{SR} is 1, there will be a maximum strength of contagion. If γ_{SR} is not 0, there will be contagion and the higher the value, the more contagion will take place. In this way, the parameter γ_{SR} can create the behavior as formulated by hypothesis (a) and (b) from [2]. In a way γ_{SR} expresses the energy level with which an emotion is being expressed and transferred. Interestingly this energy level γ_{SR} , depends on situational factors (processes and influences) at both group and individual level. The overall strength by which emotions from all the other group members are received by R in a group G , indicated by γ_R , is defined as $\gamma_R = \sum_{S \in G \setminus \{R\}} \gamma_{SR}$

The proposed model can simulate both upward and downward emotional spirals through mechanisms, with which not only an individual agent, but also the whole group of agents can get to a higher or lower level of emotion. Each agent transfers an emotion value q between 0 and 1. The model makes it possible for each agent in certain situations to approximate values like 0 and 1, or values in between. Thus it represents upward or downward spirals, where each of the agents will get to a higher or lower level over time. Each agent will reach its own emotional equilibrium within the group. Suppose G is a group of agents. The dynamics of an agent R 's emotion level is described as

$$dq_R/dt = \gamma_R [\beta_R PI + (1-\beta_R) NI - q_R] . \quad (2)$$

The upward or downward direction of the change in an agent R 's emotional level over time depends on parameter β_R , and the speed of the ascend or descend on parameter γ_R . Here

$$\gamma_R = \sum_{S \in G \setminus \{R\}} \gamma_{SR} . \quad (3)$$

with

$$\gamma_{SR} = \epsilon_S \alpha_{SR} \delta_R . \quad (4)$$

Furthermore, PI and NI are the positive and negative impact of received emotion from the other group members respectively, which will be specified in more detail below. The parameter β_R defines the overall impact as a weighted combination of the two contributions. By varying the values of the β_R 's, upward as well as downward spirals can be simulated. If $\beta_R = 1$ then the receiver is only susceptible for positive impact. If $\beta_R = 0$, then the receiver is only susceptible to negative impact. Any number between 0 and 1 represents a person who is more or less susceptible to positive and negative impact. E.g., if $\beta_R = 0.8$, the agent will be infected by 80% with PI and by 20% with NI . In more detail the positive and negative impacts of the other group members are defined as:

$$PI = 1 - (1-q_R^*) (1-q_R) . \quad (5)$$

$$NI = q_R^* q_R . \quad (6)$$

Here

$$q_R^* = \sum_{S \in G \setminus \{R\}} w_{SR} q_S . \quad (7)$$

is a weighted sum of the emotion levels of the other group members with weights

$$w_{SR} = \epsilon_S \alpha_{SR} / \sum_{C \in G \setminus \{R\}} \epsilon_C \alpha_{CR} . \quad (8)$$

By filling these in the equation (2), the detailed set of equations for group G is for all $R \in G$:

$$dq_R/dt = \gamma_R [\beta_R (1 - (1 - q_R^*) (1 - q_R)) + (1 - \beta_R) q_R^* q_R - q_R] . \quad (9)$$

Note that the model presented so far represents the emotional states of all agents within a group separately; the question of how these separate individual emotional states can be interpreted and aggregated by another agent, in order to assess the collective emotional state of a group, is addressed in Section 6.

3 Simulation Results for the Emotion Contagion Spiral Model

Inspired by the theory put forward in [9], the proposed model can simulate both upward and downward emotional spirals. A large number of simulations have been performed, using standard numerical simulation software, resulting in a variety of interesting patterns. In this section some of the simulation results are discussed. More simulation results can be found in Appendix A in [24]. The next section presents results of a mathematical analysis in which for most patterns their occurrence was proven, under certain conditions.

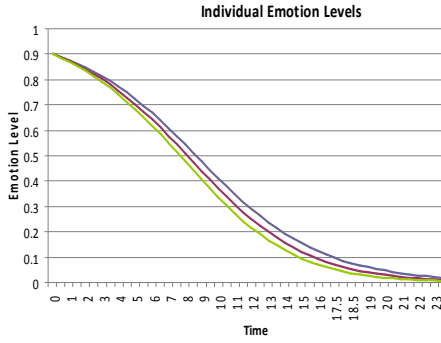


Figure 2: Simulation trace 1 (all $\beta=0$, all $\delta_i=0.6$, $\delta_b=0.7$, $\delta_c=0.8$, and all $w_{DC}=0.2$)

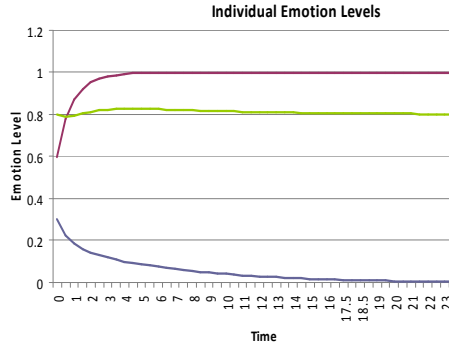


Figure 3: Simulation trace 2 ($\beta(a, b, c) = (0, 1, 0.8)$, all $\delta_R=0.9$, all $w_{DC}=0.9$)

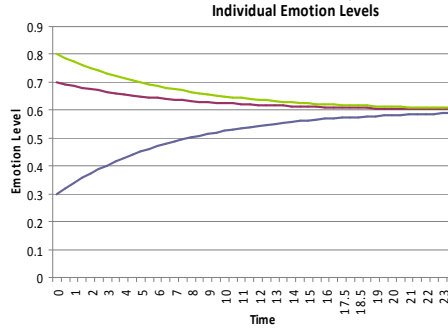


Figure 4: Simulation trace 3 (all $\beta=0.5$, all $\delta_R=0.1$, all $w_{DC}=0.9$)

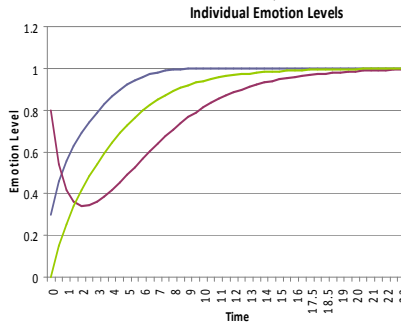


Figure 5: Simulation trace 4 ($\beta(a, b, c) = \beta(1, 0.3, 0.8)$, all $\delta_R=0.9$, $w_{ba}=0.625$, $w_{ca}=0.375$, $w_{ab}=0.64$, $w_{cb}=0.36$, $w_{ac}=0.4$, $w_{bc}=0.6$)

All simulations presented are for a group of 3 agents, infecting each other with the same emotion. A first pattern found is that when the β 's of all three agents are set to 0, the emotion levels of all of them will approximate 0, with speed depending on the δ_R (susceptibility) and ϵ_S α_{SR} (individual and group characteristics); see Fig. 2 (with time on the x-axis and emotion

strength on the y-axis). The reverse happens when all β 's are set to 1, then all agents will achieve an equilibrium of 1. The occurrence of these patterns have been proved mathematically in Theorem 2 discussed in the next section.

Another situation occurs when the three agents have their β 's set to: 0, 1 and any other number. A situation was simulated in which agent a is susceptible only with negative impact ($\beta = 0$), agent b is only susceptible with positive impact ($\beta = 1$), and agent c is susceptible to more positive than negative impact ($\beta = 0.8$). In Fig. 3, it is shown that in this case all equilibria match the agent's β . The speed of ascend or descend again depends on the susceptibility of the agent (setting of δ_R) and the situational factors at the individual and group level (represented by ϵ_S and α_{SR}). This illustrates the more general result expressed in Proposition 3, discussed in the next section. A next simulated situation (see Fig. 4) is one where all three agents are equally susceptible to positive and negative impact, by setting every agent's β to 0.5. In this situation all agents approximate equilibrium at 0.6; this equilibrium is the average of the initial emotional level. This simulation illustrates Theorem 3, discussed in the next section. In the next situation presented the settings are: $\beta(a, b, c) = \beta(1, 0.3, 0.8)$, as shown in Fig. 5. This represents a situation where agent a is only or fully susceptible to positive impact, agent b is susceptible more towards negative impact and agent c is more susceptible towards positive impact. Interestingly, agent b does not have equilibrium of 0 or below 0.5: all agents have equilibrium of 1. An indication for the height of the equilibrium could be the average β , which is 0.7 in this situation. This makes it possible to lift the emotional level of all group members to make the group-as-a-whole achieve an upward spiral [9]. In the mathematical analysis such behavior has been proved to occur (between two agents) in Theorem 4.

4 Mathematical Analysis for the Emotion Contagion Spiral Model

This section presents some of the results of a mathematical analysis of the model that has been made. More results and proofs can be found in Appendix B in [24]. First, the following conditions on monotonicity have been found.

Proposition 1 (Monotonicity Conditions)

- (a) If $\beta_A = 0$ then $q_A(t)$ is always monotonically decreasing; it is strictly decreasing when $q_A^*(t) < 1$ and $q_A(t) > 0$.
- (b) If $\beta_B = 1$ then $q_B(t)$ is always monotonically increasing; it is strictly increasing when $q_B^*(t) > 0$ and $q_B(t) < 1$.
- (c) If $\beta_A \leq 0.5$ and $q_A^*(t) \leq q_A(t)$ then $q_A(t)$ is monotonically decreasing; it is strictly decreasing when $q_A^*(t) < q_A(t)$.
- (d) If $\beta_B \geq 0.5$ and $q_B^*(t) \geq q_B(t)$ then $q_B(t)$ is monotonically increasing; it is strictly increasing when $q_B^*(t) > q_B(t)$.

Next, equilibria have been investigated. First, conditions have been established for the case of an equilibrium with one of the emotion values 0 or 1.

Proposition 2

Suppose all w_{SR} are nonzero. Then for an equilibrium the following holds:

- (a) If $q_A = 0$ then $\beta_A = 0$ or $q_C = 0$ for all C
- (b) If $q_B = 1$ then $\beta_B = 1$ or $q_C = 1$ for all C

Based on this, the following theorem provides the possibilities for equilibria concerning those subgroups with β is 0 or 1.

Theorem 1 (Equilibria for members for which β is 0 or 1)

Suppose all w_{SR} are nonzero. Let the two subsets $S_0, S_1 \subseteq G$ be given by

$$S_0 = \{ A \in G \mid \beta_A = 0 \} \quad S_1 = \{ B \in G \mid \beta_B = 1 \}$$

Then for an equilibrium the following holds:

- (a) If $A \in S_0$ then $q_A = 0$ or $q_C = 1$ for all $C \neq A$. If $B \in S_1$ then $q_B = 1$ or $q_C = 0$ for all $C \neq B$.
- (b) If $\#(S_0) \geq 2$, i.e., there are at least two members A_1 and A_2 with $\beta_{A_1} = 0$ and $\beta_{A_2} = 0$, then either $q_A = 0$ for all $A \in S_0$ or $q_C = 1$ for all $C \in G$.
- (c) If $\#(S_1) \geq 2$, i.e., there are at least two members B_1 and B_2 with $\beta_{B_1} = 1$ and $\beta_{B_2} = 1$, then either $q_B = 1$ for all $B \in S_1$ or $q_C = 0$ for all $C \in G$.
- (d) If $\#(S_0) \geq 2$ and $\#(S_1) \geq 2$, then there are three possibilities:
 - (i) $q_C = 0$ for all $C \in G$
 - (ii) $q_C = 1$ for all $C \in G$
 - (iii) $q_A = 0$ for all $A \in S_0$ and $q_B = 1$ for all $B \in S_1$

In the specific case, that for all group members β is 0 or 1, a complete classification of equilibria can be obtained; for an example, see Fig. 2.

Theorem 2 (Equilibria when all β 's are equal to 0 or 1)

Suppose all w_{SR} are nonzero and for all C it holds $\beta_C = 0$ or $\beta_C = 1$, in other words, the whole group G is partitioned into the two subsets

$$S_0 = \{ A \in G \mid \beta_A = 0 \} \text{ and } S_1 = \{ B \in G \mid \beta_B = 1 \}.$$

Then for an equilibrium the following hold:

- (a) If $S_0 = G$ and $S_1 = \emptyset$, i.e., $\beta_C = 0$ for all C , then either $q_C = 0$ for all C (attracting) or $q_C = 1$ for all C (non-attracting).
- (b) If $S_1 = G$ and $S_0 = \emptyset$, i.e., $\beta_C = 1$ for all C , then either $q_C = 0$ for all C (non-attracting) or $q_C = 1$ for all C (attracting).
- (c) If $\#(S_0) = \#(S_1) = 1$, i.e., there is exactly one member A with $\beta_A = 0$, and exactly one member B with $\beta_B = 1$, then there are two possibilities:
 - (i) $q_A = 0$ for $A \in S_0$ and q_B has any value for $B \in S_1$
 - (ii) $q_B = 1$ for $B \in S_1$ and q_A has any value for $A \in S_0$
- (d) If $\#(S_0) = 1$ and $\#(S_1) \geq 2$, i.e., there is exactly one member A with $\beta_A = 0$, and there are at least two members B_1 and B_2 with $\beta_{B_1} = \beta_{B_2} = 1$, then there are two possibilities:
 - (i) $q_C = 0$ for all $C \in G$
 - (ii) $q_B = 1$ for all $B \in S_1$ and q_A has any value for $A \in S_0$
- (e) If $\#(S_1) = 1$, and $\#(S_0) \geq 2$, i.e., there is exactly one member B with $\beta_B = 1$, and there are at least two members A_1 and A_2 with $\beta_{A_1} = \beta_{A_2} = 0$, then there are two possibilities:
 - (i) $q_C = 1$ for all $C \in G$
 - (ii) $q_A = 0$ for all $A \in S_0$ and q_B has any value for $B \in S_1$
- (f) If $\#(S_0) \geq 2$ and $\#(S_1) \geq 2$, i.e., there are at least two members A_1 and A_2 with $\beta_{A_1} = \beta_{A_2} = 0$ and also at least two members B_1 and B_2 with $\beta_{B_1} = \beta_{B_2} = 1$, then there are three possibilities:
 - (i) $q_C = 0$ for all $C \in G$
 - (ii) $q_C = 1$ for all $C \in G$
 - (iii) $q_A = 0$ for all $A \in S_0$ and $q_B = 1$ for all $B \in S_1$

For the specific case of three group members, where one member has β is 0, one has 1 and one has neither, the following holds; for an example, see Fig. 3.

Proposition 3 (A case for 3 members)

Consider a group G which consists of three members named by a, b, c with $\beta_a = 0$, $\beta_b = 1$, and $\beta_c = \beta$, where $0 < \beta < 1$ is assumed. Moreover, suppose all w_{SR} are nonzero. Then the following are the possibilities for equilibria:

- (i) $q_a = q_b = q_c = 0$
- (ii) $q_a = q_b = q_c = 1$
- (iii) $q_a = 0$, $q_b = 1$ and $q_c = \beta w_{bc} / ((1-\beta)w_{ac} + \beta w_{bc})$

In particular, when $w_{ac} = w_{bc}$, then the value for q_c in (iii) is β .

The following proposition shows that only in trivial cases a group member with β not 0 or 1 can reach 0 or 1.

Proposition 4 ($q_A = 0$ with $\beta_A > 0$ or $q_B = 1$ with $\beta_B < 1$)

Suppose all w_{SR} are nonzero. Then for an equilibrium it holds

- (i) If $q_A = 0$ for some A with $\beta_A > 0$ then $q_C = 0$ for all $C \in G$.
- (ii) If $q_B = 1$ for some B with $\beta_B < 1$ then $q_C = 1$ for all $C \in G$.

The case that all group member converge to an equal equilibrium value which is not 0 or 1, only occurs when all β 's are 0.5; for an example, see Fig. 4.

Theorem 3 (Equal equilibrium values for all members)

Suppose all w_{SR} are nonzero, then for an equilibrium the following are equivalent:

- (i) For some q with $0 < q < 1$ it holds $q_C = q$ for all C.
- (ii) For all C it holds $\beta_C = 0.5$.

For the case of two persons, a complete classification can be found, as shown in the following theorem.

Theorem 4 (The case of two persons)

Suppose the group consists of two persons named by a and b. Then for an equilibrium, there are the following possibilities:

- (i) When $\beta_a + \beta_b \neq 1$ the only two possibilities are:

$q_a = q_b = 0$	attracting when	$\beta_a + \beta_b < 1$
$q_a = q_b = 1$	attracting when	$\beta_a + \beta_b > 1$
- (ii) When $\beta_a + \beta_b = 1$ attracting equilibria occur where q_a and q_b get values between 0 and 1.

5 Formal Verification of the Emotion Contagion Spiral Model

This section addresses the analysis of the emotion contagion spiral model by verification of dynamic properties. Following [5], the dynamics of a model can be analyzed by specifying certain dynamic statements that are (or not) expected to hold in terms of temporal logical and numerical expressions, and automatically verifying these statements against simulation traces. The purpose of this type of verification is to check whether the model behaves as it should. 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 t and A), or whether eventually an equilibrium value is reached. Other more complex examples can be found in the propositions and theorems presented in the previous section. By running a large number of simulations and automatically verifying such properties against the resulting simulation traces, the modeler can easily locate sources of errors in the model.

For the emotion contagion spiral model, a number of such dynamic properties have been formalized in the language TTL [5] and automatically checked. The temporal predicate logical language TTL supports formal specification and analysis of dynamic properties, covering both qualitative and quantitative aspects. 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 (sorted) temporal predicate logic statements that can be formulated with respect to traces based on the state ontology Ont in the following manner. Given a trace γ over state ontology Ont, the state in γ at time point t is denoted by $state(\gamma, t)$. These states can be related to state properties via the formally defined satisfaction relation denoted by the infix predicate \models : $state(\gamma, t) \models p$ denotes that state property p holds in trace γ at time t . Based on these statements, dynamic properties can be formulated in a formal manner in a sorted predicate logic, using quantifiers over time and traces and the usual logical connectives such as \neg , \wedge , \vee , \Rightarrow , \forall , \exists . A dedicated software environment has been developed for TTL, featuring both a Property Editor for building and editing TTL properties and a Checking Tool that enables automated formal verification of such properties against a set of (simulated or empirical) traces. Based on the language TTL, different

types of dynamic properties of the emotion contagion spiral processes have been formalized, such as: properties addressing limit behavior (equilibria reached), properties of the process from initial values to the equilibria and comparative properties that relate two traces for two different parameter settings of the model. Below, a number of these properties are introduced, both in semi-formal and in informal notation (note that they are all defined for a particular trace γ (or γ_1 and γ_2), and sometimes for a particular time interval between t_b and t_e):

P1a - Emotional stability for agent a around value x

For all time points t between t_b and t_e in trace γ
the level of emotion of agent a is between $x - \alpha$ and $x + \alpha$ (where α is a constant)

P1a(γ :TRACE, t_b , t_e :TIME, x :REAL, a :AGENT, α :REAL) \equiv
 $\forall t:\text{TIME} \forall y:\text{REAL} \quad \text{state}(\gamma, t) \models \text{emotion}(\text{agent}(a), y) \ \& \ t_b \leq t \leq t_e \Rightarrow x - \alpha \leq y \leq x + \alpha$

Property P1a can be used to check whether an agent's level of emotion stays around a certain (given) value. For example, for $\alpha = 0.000001$, property P1a(traceFig3, 15, 50, 1.0, b, 0.000001) was true. One step further, P1a can be used as a building block to check the propositions and theorems related to equilibria presented in Section 4 against the generated traces. For example, property P1b checks whether Theorem 3 holds:

P1b - Equal Equilibria for Beta's of 0.5

If for all agents a_1 and a_2 , $w_{a_1 a_2}$ is nonzero in trace γ
then if for all a , $\beta_a = 0.5$, eventually the same equilibrium q
(between 0 and 1) will occur for all agents
and if for all agents eventually the same equilibrium q
(between 0 and 1) will occur, $\beta_a = 0.5$ for all agents a .

P1b(γ :TRACE, α :REAL) \equiv
 $[\forall a_1, a_2:\text{AGENT} [a_1 \neq a_2 \Rightarrow \exists w:\text{REAL} > 0 [\text{state}(\gamma, 1) \models \text{has_weight_for}(\text{agent}(a_1), \text{agent}(a_2), w)]]] \Rightarrow$
 $[[\forall a:\text{AGENT} \text{state}(\gamma, 1) \models \text{has_beta}(\text{agent}(a), 0.5)] \Rightarrow [\exists q:\text{REAL} \forall a:\text{AGENT} \text{P1b}(\gamma, 40, 50, q, a, \alpha)]] \ \& \$
 $[[\exists q:\text{REAL} \forall a:\text{AGENT} \text{P1b}(\gamma, 40, 50, q, a, \alpha)] \Rightarrow [\forall a:\text{AGENT} \text{state}(\gamma, 1) \models \text{has_beta}(\text{agent}(a), 0.5)]]$

This property, which has been proven in the mathematical analysis, has been checked for $\alpha = 0.15$ for all generated traces, and indeed was confirmed.

P2a - Monotonic Increase of Emotion¹

For all time points t_1 and t_2 with $t_1 < t_2$ between t_b and t_e in trace γ
if at t_1 the level of emotion of agent a is x_1 and at t_2 the level of emotion of agent a is x_2
then $x_1 \leq x_2$.

P2a(γ :TRACE, t_b , t_e :TIME, a :AGENT) \equiv
 $\forall t_1, t_2:\text{TIME} \forall x_1, x_2:\text{REAL}$
 $\text{state}(\gamma, t_1) \models \text{emotion}(\text{agent}(a), x_1) \ \& \ \text{state}(\gamma, t_2) \models \text{emotion}(\text{agent}(a), x_2) \ \& \ t_b \leq t_1 \leq t_e \ \& \ t_b \leq t_2 \leq t_e \ \& \ t_1 < t_2$
 $\Rightarrow x_1 \leq x_2$

Property P2a and the variant P2b addressing monotonic decrease (by replacing \leq in the consequent by \geq) can be used to check whether an agent's level of emotion increases or decreases monotonically over a certain interval. Such monotonicity, for example, occurs for agent a during the whole trace shown in Figure 3 (i.e., property P2b(traceFig3, 1, 50, a) succeeded). Furthermore, these properties can be used as building blocks to check the propositions and theorems related to monotonicity presented in Section 4 against the generated traces. For example, property P2c checks whether part (c) and (d) of Proposition 1 hold:

P2c - Conditional Monotonicity

For all agents a_1 ,
if $\beta_{a_1} > 0.5$ and $q_{a_1}^* \geq q_{a_1}$ between t_b and t_e in trace γ
then q_{a_1} is monotonically increasing during this interval
and if $\beta_{a_1} < 0.5$ and $q_{a_1}^* \leq q_{a_1}$ between t_b and t_e in trace γ
then q_{a_1} is monotonically decreasing during this interval.

¹ A strict variant of such properties can be created by replacing \leq by $<$.

P2c(γ :TRACE, tb , te :TIME) =
 $\forall a1:AGENT \quad [[\forall t:TIME \exists a2,a3:AGENT \exists b,x1,x2,x3,w2,w3:REAL$
 $state(\gamma, 1) \models has_beta(agent(a1),b) \ \& \ b > 0.5 \ \& \ state(\gamma, t) \models emotion(agent(a1), x1) \ \&$
 $state(\gamma, t) \models emotion(agent(a2), x2) \ \& \ state(\gamma, t) \models emotion(agent(a3), x3) \ \& \ a2 \neq a3 \ \& \ tb \leq t \leq te \ \&$
 $state(\gamma, 1) \models has_weight_for(agent(a2),agent(a1),w2) \ \& \ state(\gamma, 1) \models has_weight_for(agent(a3),agent(a1),w3) \ \&$
 $w2 * x2 + w3 * x3 \geq w1]$
 $\Rightarrow p2a(\gamma, tb, te, a1)] \ \&$
 $[[\forall t:TIME \exists a2,a3:AGENT \exists b,x1,x2,x3,w2,w3:REAL$
 $state(\gamma, 1) \models has_beta(agent(a1),b) \ \& \ b < 0.5 \ \& \ state(\gamma, t) \models emotion(agent(a1), x1) \ \&$
 $state(\gamma, t) \models emotion(agent(a2), x2) \ \& \ state(\gamma, t) \models emotion(agent(a3), x3) \ \& \ a2 \neq a3 \ \& \ tb \leq t \leq te \ \&$
 $state(\gamma, 1) \models has_weight_for(agent(a2),agent(a1),w2) \ \& \ state(\gamma, 1) \models has_weight_for(agent(a3),agent(a1),w3) \ \&$
 $w2 * x2 + w3 * x3 \leq w1]$
 $\Rightarrow p2b(\gamma, tb, te, a1)]$

Here, q_{a1}^* is calculated as explained in Formula (3). This property has been confirmed for all possible intervals in all generated traces.

P3 - Emotion Approaches Value x with Speed s

For all time points $t1$ and $t2$ between tb and te in trace γ
 if \quad at $t1$ the level of emotion of agent a is $x1$ and \quad at $t2$ the level of emotion of agent a is $x2$
 and $\quad t2 = t1 + 1$
 then $\quad s * |x - x1| \geq |x - x2|$ (where s is a constant < 1).

P3(γ :TRACE, tb , te :TIME, x :REAL, a :AGENT) =
 $\forall t1,t2:TIME \forall x1,x2:REAL$
 $state(\gamma, t1) \models emotion(agent(a), x1) \ \& \ state(\gamma, t2) \models emotion(agent(a), x2) \ \& \ tb \leq t1 \leq te \ \& \ tb \leq t2 \leq te \ \& \ t2 = t1 + 1$
 $\Rightarrow |x - x1| * s \geq |x - x2|$

Property P3 can be used to check whether an agent's level of emotion approaches some given value x , and additionally determines the speed s with which this happens (where $0 < s < 1$, and a high s denotes a slow speed). For the trace shown in Fig. 3, it turned out that agent a approaches emotion level 0 with a speed of approximately 0.959, agent b approaches 1 with a speed of 1.000, and agent c approaches 0.8 with a speed of 0.999.

P4 - Higher Beta's lead to Higher Emotion Levels

If \quad for all agents the initial level of emotion is higher (or equal) in trace $\gamma1$ than in $\gamma2$
 and \quad for all agents the beta is higher (or equal) in trace $\gamma1$ than in $\gamma2$
 then \quad for all agents the final level of emotion will be higher (or equal)
 in trace $\gamma1$ than in $\gamma2$.

P4($\gamma1, \gamma2$:TRACE, tb , te :TIME) =
 $[\forall a:AGENT \exists x1,x2:REAL$
 $state(\gamma1, tb) \models emotion(agent(a),x1) \ \& \ state(\gamma2, tb) \models emotion(agent(a),x2) \ \& \ x1 \geq x2] \ \& \ [\forall a:AGENT \exists x1,x2:REAL \ state(\gamma1,$
 $tb) \models has_beta(agent(a),x1) \ \& \ state(\gamma2, tb) \models has_beta(agent(a),x2) \ \& \ x1 \geq x2] \Rightarrow$
 $[\forall a:AGENT \exists x1,x2:REAL \ state(\gamma1, te) \models emotion(agent(a),x1) \ \& \ state(\gamma2, te) \models emotion(agent(a),x2) \ \& \ x1 \geq x2]$

This property can be used to compare traces with different parameter settings. It turned out to hold for all generated traces, as long as the initial values were not 0 or 1.

6 Integrating the Emotion Spiral Model within an Agent Model

The emotion contagion spiral model described in the previous sections has been integrated within an ambient agent model to analyse the occurring dynamics of emotion contagion spirals. The ambient agent predicts the level of a given type of emotion (considered positive in the case study presented here) in the group and based on an assessment of this it proposes actions. A generated assessment indicates when the group emotion level at some (future) time point is predicted to be too low, compared to a certain norm (EN). When the agent detects this, it comes up with action proposals. As an input for the predictions the concept expressed emotion level ($\mathcal{E}_S q_A$) is used: the emotion level that can be observed from someone's face, for example, by use of a face reader. To integrate the emotion contagion spiral model within an agent model, a generic agent model for human-aware ambient computing (see [4]) was used as a point of departure, as was done in [6].

Assessment of emotion contagion spirals

The dynamic properties defining the model that reasons about emotion contagion spirals are described below. Here the beliefs on emotion expressiveness, openness, and channel strengths are assumed to be initially given and to persist until they are changed. An example scenario is assumed where at some (initial) point in time the emotion levels of the members are observed, and from that time point onwards, the emotion levels for subsequent time points are predicted.

First the role of observed expressed emotions is formalised. The agent is assumed to be connected to observation equipment in the form of a face reader with software that detects emotion expressions from face images. This expressed emotion EV results from the emotion level V and the expressiveness E by which the emotion is displayed on the face. In the model it is assumed that the expressed emotion level is formalised as the product $V \cdot E$. Note that this means that it is assumed that the expressiveness (being a number between 0 and 1) always reduces the level of the emotion: $EV \leq E$. In other words, this assumption excludes the situation that an emotion level is expressed that is not there (no faking of emotions). Moreover, note that in ADR2 below it is assumed that the expressiveness factor E is nonzero. Then under the assumptions discussed above, from an expressed emotion level EV the emotion level V itself can be determined as $V = EV/E$.

ADR1 Observing group members' expressed emotion levels

If the agent observes an expressed emotion level
then the ambient agent will believe this.
observes(agent, has_expressed_emotion_level_at(A, V, T))
→ belief(agent, has_expressed_emotion_level_at(A, V, T))

ADR2 Generating an emotion level belief from a belief on an expressed emotion level

If the agent believes that a group member has expressed emotion level EV
and that this group member has expressiveness E
then it will generate a belief that this group member has emotion level EV/E
belief(agent, has_expressed_emotion_level_at(A, EV, T)) & belief(agent, has_expressiveness(E))
→ belief(agent, has_emotion_level_at(A, EV/E, T))

The following two properties show how the specific emotion spiral model introduced here is integrated within the agent model.

ADR3 Generating beliefs on contagion strengths

If the ambient agent believes that B has expressiveness E
and the ambient agent believes that the channel from B to A has strength C
and the ambient agent believes that A has openness D
then the ambient agent will believe that the contagion strength from B to A will be $E \cdot C \cdot D$
belief(agent, has_expressiveness(B, E)) & belief(agent, has_channel_strength(B, A, C)) &
belief(agent, has_openness(A, D))
→ belief(agent, has_contagion_strength(B, A, E * C * D))

ADR4 Updating beliefs on emotion levels

If $A \neq B$ and $B \neq C$ and $C \neq A$
and the ambient agent believes that A has emotion level $V1$ at time T
and the ambient agent believes that B has emotion level $V2$ at time T
and the ambient agent believes that C has emotion level $V3$ at time T
and the ambient agent believes that the contagion strength from B to A is $CS2$
and the ambient agent believes that the contagion strength from C to A is $CS3$
and the ambient agent believes that the step size is DT
and the ambient agent believes that the A has orientation $BETA1$
then the ambient agent will believe that the emotion level of A will be
 $V1 + (CS2 + CS3) \cdot$
 $[BETA1 \cdot (1 - (1 - ((CS2 / (CS2 + CS3)) \cdot V2 + (CS3 / (CS2 + CS3)) \cdot V3)) \cdot (1 - V1)) +$
 $(1 - BETA1) \cdot ((CS2 / (CS2 + CS3)) \cdot V2 + (CS3 / (CS2 + CS3)) \cdot V3) \cdot V1 - V1] \cdot DT$
at time $T + DT$

$A \neq B \ \& \ B \neq C \ \& \ C \neq A \ \&$
 $\text{belief}(\text{agent}, \text{has_emotion_level_at}(A, V1, T)) \ \& \ \text{belief}(\text{agent}, \text{has_emotion_level_at}(B, V2, T)) \ \&$
 $\text{belief}(\text{agent}, \text{has_emotion_level_at}(C, V3, T)) \ \&$
 $\text{belief}(\text{agent}, \text{has_contagion_strength}(B, A, CS2)) \ \& \ \text{belief}(\text{agent}, \text{has_contagion_strength}(C, A, CS3)) \ \&$
 $\text{belief}(\text{agent}, \text{step_size}(DT))$
 $\rightarrow \text{belief}(\text{agent}, \text{has_emotion_level_at}(A, V1 + (CS2+CS3) * [\text{BETA1} * (1 - (1 - ((CS2 / (CS2+CS3)) * V2 + (CS3 / (CS2+CS3)) * V3)) * (1 - V1)) + (1 - \text{BETA1}) * ((CS2 / (CS2+CS3)) * V2 + (CS3 / (CS2+CS3)) * V3) * V1 - V1] * DT, T+DT))$

An analysis also involves an assessment of the (expected) level of the group's emotion. To this end, first a belief on the group's emotion level is generated.

ADR5 Determining beliefs on the group's emotion level

If the ambient agent believes that the group members have emotion levels $V1, V2, V3$ and relevance $R1, R2, R3$ respectively then it will believe that the group's emotion level is $R1*V1 + R2*V2 + R3*V3$.
 $\text{belief}(\text{agent}, \text{has_emotion_level_at}(a1, V1, T)) \ \& \ \text{belief}(\text{agent}, \text{has_emotion_level_at}(a2, V2, T)) \ \&$
 $\text{belief}(\text{agent}, \text{has_emotion_level_at}(a3, V3, T)) \ \&$
 $\text{belief}(\text{agent}, \text{has_relevance}(a1, R1)) \ \& \ \text{belief}(\text{agent}, \text{has_relevance}(a2, R2)) \ \&$
 $\text{belief}(\text{agent}, \text{has_relevance}(a3, R3))$
 $\rightarrow \text{belief}(\text{agent}, \text{group_emotion_level_at}(R1*V1 + R2*V2 + R3*V3, T))$

An assessment is generated when the predicted group emotion level at some time point is too low, compared to a certain norm. The assessment includes an estimation of how much the group emotion level is too low (the *group emotion deficient*):

ADR6 Assessment of the group's emotion level

If the ambient agent believes that the group emotion level V at time T is lower than the emotion norm EN , then it will assess the situation as having a group emotion deficient $EN - V$ at T .
 $\text{belief}(\text{agent}, \text{group_emotion_level_at}(V, T)) \ \& \ \text{belief}(\text{agent}, \text{group_emotion_norm}(EN)) \ \& \ V < EN$
 $\rightarrow \text{assessment}(\text{agent}, \text{group_emotion_deficient_at}(EN - V, T))$

Generating proposals for support actions

Using the assessment based on the integrated emotion spiral model, a support model generates support actions. The support model used was fully adopted from [6]; it uses a heuristic approach. When a negative assessment of the (future) group emotion state is made, then the ambient agent proposes actions to the team leader, in order to avoid such states. To this end, two heuristics are applied: (1) let the group members with lowest emotion levels get less impact on the other members, and get more impact from the other members, and (2) let the group members with highest emotion levels get more impact on the other members, and get less impact from the other members. A low and high threshold are assumed for this. For an overview of the action options based on the two heuristics, see Table 3. The extent by which an action is proposed depends on the deficiency measure indicated by the assessment. Moreover, a feasibility ranking of the possible actions is taken into account; for more details, see [6].

	<i>person under low threshold</i>	<i>person above high threshold</i>
<i>expressiveness</i>	decrease	Increase
<i>channels: to others</i>	decrease	Increase
<i>from others</i>	increase	Decrease

Table 3: Overview of the action options

avoid such states. To this end, two heuristics are applied: (1) let the group members with lowest emotion levels get less impact on the other members, and get more impact from the other members, and (2) let the group members with highest emotion levels get more impact on the other members, and get less impact from the other members. A low and high threshold are assumed for this. For an overview of the action options based on the two heuristics, see Table 3. The extent by which an action is proposed depends on the deficiency measure indicated by the assessment. Moreover, a feasibility ranking of the possible actions is taken into account; for more details, see [6].

7 Simulation Results for the Ambient Agent Model

The LEADSTO software environment [9] has been used to perform a number of simulation experiments for the agent model for group emotion spiral support. An example scenario is used to illustrate it. The simulation for the assessment is discussed in Section 7.1, and Section 7.2 shows the generation of support actions.

7.1 Simulation of the assessment of emotion contagion spirals

In this section the simulation results of the analysis process are shown in an example scenario that represents a situation where the group emotion is happiness and is analysed by the ambient agent. In this example, the ambient agent generates beliefs on the individual emotion levels of three group members, named Arnie, Bernie and Charlie (see ADR2), and of the group emotion level at different points in time (see ADR5). The agent also assesses the (expected) group's emotion deficient at a future time point based on its belief of the group emotion level and the norm for the group emotion level. The norm of the group emotion can be set by the modeler and represents in this example an optimal level of happiness, at which the team can perform as optimal as possible. The norm was set to 0.60 in this example.

In this example scenario Arnie, Bernie and Charlie are all not very happy (initial emotion levels are 0.3 and 0.1). They are all very open to receive each others happiness emotions, all have an openness δ of 0.9 . Arnie can send his emotions most effectively to others, because his contagion strength, which is his channel α multiplied by his expressiveness ε , is 0.72 for both Bernie and Charlie. Bernie can send emotions less effectively, his contagion strength is 0.45 . Charlie can send his emotions with even less power: his contagion strength is 0.09 . For an overview of the settings, see Table 4.

Table 4: Overview of the parameter settings

	<i>Arnie</i>	<i>Bernie</i>	<i>Charlie</i>
Initial emotion level q	0.3	0.1	0.1
Impact β	0.3	1	0.6
Contagion strength $\varepsilon_a \cdot \alpha_{ab}$	0.72		
Contagion strength $\varepsilon_a \cdot \alpha_{ac}$	0.72		
Contagion strength $\varepsilon_b \cdot \alpha_{ba}$		0.45	
Contagion strength $\varepsilon_b \cdot \alpha_{bc}$		0.45	
Contagion strength $\varepsilon_c \cdot \alpha_{ca}$			0.09
Contagion strength $\varepsilon_c \cdot \alpha_{cb}$			0.09
openness δ	0.9	0.9	0.9
relevance ρ	0.34	0.33	0.33

In Figure 6 a simulation trace is shown in which the horizontal axis represents time, and the vertical axis represents quantitative information about generation of ambient agent's beliefs on the individual and group emotion levels at different (future) time points. In this situation, the total group emotion level goes from 0.49 downwards and through an upwards spiral mechanism to 0.58 in 500 time steps. This means that the group emotion level is always below the norm of 0.60 . In this analysis model, our ambient agent predicts the future development of the group emotion level and this prediction shows that it will stay below the norm for all the future time steps. In this case it can propose appropriate actions to the team leader early in time, to help the group emotion level get above the norm faster. The simulations are based on step size $\Delta t = 0.1$.

On the x-axis in Figure 6, time goes from 0 to 1 . This time actually represents processing time of the ambient agent. The idea is that the agent reads the emotions of the persons at time point 0 and from that time point the ambient agent starts to generate beliefs on the development of the emotion levels of the group members and the group as a whole. The developments of the emotion levels (simulated by the ambient agent from time point 0 to 0.5) are estimated for real future time points 0 to 5 . At time point 0.5 on the x-axis, the agent makes the assessment of an expected emotion deficiency for real future time point 5 . The ambient agent assesses that on future time point 5 , there is a group emotion deficiency to be expected (of about 0.04).

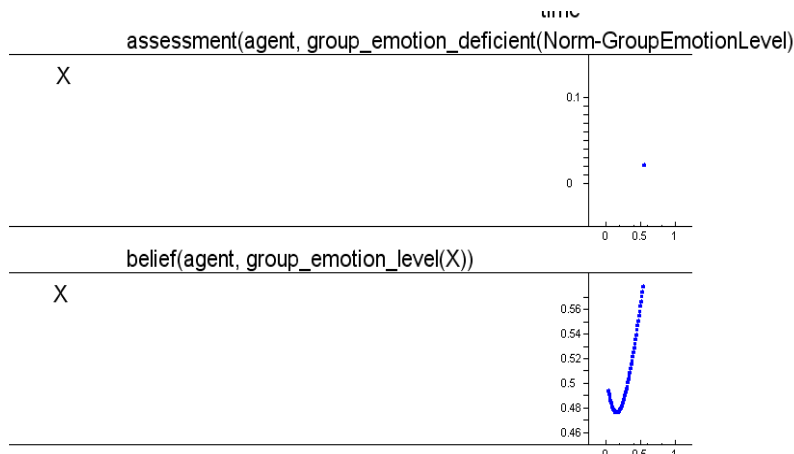


Figure 6: Simulation trace of the analysis processes

5.2 Simulation of the support process

In this section, the example scenario of the previous section is extended with the support of the ambient agent. The assumption is made that Arnie, Bernie and Charlie are working on a task together that is perhaps stressful, since they are not very happy (initial emotion levels are 0.3 or 0.1). Arnie is very charismatic and he works together a lot with Bernie and Charlie, this is represented in his high contagion strength. Charlie on the other hand is very introvert and therefore his contagion strength is weak. Bernie has a medium contagion strength. All three are open to receive happy emotions from others, since they all have a high level of openness. In the previous section it was shown that the ambient agent predicted the future development of the group emotion level, namely an upward spiral that still was below the norm at future time point 5. Therefore, based on its heuristics, the ambient agent detects which group members are high or low emotion members, and generates action options that decrease or increase parameters related to these members: expressiveness or channel strength. After ranking these options, the agent proposes to the group leader those options, which do not exceed a certain feasibility threshold. An example of (a part of) such a trace is shown in Figure 7. Here, time is on the horizontal axis, and state properties are on the vertical axis. A dark box indicates that a state property is true. Figure 7 shows that the ambient agent detects the high and/or low emotion members (Charlie is detected as a high emotion member and Bernie as a low emotion member.) (see SDR1 and SDR2 in [6]), the action-options are ranked (see SDR9 in [6]) and the ambient agent proposes the actions that do not exceed the feasibility threshold to the group leader (see SDR10 in [6]).

8 Discussion

Within teams performing critical tasks, a team leader is responsible for a good spirit in the team. Due to high pressure emotions within the team may easily take the form of a negative spiral, it is challenging to regulate such patterns. Recent literature on emotion contagion spirals addresses how such spirals may occur. Most existing computational models of emotional processes represent emotion as a process or state that depends on observed stimuli by a single agent; e.g., [7], [17], [22].

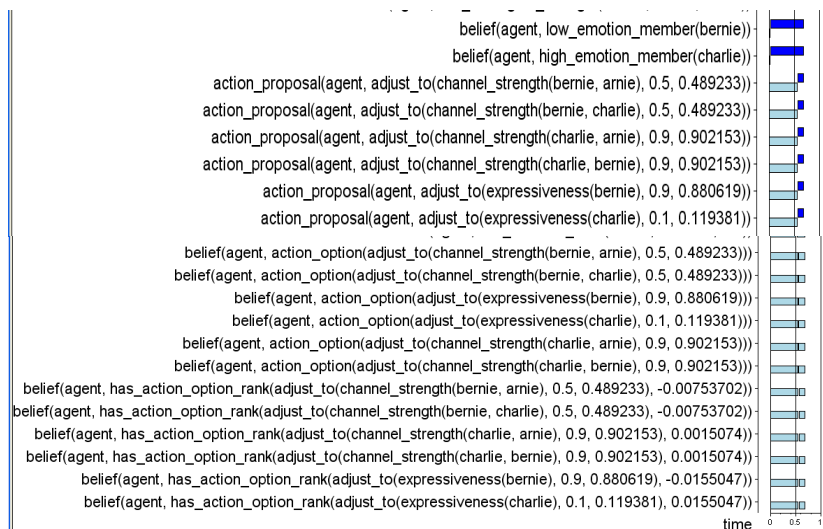


Figure 7: Simulation trace for the support process

These models of emotion differ from our proposed model, in that the focus in these models lies more on individual emotions, not on collective emotion. Recently researchers have started to investigate emotions in a social context more extensively. For the work reported in the current paper, more specific work on emotion contagion spirals was taken as a point of departure; cf. [8], [9], [10]. In the current paper, first a multi-agent-based model for emotion contagion spirals has been presented and analyzed. Although an extensive empirical validation is left for future work, it turned out that the model is able to produce various interesting emerging patterns as described (informally) in the psychological literature, including the upward and downward emotion spirals discussed in [9]. Although this is not an exhaustive proof, it is an important indication that the model behaves as expected. In contrast to most existing (symbolic) agent-based modeling approaches, the current approach represents a multi-agent system using numerical techniques.

Literature on computational models of emotion contagion spirals is scarce. The only computational models that come close to the process modeling of this current work can be found in the area of social science, named social diffusion modeling. Examples of social diffusion models are: the diffusion of social movements like political interests and parties, see [14], and crowd behavior, as in emergency evacuation, see [18]. Most social diffusion models follow the diffusion of innovations model of Rogers, in which it is posed that the diffusion process of innovations proceeds in the form of an S-shaped curve: the contagion of an innovation starts slow, but then accelerates rapidly, followed by a rapid deceleration [20]. Even though social diffusion models can simulate the contagion of a certain innovation and use similar concepts as the current work does, such as a sender, receiver and communication channel, these computational models of social diffusion also differ from our model, in the way that they model the complex spread of innovations as diffusion that is asymmetric in time, irreversible, and nondeterministic. Our model of emotion contagion spirals, models the continuous spread of emotions among the group members over time, which can have many patterns in it and is reversible in time.

The model for emotion contagion spirals was taken as a point of departure for an ambient

agent model that uses the computational model to assess the expected emotion contagion spirals at future time points, and to propose actions to the team leader to regulate these spirals. The generic agent model for human-aware ambient intelligence applications described in [4] was taken as a point of departure, as also was chosen in [6]. One of the possible applications of the resulting ambient agent model could be analyzing and supporting group emotion in virtual meetings. For example, when two groups at two locations in the world are video-conferencing, a software agent could measure the group emotion of both groups and could show the emotion level of the other group to the group leaders. The ambient software agent could then, if necessary, provide support to the group leaders, e.g. when is the best time to let the other group make a decision, or how to calm the other group down after their anger level got too high during decision making.

In follow-up research, more attention will be paid to the model's more detailed external validation of the model for emotion contagion spirals. The mathematical and automated analyses described above have been successfully performed to guarantee internal validity, and it fits to patterns described informally in (social) psychological literature. Nevertheless, this does not guarantee that the model is directly applicable to humans in a more detailed and more quantitative manner, and in particular it does not show which personality parameter values fit which person. Therefore, as a next step, a more detailed validation of the model in laboratory experiments is planned. The idea is to create a setting in which various humans interact in a room, while continuously being subject to (physiological) measurements (e.g., using emotion recognition approaches as discussed in [11]) to assess their emotions. The obtained data can then be used in order to fine-tune the model using adaptive and machine learning techniques. This will not only provide a more detailed validation of the model, but also result in realistic parameter settings for different types of individuals.

Concerning further work, a number of factors can be refined or added to the model. For instance, recently a new perspective has emerged that describes leaders as the managers of group emotions [19]. According to this perspective, every group member can assume a leadership role by providing certainty and direction during times of ambiguity to create shared emotion within the group. The gender of this group leader also has an important impact on the emerging emotion contagion processes.

Another possibility for future work is to combine two different models addressing the transfer of emotions between group members, namely the absorption model presented in [3], and the model for spirals introduced in the current paper. Within a heterogeneous group, some members may absorb emotions while others may amplify emotions. The former type of members may be described by the model from [3], whereas the latter type of members better fit the model in the current paper. By combining the two models a more heterogeneous group may be modeled.

A final possibility to extend the model is to consider multiple emotions. Currently, the group contagion spirals of only one emotion can be modeled. It will be interesting, for example, to study the impact of simultaneous occurrences of happiness and anger within the same group, or the interaction between anger and fear within a group. For specific types of emotions, specific values may have to be estimated, e.g. α , δ , ρ . However, if also interaction between different emotions is to be addressed (for example, anger in one person affecting fear in another person), more specific work is needed, which is planned for the future.

References

1. Barsade, S.G. (2002). The ripple effect: Emotional contagion and its influence on group behavior. *Administrative Science Quarterly*, 47(4), 644-675.

2. Barsade, S.G. and Gibson, D.E. (1998). Group Emotion: a View from Top and Bottom. In: D. Gruenfeld, E. Mannix and M. Neale, (eds.), *Research on managing groups and teams*, JAI Press, Stamford (1998), pp. 81–102.
3. Bosse, T., Duell, R., Memon, Z.A., Treur, J., and Wal, C.N. van der, A Multi-Agent Model for Mutual Absorption of Emotions. In: Otamendi, J., Bargiela, A., Montes, J.L., Pedrera, L.M.D. (eds.), *Proceedings of the 23rd European Conference on Modelling and Simulation, ECMS'2009*, 2009, pp. 212-218.
4. Bosse, T., Hoogendoorn, M., Klein, M., and Treur, J., A Generic Agent Architecture for Human-Aware Ambient Computing. In: Mangina, E., Carbo, J., and Molina, J.M. (eds.), *Agent-Based Ubiquitous Computing*. Series on Ambient and Pervasive Intelligence, vol. 1. World Scientific Publishers: Atlantis Press, 2009, pp. 35-62. Shorter version in: M. Mühlhäuser, A. Ferscha, and E. Aitenbichler (eds.), *Constructing Ambient Intelligence: Aml-07 Workshops Proceedings*. Communications in Computer and Information Science (CCIS), vol. 11, Springer Verlag, 2008, pp. 93-103.
5. Bosse, T., Jonker, C.M., Meij, L. van der, Sharpanskykh, A., and Treur, J. (2009). Specification and Verification of Dynamics in Agent Models. *Intern. Journal of Cooperative Information Systems*, vol. 18, 2009, pp. 167 - 193.
6. Duell, R., Memon, Z.A., Treur, J., and Wal, C.N. van der, An Ambient Agent Model for Group Emotion Support. In: *Proceedings of the Third International Conference on Affective Computing and Intelligent Interaction, ACII'09*. IEEE Computer Society Press, 2009, to appear.
7. Elliott, C. (1992). *The Affective Reasoner: A Process Model of Emotions in a Multi-Agent System*. PhD Dissertation, Northwestern University. Technical Report No.32.
8. Frederickson, B.L., and Branigan, C. (2005). Positive Emotions broaden the scope of attention and thought-action repertoires. *Cognition and Emotion*. 19(3), 313-332.
9. Frederickson, B.L., and Joiner, T. (2002). Positive emotions trigger upward spirals toward emotional well-being. *Psychological Science*. 13(2), 172-175.
10. Frederickson, B.L. (2001). The role of positive emotions in positive psychology: The broaden-and-build theory of positive emotions. *American Psychologist*, 56,218-226.
11. Goldman, A.I., and Sripada, C.S. (2005). Simulationist models of face-based emotion recognition. *Cognition*, vol. 94, pp. 193-213.
12. Hareli, S., and Rafaeli, A. (2008). Emotion cycles: On the social influence of emotion in organizations. *Research in Organizational Behavior*, 28, pp 35-59.
13. Hatfield, E., Cacioppo, J.T., and Rapson, R.L. (1994). *Emotional contagion*. Cambridge University Press.
14. Hedström, Peter, Rickard Sandell and Charlotta Stern (2000), Mesolevel Networks and the Diffusion of Social Movements: The Case of the Swedish Social Democratic Party, *American J. of Sociology*, 106 (1): 145-172.
15. Lazarus, R.S. (1991). *Emotion and adaptation*. New York: Oxford University Press.
16. LeBon, G. (1897). *The Crowd. A Study of the Popular Mind*. London: Unwin.
17. Marsella, S. and Gratch, J. (2009). EMA: A process model of appraisal dynamics, *Journal of Cognitive Systems Research*, vol. 10, no. 1, pp. 70-90.
18. Pan, X., Han, C., Dauber, K., Law, K.: Human and social behaviour in computational modeling and analysis of egress. *Automation in Construction* 15(4), 448–461 (2006).
19. Pescosolido, A.T. (2002). Emergent Leaders as Managers of Group Emotions. *The Leadership Quarterly*. 13(5), 583-599.
20. Rogers, E. (1983). *Diffusion of Innovations*. New York: Free Press.
21. Schoenewolf, G. (1990). Emotional Contagion: Behavioral induction in individuals and groups. *Modern Psycho-analysis*, 15, 49-61
22. Silverman, B.G. (2001). More Realistic Human Behavior Models for Agents in Virtual Worlds: Emotion, Stress, and Value Ontologies. T.R., Univ. of Penn./ACASA.
23. Totterdell, P., Kellet, S., Teuchmann, K., and Briner, R.B. (1998). Evidence of mood linkage in work groups. *Journal of Personality and Social Psychology*, 74, 1504-1515.
24. <http://www.cs.vu.nl/~tbosse/emotion/PRIMA09/>