Modelling the Reciprocal Interaction between Believing and Feeling from a Neurological Perspective

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Abstract. By adopting neurological theories on the role of emotions and feelings, an agent model is introduced incorporating the reciprocal interaction between believing and feeling. The model describes how the strength of a belief may not only depend on information obtained, but also on the emotional responses on the belief. For feeling emotions a recursive body loop is assumed. The model introduces a second feedback loop for the interaction between feeling and belief. The strength of a belief and of the feeling both result from the converging dynamic pattern modelled by the combination of the two loops. For some specific cases it is described, for example, how for certain personal characteristics an optimistic world view emerges, or, for other characteristics, a pessimistic world view.

1 Introduction

Already during the process that they are generated beliefs trigger emotional responses that result in certain feelings. However, the process of generation of a belief is not fully independent of such associated feelings. In a reciprocal manner, the generated feelings may also have a strengthening or weakening effect on the belief during this process. Empirical work such as described in, for example, (Eich, Kihlstrom, Bower, Forgas, and Niedenthal, 2000; Forgas, Laham, and Vargas, 2005; Forgas, Goldenberg, and Unkelbach, 2009; Niedenthal, 2007; Schooler and Eich, 2000; Winkielman, Niedenthal, and Oberman, 2009), reports such types of effects of emotions on beliefs, but does not relate them to neurological findings or theories. In this paper, adopting neurological theories on emotion and feeling, a computational dynamic agent model is introduced that models this reciprocal interaction between feeling and believing. The computational model, which is based on neurological theories on the embodiement of emotions as described, for example, in (Damasio, 1994, 1996, 1999, 2004; Winkielman, Niedenthal, and Oberman, 2009)'s, describes how the generation of a belief may not only depend on an (external) informational source, but also takes into account how the belief triggers an emotional response that leads to a certain feeling. More specifically, in accordance with, for example (Damasio, 1999, 2004), for feeling the emotion associated to a belief a converging recursive body loop is assumed. A second converging feedback loop introduced in the model, inspired the Somatic Marker Hypothesis (Damasio, 1994, 1996), involves the interaction back from the feeling to the belief. Thus a combination of two loops is obtained, where connection strengths within these loops in principle are person-specific. Depending on these personal characteristics, from a dynamic interaction within and between the two loops, an equilibrium is reached for both the strength of the belief and of the feeling.

To illustrate the model, the following example scenario is used. A person is parking his car for a short time at a place where this is not allowed. When he comes back, from some distance he observes that a small paper is attached at the front window of the car. He starts to generate the belief that the paper represents a charge to be paid. This belief generates a negative feeling, which has an impact on the belief by strengthening it. Coming closer, some contours of the type of paper that is attached become visible. As these are not clearly recognized as often occurring for a charge, the person starts to generate a second belief, namely that it concerns an advertising of a special offer. This belief generates a positive feeling which has an impact on the latter belief by strengthening it.

In this paper, first in Section 2 Damasio's theory on the generation of feelings based on a body loop is briefly introduced. Moreover, the second loop is introduced, the one between feeling and belief. In Section 3 the model is described in detail. Section 4 presents some simulation results. In Section 5 a mathematical analysis of the equilibria of the model is presented. Finally, Section 6 is a discussion.

2 From Believing to Feeling and Vice Versa

In this section the interaction between believing and feeling is discussed in some more detail from a neurological perspective, in both directions: from believing to feeling, and from feeling to believing.

2.1 From Believing to Feeling

As any mental state in a person, a belief state induces emotions felt within this person, as described by Damasio (1999, 2004); 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. As far as I can fathom, few if any exceptions of any object or event, actually present or recalled from memory, are ever neutral in emotional terms. Through either innate design or by learning, we react to most, perhaps all, objects with emotions, however weak, and subsequent feelings, however feeble.' (Damasio, 2004, p. 93)

In some more detail, emotion generation via a body loop roughly proceeds according to the following causal chain; see Damasio (1999, 2004):

belief → preparation for the induced bodily response →
induced bodily response → sensing the induced bodily response →
sensory representation of the induced bodily response → induced feeling

As a variation, an 'as if body loop' uses a direct causal relation

preparation for the induced bodily response →
sensory representation of the induced bodily response

as a shortcut in the causal chain. The body loop (or as if body loop) is extended to a recursive body loop (or recursive as if body loop) by assuming that the preparation of the bodily response is also affected by the state of feeling the emotion:

feeling $\rightarrow$ preparation for the bodily response

as an additional causal relation. Such recursiveness is also assumed by Damasio (2004), as he notices that what is felt by sensing is actually a body state which is an internal object, under control of the person:

> 'The brain has a direct means to respond to the object as feelings unfold because the object at the origin is inside the body, rather than external to it. The brain can act directly on the very object it is perceiving. It can do so by modifying the state of the object, or by altering the transmission of signals from it. The object at the origin on the one hand, and the brain map of that object on the other, can influence each other in a sort of reverberative process that is not to be found, for example, in the perception of an external object.' (…)
>
> 'In other words, feelings are not a passive perception or a flash in time, especially not in the case of feelings of joy and sorrow. For a while after an occasion of such feelings begins – for seconds or for minutes – there is a dynamic engagement of the body, almost certainly in a repeated fashion, and a subsequent dynamic variation of the perception. We perceive a series of transitions. We sense an interplay, a give and take.' (Damasio, 2004, pp. 91-92)

Thus the obtained model is based on reciprocal causation relations between emotion felt and body states, as roughly shown in Figure 1.

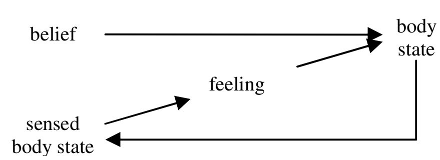

Figure 1: Body loop induced by a belief

Within the model presented in this paper both the bodily response and the feeling are assigned a level or gradation, expressed by a number, which is assumed dynamic; for example, the strength of a smile and the extent of happiness. The causal cycle is modelled as a positive feedback loop, triggered by a mental state and converging to a certain level of feeling and body state. Here in each round of the cycle the next body state has a level that is affected by both the mental state and the level of the feeling state, and the next level of the feeling is based on the level of the body state.

2.2 From Feeling to Believing

In an idealised rational agent the generation of beliefs might only depend on informational sources and be fully independent from non-informational aspects such as emotions. However, in real life persons may, for example, have a more optimistic or pessimistic character and affect their beliefs in the sense that an optimist person strengthens beliefs that have a positive feeling associated and a pessimistic person strengthens beliefs with a negative associated feeling. Thus the strengths of beliefs may depend on non-informational aspects of mental processes and related personal characteristics. To model this for the case of feelings a causal relation

feeling $\rightarrow$ belief

can be added. This introduces a second recursive loop, as shown in Figure 2.

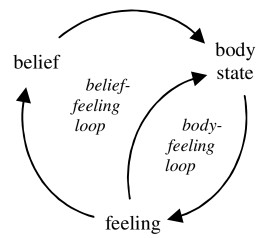

Figure 2: The two recursive loops related to a belief

From a neurological perspective the existence of a connection from feeling to belief may be considered plausible, as neurons involved in the belief and in the associated feeling will often be activated simultaneously. Therefore such a connection from feeling to belief may be developed based on a general Hebbian learning mechanism (Hebb, 1949; Bi and Poo, 2001) that strengthens connections between neurons that are activated simultaneously, similar to what has been proposed for the emergence of mirror neurons; e.g., (Keysers and Perrett, 2004; Keysers and Gazzola, 2009).

Another type of support for a connection from feeling to belief can be found in Damasio's Somatic Marker Hypothesis; cf. (Damasio, 1994, 1996; Bechara and Damasio, 2004; Damasio, 2004). This is a theory on decision making which provides a central role to emotions felt. Each decision option induces (via an emotional response) a feeling which is used to mark the option. For example, when a negative somatic marker is linked to a particular option, it provides a negative feeling for that option. Similarly, a positive somatic marker provides 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. (…) on occasion somatic markers may operate covertly (without coming to consciousness) and may utilize an 'as-if-loop'.' (Damasio, 1994, p. 173-174)

Usually the Somatic Marker Hypothesis is applied to provide endorsements or valuations for options for a person's actions. However, it may be considered plausible that such a mechanism is applicable to valuations of internal states such as beliefs as well.

3 The Detailed Agent Model for Believing and Feeling

Informally described theories in scientific disciplines, for example, in biological or neurological contexts, often are formulated in terms of causal relationships or in terms of dynamical systems. To adequately formalise such a theory the hybrid dynamic modelling language LEADSTO has been developed that subsumes qualitative and quantitative causal relationships, and dynamical systems; cf. (Bosse, Jonker, Meij and Treur, 2007). This language has been proven successful in a number of contexts, varying from biochemical processes that make up the dynamics of cell behaviour (cf. Jonker, Snoep, Treur, Westerhoff, Wijngaards, 2008) to neurological and cognitive processes (e.g., Bosse, Jonker, Los, Torre, and Treur, 2007; Bosse, Jonker, and Treur, 2007, 2008). Within LEADSTO the temporal relation a ↠ b denotes that when a state property a occurs, then after a certain time delay (which for each relation instance can be specified as any positive real number), state property b will occur. In LEADSTO both logical and numerical calculations can be specified in an integrated manner, and a dedicated software environment is available to support specification and simulation.

An overview of the agent model for believing and feeling is depicted in Figure 3. This picture also shows representations from the detailed specifications explained below. However, note that the precise numerical relations between the indicated variables V shown are not expressed in this picture, but in the detailed specifications of properties below, which are labeled by LP1 to LP9 as also shown in the picture.

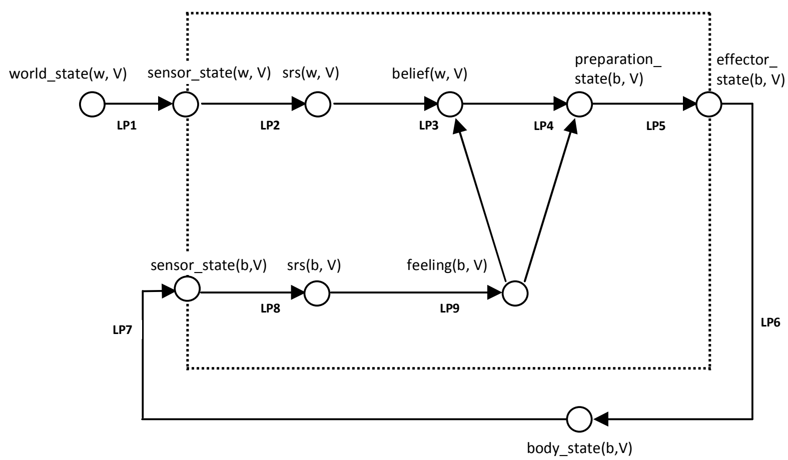

Figure 3: Overview of the agent model

The detailed specification (both informally and formally) of the agent model is presented below. Here capitals are used for (assumed universally quantified) variables. First the part is presented that describes the basic mechanisms to generate a belief state and the associated feeling. The first dynamic property addresses how properties of the world state can be sensed.

LP1 Sensing a world state
If world state property W occurs of strength *V*
then a sensor state for W of strength *V* will occur.
world_state(W, V) ↠ sensor_state(W, V)

For the example scenario this dynamic property is used by the agent to observe both the paper attached looking like a charge and the paper type looking like an offer; to this end the variable W is instantiated by charge and offer. From the sensor states, sensory representations are generated according to the dynamic property LP2. Note that also here for the example the variable W is instantiated as indicated.

LP2 Generating a sensory representation for a sensed world state
If a sensor state for world state property W with level *V* occurs,
then a sensory representation for W with level *V* will occur.
sensor_state(W, V) $\twoheadrightarrow$ srs(W, V)

Next the dynamic property for the process for belief generation is described, where both the sensory representation and the feeling play their role. This specifies part of the loop between belief and feeling. The resulting level for the belief is calculated based on a function $g(\beta, V_1, V_2)$ of the original levels.

LP3 Generating a belief state for a feeling and a sensory representation
If a sensory representation for w with level V_1 occurs,
and the associated feeling of b with level V_2 occurs
and the belief for w has level V_3
and β_1 is the person's orientation for believing
and γ_1 is the person's flexibility for beliefs
then a belief for w with level $V_3 + \gamma_1 (g(\beta_1, V_1, V_2)-V_3) \Delta t$ will occur.
srs(w, V_1) & feeling(b, V_2) & belief(w, V_3) $\twoheadrightarrow$ belief(w, $V_3 + \gamma_1$ (g(β_1, V_1,V_2) - V_3) Δt)

For the function $g(\beta, V_1, V_2)$ the following has been taken:

$$g(\beta, V_1, V_2) = \beta(1-(1-V_1)(1-V_2)) + (1-\beta)V_1V_2$$

Note that this formula describes a weighted sum of two cases. The most positive case considers the two source values as strengthening each other, thereby staying under *1*: combining the imperfection rates $1-V_1$ and $1-V_2$ of them provides a decreased rate of imperfection expressed by:

$$1-(1-V_1)(1-V_2)$$

The most negative case considers the two source values in a negative combination: combining the imperfections of them provides an increased imperfection. This is expressed by

$$V_1V_2$$

The factor β can be used to model the characteristic of a person that expresses the person's orientation (from *0* as most negative to *1* as most positive).

Dynamic property LP4 describes the emotional response to a belief in the form of the preparation for a specific bodily reaction. This specifies part of the loop between feeling and body state. This dynamic property uses the same combination model based on $g(\beta, V_1, V_2)$ as above.

LP4 From belief and feeling to preparation of a body state
If belief w with level V_1 occurs
and feeling the associated body state b has level V_2
and the preparation state for b has level V_3
and β_2 is the person's orientation for emotional response
and γ_2 is the person's flexibility for bodily responses
then preparation state for body state b will occur with level $V_3 + \gamma_2 (g(\beta_2, V_1, V_2)-V_3) \Delta t$.
belief(w, V_1) & feeling(b, V_2) & preparation_state(b, V_3)
$\twoheadrightarrow$ preparation_state(b, V_3+γ_2 (g(β_2, V_1, V_2)-V_3) Δt)

Dynamic properties LP5 to LP9 describe the body loop.

LP5 From preparation to effector state for body modification
If preparation state for body state B occurs with level *V*,
then the effector state for body state B with level *V* will occur.
preparation_state(B, V) $\twoheadrightarrow$ effector_state(B, V)

LP6 From effector state to modified body state
If the effector state for body state B with level *V* occurs,
then the body state B with level *V* will occur.
effector_state(B, V) $\twoheadrightarrow$ body_state(B, V)

LP7 Sensing a body state
If body state B with level *V* occurs,
then this body state B with level *V* will be sensed.
body_state(B, V) $\twoheadrightarrow$ sensor_state(B, V)

LP8 Generating a sensory representation of a body state
If body state B with level *V* is sensed,
then a sensory representation for body state B with level *V* will occur.
sensor_state(B, V) $\twoheadrightarrow$ srs(B, V)

LP9 From sensory representation of body state to feeling
If a sensory representation for body state B with level *V* occurs,
then B is felt with level *V*.
srs(B, V) $\twoheadrightarrow$ feeling(B, V)

Alternatively, dynamic properties LP5 to LP8 can also be replaced by one dynamic property LP10 describing an as if body loop as follows.

LP10 From preparation to sensed body state
If preparation state for body state B occurs with level *V*,
then the effector state for body state B with level *V* will occur.
preparation_state(B, V) $\twoheadrightarrow$ srs(B, V)

4 Example Simulation Results

Based on the model described in the previous section, a number of simulations have been performed. Some example simulation traces are included in this section as an illustration; see Figures 4 and Figure 5 (here the time delays within the temporal LEADSTO relations were taken 1 time unit). In Figure 4 two different traces are shown with different characteristics. Note that the scaling of the vertical axis differs per graph. For both traces the world state shows an offer with a rather modest strength of *0.3*. Moreover both $\gamma_1 = 0.6$ and $\gamma_2 = 0.6$. Simulation trace 1 at the left hand side has $\beta_1 = 0.5$ and $\beta_2 = 0.5$, whereas simulation trace 2 at the right hand side has $\beta_1 = 0.5$ and $\beta_2 = 1$. In trace 1 the belief (and also the feeling) gets the same strength as the stimulus, namely *0.3*; here no effect of the emotional response is observed. However, in trace 2 the belief gets a higher strength (namely *0.65*) due to the stronger emotional response (with feeling getting strength *1*). This shows how a belief can be affected in a substantial manner by the feedback from the emotional response on the belief.

In Figure 5 the complete example scenario for the car parking case discussed earlier is shown. The world state shows something that (from a distance) looks like a charge with strenght *0.8* until time point 225; this is indicated by the dark line in the upper part of Figure 5. For this case $\beta_1 = 0.8$ and $\beta_2 = 0.4$ was taken, which means a modest role for the emotional response. The belief in a charge leads to an increasingly strong emotional body state *b1* and via the related feeling, the belief reaches a strength a bit above *0.9*. However, having come closer to the car, after time point 225 the world state shows with strength *0.8* something that is more like an offer, whereas the strength of the charge shown drops to *0.05*, which also was the strength of the offer before time point 225. As a consequence the belief in a charge drops and based on a different emotion response on the offer belief based on body state *b2* the strength of the belief in an offer increases until above *0.9*.

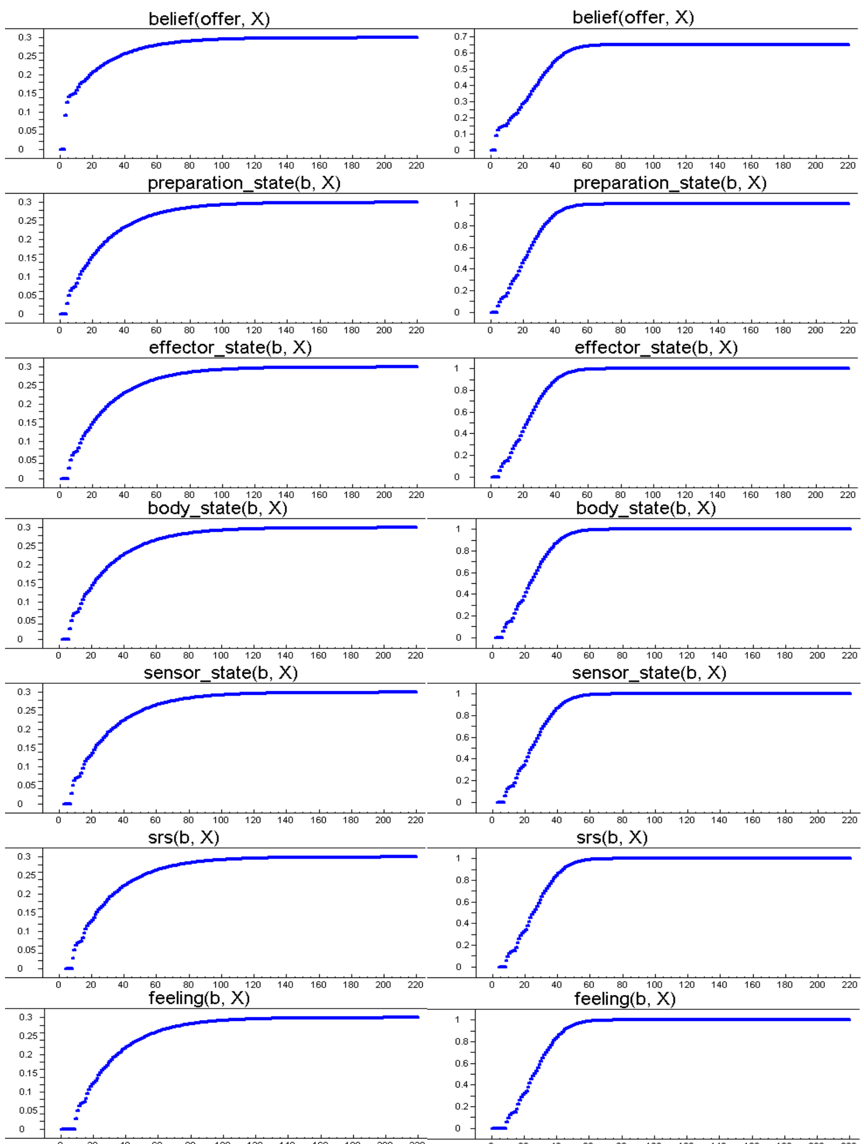

Figure 4: Two example traces: (1) $\beta_1 = 0.5$ and $\beta_2 = 0.5$, (2) $\beta_1 = 0.5$ and $\beta_2 = 1$.

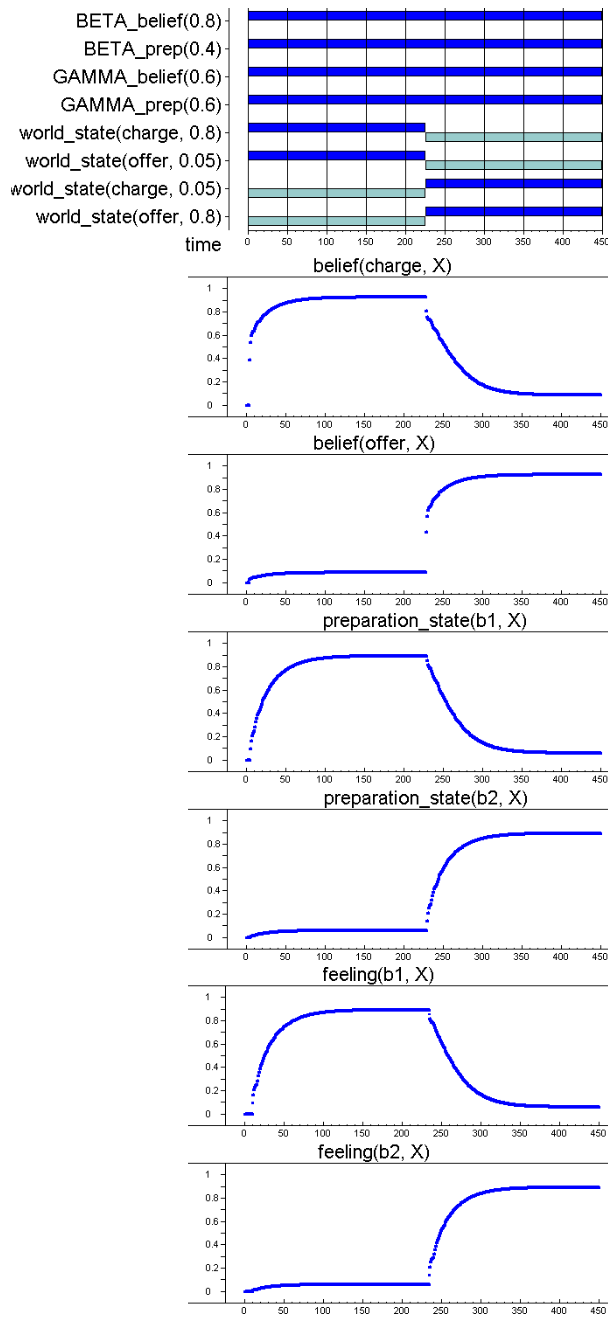

Figure 5: Trace for the car parking case with $\beta_1 = 0.8$ and $\beta_2 = 0.4$.

5 Mathematical Analysis

In the example simulations discussed above it was shown that for a time period with a constant environment, the strengths of beliefs, body states and feelings reach a stable equilibrium. By a mathematical analysis it can be addressed which types of equilibria are possible. To this end equations for equilibria can be determined from the dynamical model equations for the belief and the preparation state level, which can be expressed as differential equations as follows (with $b(t)$ the level of the belief, $s(t)$ of the stimulus, $f(t)$ of the feeling, and $p(t)$ of the preparation for the body state at time t).

$$db(t)/dt = \gamma_1 (\beta_1(1-(1-s(t))(1-f(t))) + (1-\beta_1)s(t)f(t) - b(t))$$
$$dp(t)/dt = \gamma_2 (\beta_2(1-(1-b(t))(1-f(t))) + (1-\beta_2)b(t)f(t) - p(t))$$

To obtain equations for equilibria, constant values for all variables are assumed (also the ones that are used as inputs such as the stimuli). Then in all of the equations the reference to time t can be left out, and in addition the derivatives $db(t)/dt$ and $dp(t)/dt$ can be replaced by 0. Assuming γ_1 and γ_2 nonzero, this leads to the following equations.

$$\beta_1(1-(1-s)(1-f)) + (1-\beta_1)sf - b = 0$$
$$\beta_2(1-(1-b)(1-f)) + (1-\beta_2)bf - p = 0$$

As for an equilibrium it also holds that $f = p$, this results in the following two equations in b, f, and s:

$$\beta_1(1-(1-s)(1-f)) + (1-\beta_1)sf - b = 0 \qquad (1)$$
$$\beta_2(1-(1-b)(1-f)) + (1-\beta_2)bf - f = 0 \qquad (2)$$

For the general case (1) can directly be used to express b in f, s and β_1. Using this, in (2) b can be replaced by this expression in f, s and β_1, which transforms (2) into a quadratic equation in f with coefficients in terms of s and the parameters β_1 and β_2. Solving this quadratic equation algebraically provides a complex expression for f in terms of s, β_1 and β_2. Using this, by (1) also an expression for b in terms of s, β_1 and β_2 can be found. As these expressions become rather complex, only an overview for a number of special cases is shown in Table 1 (for 9 combinations of values 0, 0.5 and 1 for both β_1 and β_2). For these cases the equations (1) and (2) can be substantially simplified as shown in the second column (for equation (1)) and second row (for equation (2)). The shaded cases are instable (not attracting), so they only occur when these values are taken as initial values.

As can be seen in this table, for persons that are pessimistic for believing ($\beta_1 = 0$) and have a negative profile in generating emotional responses ($\beta_2 = 0$), reach a stable equilibrium for which both the belief and the feeling have level 0. The opposite case occurs when a person is optimistic for believing ($\beta_1 = 1$) and has a positive profile in generating emotional responses ($\beta_2 = 1$). Such a person reaches a stable equilibrium for which both the belief and the feeling have level 1. For cases where one of these β_1 and β_2 is 0 and the other one is 1, a stable equilibrium is reached where the belief gets the same level as the stimulus: $b = s$. When a person is in the middle between optimistic and pessimistic for believing ($\beta_1 = 0.5$), for the case of a negative profile in generating emotional responses the stable belief reached gets half of the level of the stimulus, whereas for the case of a positive profile in generating emotional responses the stable belief reached gets *0.5* above half of the level of the stimulus (which is the *0.65* shown in the second trace in Figure 4). This clearly shows the effect of the feeling on the belief. The case where both $\beta_1 = 0.5$ and $\beta_2 = 0.5$ is illustrated in the first trace in Figure 4: $b = f = s$.

<table>
<tr><td></td><td>β_2 eq. (2)</td><td colspan="2">0</td><td>0.5</td><td colspan="2">1</td></tr>
<tr><td>β_1</td><td>eq. (1)</td><td>$f = 0$</td><td>$b = 1$</td><td>$b = f$</td><td>$f = 1$</td><td>$b = 0$</td></tr>
<tr><td rowspan="2">0</td><td rowspan="2">$b = sf$</td><td rowspan="2">$b = f = 0$</td><td rowspan="2">$b = f = s = 1$</td><td>$b = f = 0$</td><td rowspan="2">$b = s$
$f = 1$</td><td>$b = s = 0$</td></tr>
<tr><td>$b = f$ and $s = 1$</td><td>$b = f = 0$</td></tr>
<tr><td>0.5</td><td>$b = (s + f)/2$</td><td>$b = s/2$
$f = 0$</td><td>$b = f = s = 1$</td><td>$b = f = s$</td><td>$b = (s + 1)/2$
$f = 1$</td><td>$b = f = s = 0$</td></tr>
<tr><td rowspan="2">1</td><td rowspan="2">$1-b = (1-s)(1-f)$</td><td rowspan="2">$b = s$
$f = 0$</td><td>$b = f = 1$</td><td>$b = f = 1$</td><td rowspan="2">$b = f = 1$</td><td rowspan="2">$b = f = s = 0$</td></tr>
<tr><td>$b = s = 1$</td><td>$b = f$ and $s = 0$</td></tr>
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Table 1: Overview of equilibria for 9 cases of parameter settings.

6 Discussion

In this paper an agent model was introduced incorporating the reciprocal interaction between believing and feeling based on neurological theories that address the role of emotions and feelings. A belief usually triggers an emotional response. Conversely, a belief may not only depend on information obtained, but also on this emotional response, as, for example, shown in literature such as (Eich et al., 2000; Forgas et al., 2005; Forgas et al., 2009; Niedenthal, 2007; Schooler and Eich, 2000). Accordingly, the introduced model describes more specifically how a belief generates an emotional response that is felt, and on the other hand how the emotion that is felt affects the belief. For feeling the emotion, based on elements taken from (Damasio, 1999, 2004; Bosse, Jonker and Treur, 2008), a converging recursive body loop is included in the model. As a second loop the model includes a converging feedback loop for the interaction between feeling and belief. The causal relation from feeling to belief in this second loop was inspired by the Somatic Marker Hypothesis described in (Damasio, 1994, 1996; Bechara and Damasio, 2004), and may also be justified by a Hebbian learning principle (cf. Hebb, 1949; Bi and Poo, 2001), as also has been done for the functioning of mirror neurons; e.g., (Keysers and Perrett, 2004; Keysers and Gazzola, 2009). Both the strength of the belief and of the feeling emerge as a result of the dynamic pattern generated by the combination of the two loops. The model was specified in the hybrid dynamic modelling language LEADSTO, and simulations were performed in its software environment; cf. (Bosse, Jonker, Meij, and Treur, 2007). A mathematical analysis of the equilibria of the model was discussed. The model was illustrated using an example scenario where beliefs are affected by negative and positive emotional responses.

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