A Computational Model for Adaptive Emotion Regulation

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Abstract. Emotion regulation describes how a subject can use certain strategies to affect emotion response levels. Usually, models for emotion regulation assume mechanisms based on feedback loops that indicate how to change certain aspects of behaviour or cognitive functioning in order to get a more satisfactory emotion response level. Adaptation of such feedback loops is usually left out of consideration. In this paper, a computational model for adaptive emotion regulation is introduced. This model includes mechanisms for adaptivity of the degree of flexibility of the emotion regulation process. Based on this computational model, a number of simulation experiments have been performed and evaluated.

1 Introduction

Since a number of decades, there is global consensus that emotions have various functions. They have a facilitating function in decision making, prepare a person for rapid motor responses, provide information regarding the ongoing match between organism and environment, and script our social behaviour. In the past two decades, psychological research on emotions has started to focus more on *emotion regulation* (e.g., Gross, 1998; Davidson, Putnam, and Larson, 2000; Gross, 1998, 2001; Ochsner and Gross, 2005; Thompson, 1994), i.e., the process humans undertake to increase, maintain or decrease their emotion response.

Usually, models for emotion regulation are conceptualised as dynamical systems based on feedback loops that indicate how to change certain aspects of behaviour or cognitive functioning in order to get a more satisfactory emotion response level. Such feedback loops have certain characteristics, for example, concerning sensitivity and flexibility of the adjustments made. Too sensitive feedback loops may result in stressful and energy-consuming behaviour involving frequent adjustments, whereas feedback loops that are not sensitive enough may result in long periods of less desirable emotions. To obtain a balanced form of emotion regulation, either certain more or less ideal characteristics of the feedback loops in the emotion regulation system should be set at forehand, or an adaptation mechanism should be available that allows for tuning them on the fly. As it does not seem very plausible to have one set of ‘ideal’, innate characteristics applicable in various contexts, this paper takes the latter assumption as a point of departure: adaptive emotion regulation. A computational model for such adaptive emotion regulation processes is introduced that includes mechanisms to assess and adapt the degrees of flexibility of the emotion regulation process over longer periods. The ideas described by Gross (1998, 2001) formed a source of inspiration.

First, in Section 2, Gross's perspective on emotion regulation is briefly discussed. His model describes a number of strategies humans use to adjust their emotion response levels, varying from situation selection to cognitive change and response modulation. Next, in Section 3, the dynamical system modelling approach used is introduced. After that, Section 4 and 5 describe the simulation model formalising adaptive emotion regulation processes. A number of simulation results are shown, both for nonadaptive regulation (Section 6) and for adaptive regulation (Section 7). Section 8 concludes the paper with a discussion.

2 Emotion Regulation

Humans use a number of strategies to affect their level of emotion response for a given type of emotion, for example, to avoid a too high or too low emotion response level. Gross (1998, 2001) informally describes a process model of emotion regulation incorporating different types of strategies. *Antecedent-focused strategies* are applied to the process preparing for response tendencies before they are fully activated. *Response-focused strategies* are applied to the activation of the actual emotional response, when an emotion is already underway. Gross distinguishes four different types of antecedent-focused emotion regulation strategies, applied at different points in the process of emotion generation: situation selection, situation modific-ation, attentional deployment and cognitive change. A fifth strategy, response modulation, is response-focused.

The strategy *situation selection* involves a person choosing to be in a situation that for a certain emotion matches the emotional response level the person aims at. The *situation modification* strategy involves a person modifying an existing situation so as to obtain a different level of emotion. Another antecedent-focused emotion regulation strategy is *attentional deployment*. This strategy refers to shifting attention to a certain aspect. The fourth antecedent-focused emotion regulation strategy is *cognitive change*: selecting a cognitive meaning to an event. A specific type of cognitive change, which is aimed at down-regulating emotion, is reappraisal: re-evaluating a potentially emotion-eliciting situation in terms that decrease its emotional impact (Gross, 2001). An example of reappraisal is a case when a person loses a tennis match and blames the weather circumstances, instead of his own capacities. However, note that cognitive change could also be aimed at up-regulating emotion. A fifth strategy, *response modulation*, a response-focused strategy, is applied after the emotion response tendencies have been generated: a person tries to affect the process of response tendencies becoming a response. As Gross considers this strategy to be not very effective, it is not considered in the paper, although it would not be difficult to incorporate it in the computational model.

3 Modelling Approach

Modelling the various aspects involved in emotion regulation in an integrated manner poses some challenges. On the one hand, qualitative aspects have to be addressed, such as decisions to regulate one's emotion (e.g., by selecting a different situation). On the other hand, quantitative aspects have to be addressed, such as levels of emotional response.

The modelling approach based on the modelling language LEADSTO (Bosse, Jonker, Meij, and Treur, 2007) fulfils these desiderata. It integrates qualitative, logical aspects such as used in approaches based on temporal logic (e.g., Barringer et al., 1996) with quantitative, numerical aspects such as used in Dynamical Systems Theory (e.g., Ashby, 1960; Port and van Gelder, 1995). Direct temporal dependencies between state properties in two successive states are modelled by *executable dynamic properties* defined as follows. Let α and β be state properties of the form 'conjunction of atomic state properties or negations thereof', then the notation $\alpha \twoheadrightarrow_{e,\ f,\ g,\ h}\ \beta$, means:

If state property α *holds for a certain time interval with duration g,*
then after some delay (between e and f) state property β *will hold*
for a certain time interval of length h.

Here, atomic state properties can have a qualitative, logical format, such as an expression desire(d), expressing that desire d occurs, or a quantitative, numerical format such as has_value(x, v) expressing that variable x has value v.

4 Global Overview of the Simulation Model

For convenience, the model concentrates on one specific type of emotion. In principle, this can be any emotion that is considered to be a basic human emotion, e.g., sadness, happiness, or anger (Ekman, Friesen, and Ellsworth, 1972). In order to describe the regulation of such an emotion, following Gross (1998), the model takes for the four antecedent-focused emotion regulation strategies four corresponding *elements* k, indicating what is affected by the particular strategies; i.e.,

situation selection:	situation
situation modification:	sub_situation
attentional deployment:	aspect
cognitive change:	meaning

The model is generic in the sense that this set of strategies can easily be adapted. It is assumed that at each point in time, for each element k a certain choice is in effect, and this choice has a certain *emotional value* v_k attached. This emotional value contributes to the *emotion response level* ERL via an element-specific weight factor w_k, thereby taking into account a *persistency factor* β indicating the degree of persistence or slowness of adjusting of the emotion response level when new emotional values are obtained. Someone whose emotions can change very rapidly (e.g., who stops being angry in a few seconds) will have a very low β.

Humans are always searching for a certain level of emotion, depending on the person. The level of emotion aimed at depends also on the type of emotion. Most humans aim at a relatively high level of emotion for happiness, while they aim at a lower level of emotion for fear. The regulation process compares the actual emotion response level ERL to the emotion response level ERL_norm aimed at. The *difference* d between the two is the basis for adjustment of the choices made for each of the elements k; based on these adjusted choices, each element k will have an adjusted emotional value v_k. The strength of such an adjustment is expressed by a *modification factor* α_k, which represents the flexibility to change one's emotional value for a certain element. For instance, $\alpha_{situation}$ (i.e., the α_k for the element k = situation) models the flexibility to change one's situation. An overview of the variables used in the model is given in Table 1 (of which γ_k and c_k, are explained later).

Table 1. Variables addressed in the model

Variable	**Meaning**
ERL	Emotion Response Level
ERL_norm	Emotion Response Level aimed at
d	Difference between ERL and ERL_norm
β	Persistency factor for ERL
k	Elements indicating strategies incorporated
w_k	Weight of element k in adjusting ERL
v_k	Emotional value for element k
α_k	Modification factor that represents the flexibility to change the emotional value v_k of element k
γ_k	Adaptation factor that represents the flexibility to adjust modification factor α_k of element k
c_k	Costs of adjusting modification factor α_k

Some of these variables were chosen to be set at forehand and remain constant during the process (in particular ERL_norm, β, w_k, c_k, γ_k). The other variables depend on each other and on the fixed variables, as shown in a qualitative manner in the graph depicted in Figure 1.

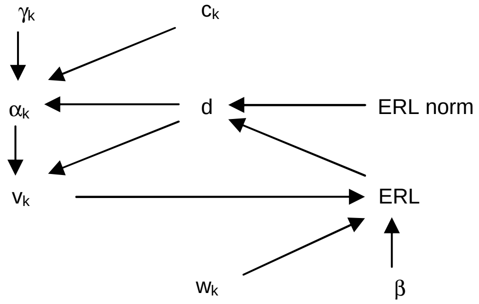

Fig. 1. Dependencies between the variables

This graph shows that the emotion response level ERL is affected by the emotional values v_k for the different elements, the weights w_k attached to these elements, and the persistency factor β. The difference d between response level and norm obviously depends on both of these factors. The emotional values v_k for the different elements are affected by this difference d and the modification factor α_k.

In the model described so far, the modification factors α_k could be taken fixed. In order to obtain a model that can adapt itself to various circumstances, however, the flexibility in adjusting emotional values v_k as expressed by the modification factors α_k need to be adaptable. For example, when a subject is adjusting its behaviour all the time in order to obtain certain emotion levels aimed at, this may result in a stressful and energy-consuming life. In such a case it is useful if the emotion regulation process can adapt itself to obtain a more peaceful mode of functioning. To obtain such adaptive capabilities, the flexibility to choose different emotional values v_k as expressed by the modification factors α_k can be adapted to an assessment of the emotion regulation process: a sort of reflection or meta-cognition about the emotion regulation process based on the history of differences d. The *adaptation factor* γ_k mediating in this adaptation process represents the personal flexibility to adjust the emotion regulation behaviour based on such an assessment. Moreover, c_k represents the *costs* or *effort* of adjusting the modification factor for element k. Note that thus the model contains two cycles (see Figure 1). One is the basic emotion regulation cycle from the v_k to ERL via d back to the v_k. The other one is the adaptation cycle from the α_k to the basic regulation cycle and back (via v_k , ERL and d back to α_k).

5 Quantitative Relations in the Simulation Model

To obtain a quantitative model, the emotion response level and the emotional values for the different elements for a given type of emotion are represented by real numbers in the interval [0, 2] (where 0 is the lowest possible emotion response level, and 2 the highest). The level of emotion to aim at (ERL_norm) is expressed by a fixed real number in the domain [0, 2]. The process of emotion regulation has a continuous, interactive and cyclic nature. An approach to model such a process is the Dynamical Systems Theory (DST) based on differential or difference equations; e.g., (Port and van Gelder, 1995). As simulation needs some form of discretisation, a set of difference equations is used, with a fixed step size s, that can be taken any size as desired.

5.1 Updating the Emotional Response Level

The emotion response level is recalculated each step by the following difference equation formula:

$$new\_ERL = (1-\beta) * \Sigma_k (w_k * v_k) + \beta * ERL$$

In this formula[1], new_ERL is the new emotion response level, and ERL is the old emotion response level. The persistency factor β is the proportion of the old emotion re-

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[1] Note that the formula is equivalent to:

$\Delta ERL = (1-\beta) * (\Sigma_k (w_k * v_k) - ERL)$ with $\Delta ERL = new\_ERL - ERL$

sponse level that is taken into account to determine the new emotion response level. The new contribution to the emotion response level is calculated by the weighted sum of the emotional values: $\Sigma_k\ w_k * v_k$. By normalisation, the sum of all the weights w_k is taken to be 1. Notice that for this difference equation an equilibrium occurs for ERL when $\Delta ERL = 0$ or, equivalently, new_ERL = ERL, i.e., when

$$ERL = \Sigma_k (w_k * v_k)$$

Within the simulation model, the update of the emotional response level is expressed by the following dynamic property in LEADSTO format (where s is the step size):

LP1 (Update Emotion Response Level)
emotion_response_level(erl)
and has_weight(situation, w1) and has_weight(sub_situation, w2)
and has_weight(aspect, w3) and has_weight(meaning, w4)
and has_emotional_value(situation, v1) and has_emotional_value(sub_situation, v2)
and has_emotional_value(aspect, v3) and has_emotional_value(meaning, v4)
$\twoheadrightarrow_{0,\,0,\,s,\,s}$
emotion_response_level((1-beta) * (w1*v1 + w2*v2 + w3*v3 + w4*v4) + beta * erl)

5.2 Updating the Emotional Values

The chosen emotional values v_k, which affect the emotion response level, are on their turn adjusted each step by the following set of difference equations:

$$d = ERL - ERL\_norm$$
$$\Delta v_k = -\alpha_k * d / d_{max}$$
$$new\_v_k = v_k + \Delta v_k$$

In these formulas, new_v_k is the new emotional value v_k, and v_k is the old emotional value, while Δv_k is the change of this emotional value. The change in emotional value v_k is calculated by the formula $-\alpha_k * d / d_{max}$. In this formula, α_k is the modification factor, and d is the difference between the actual emotion response level and the emotion response level aimed at (ERL_norm). Here d_{max} is an estimation of the maximum difference that can be reached. So d / d_{max} is the proportion of the maximal reachable level of emotion above the level of emotion aimed at (or below this level, if d is negative).

An equilibrium for the v_k occurs when $\Delta v_k = 0$ or, equivalently, $d = 0$, i.e., when the actual emotion response level ERL equals the emotion response level ERL_norm aimed at. This will also be an equilibrium for ERL, so (see above) this is the case when

$$ERL = ERL\_norm = \Sigma_k (w_k * v_k)$$

A person will ‘choose’ a more extreme change in an emotional value v_k when (s)he is more flexible in this emotional value v_k (this is the case when α_k is high), or when the emotion response level is further away from the emotion response level aimed at (i.e., when d deviates more from 0). The update of emotional values is expressed in LEADSTO format as follows:

LP2 (Update Emotional Values)
emotion_response_level(erl) and erl_norm(erl_norm)
and has_emotional_value(element, v) and has_modification_factor(element, a)
$\twoheadrightarrow_{0,\,0,\,s,\,s}$
has_emotional_value(element, v – a * (erl - erl_norm) / dmax)

5.3 Adaptation of the Modification Factors

In order to be able to simulate adaptive emotion regulation in the detailed computational model, a function is needed to evaluate the process of emotion regulation over a period of time. The following evaluation function is used:

$$\text{Eval}(d_{t\text{-}t+p}) = \text{mean}(\text{abs}(d))_{t\text{-}t+p}$$

To evaluate the emotion regulation process over the time points t until t+p (where currently p=5), the absolute difference of the actual level of emotion and the level of emotion aimed at is taken for all time points. The (arithmetic) mean value of these absolute differences provides the value of the evaluation function.

Until the model has done enough steps to perform this evaluation function for two different periods of time, the α_k's are kept persistent. After that, the evaluation function is used to adjust the modification factors α_k using the following set of difference equations:

$$\Delta\alpha_k = \gamma_k * (\alpha_k / 1+\alpha_k) * (\,(\text{Eval(new\_d)} / \text{Eval(old\_d)}) - c_k\,)$$
$$\text{new\_}\alpha_k = \alpha_k + \Delta\alpha_k$$

In these formulas, $\text{new\_}\alpha_k$ is the new modification factor α_k and γ_k represents in a numerical manner the personal flexibility to adjust the emotion regulation behaviour. When γ_k increases, in a proportional manner $\Delta\alpha_k$ will increase, and α_k will change more. The part $\alpha_k / 1+\alpha_k$ in the first place arranges that $\Delta\alpha_k$ is more or less proportional to α_k. The denominator $1+\alpha_k$ prevents α_k from under- or overadaptation when it gets very high. Furthermore, new_d is the mean value of d in the last time interval, and old_d is the mean value of d in an older time interval. The ratio Eval(new_d) / Eval(old_d) will be smaller, if the actual level of emotion response deviated relatively more from the level of emotion aimed at in the older interval than in the newer interval. Currently, for the new interval the interval from t-5 to t is taken, with t the current time point, and for the old interval the interval from t-10 to t-5. If Eval(new_d) / Eval(old_d) is smaller, $\Delta\alpha_k$ will be lower. Finally, c_k represents the costs of adjusting the modification factor for element k. When there are higher costs to adjust α_k, the value c_k is higher, and $\Delta\alpha_k$ will be lower. The following dynamic property expresses how a modification factor is changed (where the state property erl_steps_back(i, erl) represents the fact that at t-i the value of the emotion response level was erl):

LP7 (Update Modification Factors)
alphas_not_persistent_anymore
and has_modification_factor(element, a)
and has_cost(element, costs)
and has_adaptation_factor(element, gamma)
and erl_steps_back(1, erl1) and erl_steps_back(2, erl2)
and erl_steps_back(3, erl3) and erl_steps_back(4, erl4)
and erl_steps_back(5, erl5) and erl_steps_back(6, erl6)
and erl_steps_back(7, erl7) and erl_steps_back(8, erl8)
and erl_steps_back(9, erl9) and erl_steps_back(10, erl10)

$\twoheadrightarrow_{0,\,0,\,s,\,s}$
has_modification_factor(element, a + gamma * a / (1+a) * ((abs(erl1-erl_norm) + (abs(erl2-erl_norm) + (abs(erl3-erl_norm) + (abs(erl4-erl_norm) + (abs(erl5-erl_norm)) / 5) / (((abs(erl6-erl_norm) + (abs(erl7-erl_norm) + (abs(erl8-erl_norm) + (abs(erl9-erl_norm) + (abs(erl10-erl_norm)) / 5) - costs))

6 Simulation Results: Nonadaptive Regulation

A number of experiments have been performed to test what kind of behaviour can be simulated by the model. The different scenarios take different settings for the modification factors α_k and the adaptation factors γ_k. The fixed values of parameters are as shown in Table 2.

Table 2. Values of parameters used in the simulations

Parameter	Value
ERL_norm	0.5
β	0.7
s	1

Parameter	Value
w_1	0.35
w_2	0.30
w_3	0.20
w_4	0.15

The subject considered here has an optimal level of emotion of 0.5 in the domain [0, 2]. The factor β is set to 0.7, which means that in each step, 70% of the old emotional response level persists, and the remaining 30% is determined by the new emotional values. The weight attached to situation selection is 0.35, which means that the selected situation determines 35% of the 30% of the new emotion response level that is determined by the emotional values. Similarly, the weights for situation modification, attentional deployment, and cognitive change are set to 0.30, 0.20, and 0.15, respectively. The results of some of the experiments are shown and explained below. More (detailed) results of the experiments can be found at the following URL: http://double-blind-review.741.com/adapemreg.pdf.

6.1 Optimal emotion regulation

In the experiment described first, all modification factors α_k were set to 0.15, and all adaptation factors γ_k (and costs c_k) were set to 0. The initial values for the v_k were 1.90, 1.85, 1.80, 1.75, and for ERL 1.85, respectively. The results are shown in Figure 2. In such figures, time is on the horizontal axis, the values of the different variables on the vertical axis.

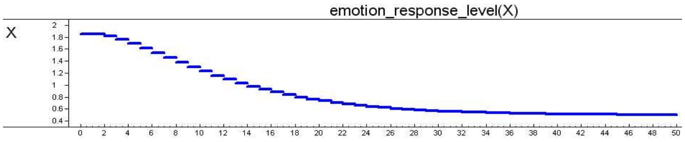

Fig. 2. Results for an optimal case ($\alpha_k = 0.15$, $\gamma_k = 0$)

The emotional response level decreases monotonically without decreasing below the level aimed at. So, the subject gradually reaches his level of emotion aimed at. The emotional values show similar behaviour (due to space limitations not shown here).

6.2 Over- and under-regulation

In a second experiment, the modification factors α_k for all elements were set to 0.4 and all adaptation factors γ_k (and costs c_k) were set to 0. This means that the subject has a relatively high flexibility in emotion regulation, for all elements. In this case, the emotion response level starts to decrease rapidly, immediate after the experiment has started. However, it decreases below the level of 0.5 aimed at. It reaches its minimum after 15 steps in the simulation, at about 0.3: the subject over-regulates the emotion. After this, the emotion response level starts to raise until it is just above the optimal level of 0.5, and stays more or less at this value aimed at. For the corresponding figure, see URL: http://double-blind-review.741.com/adapemreg.pdf.

In a third experiment discussed, the subject has a very low flexibility in emotion regulation, with a fixed α_k value of 0.01 for all elements and all γ_k (and c_k) again set to 0; see Figure 3. Here the emotion response level decreases extremely slowly: under-regulation. After 50 steps, it has only decreased by 0.3 until 1.55, still far from the level 0.5 aimed at.

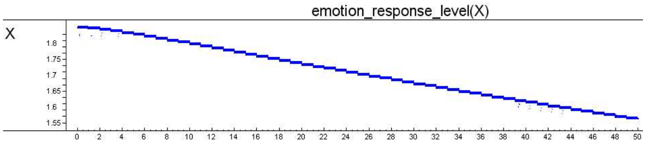

Fig. 3. An under-regulation case ($\alpha_k = 0.01$, $\gamma_k = 0$)

7 Simulation Results: Adaptive Regulation

To test the model for adaptivity of the emotion regulation process, some more experiments have been done. In this experiment, all adaptation factors γ_k were set to 0.09, and the costs c_k were set to 0.7, 0.4. 0.4, 0.6, respectively. The subject starts with a very high emotion response level of 1.8, and very high emotional values, all set to the same level of 1.8. The weights attached to the various elements are the same as earlier. The modification factors α_1 - α_4 have an initial value of 0.01, the same value as in the under-regulation experiment (see Figure 3). The result for the emotion response value is shown in Figure 4.

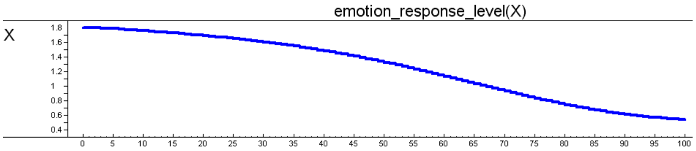

Fig. 4. An adaptive regulation case ($\gamma_k = 0.09$)

In this experiment, the emotion response level starts to decrease faster after a period of time. Because of this adaptive behaviour, the optimal level of excitement, 0.5, is reached after 100 steps. This happens, because the α_k's are not fixed anymore, but can be changed, based on an evaluation of the emotion regulation in a period in the past.

The emotional values v_k show a pattern similar to the emotion response levels over time. Some emotional values obviously decrease faster than others. The emotional value for situation selection decreases only until 1.1, and the emotional value for cognitive meaning until 0.8, while the emotional values for situation modification, attentional deployment, and response modification decrease until they are almost 0. The costs c_k for situation selection are 0.7, and for cognitive meaning 0.6, while the costs for the other elements are 0.4. These results show that the emotional values for elements with higher costs, are changed less. Figure 5 shows how the modification factors α_k change over time.

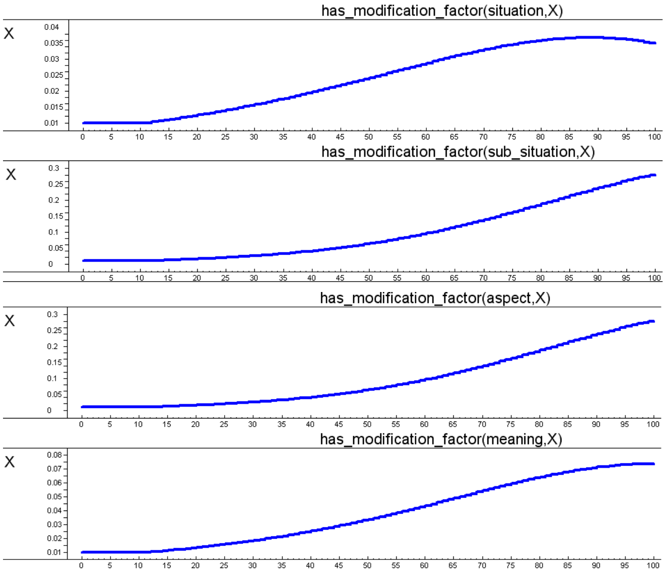

Fig. 5. Modification factors for the adaptive case

All modification factors show similar behaviour, the main difference is that the modification factors with higher costs, situation selection and cognitive meaning, rise much less than the other modification factors. While the other three modification factors rise to a value of 0.3, the modification factor for meaning rises only until around 0.08, and the modification factor for situation selection only until around 0.04. Also, the modification factor for situation selection starts to decrease again, before the simulation stops. This is the effect of the higher costs to change behaviour in situation selection or cognitive change.

8 Discussion

In this paper, a dynamical system model for adaptive emotion regulation has been introduced. The model was inspired by the (informally described) model of Gross (1998, 2001). The adaptive emotion regulation model has been constructed using the high-level modelling language LEADSTO, integrating both quantitative aspects (such as levels of emotional response) and qualitative aspects (such as decisions to regulate one's emotion). Simulation experiments have been performed for different situations, by using different settings for the modification factors and adaptation factors:

- for more or less ideal non-adaptive regulation,
- for nonadaptive cases of over-regulation and under-regulation, and
- for adaptive cases, changing under- or over-regulation into a more optimal form of regulation.

The simulation results are consistent with the behaviour for different cases as described by Gross.

Although the process of emotion regulation is widely investigated in the literature (e.g., Davidson, Putnam, and Larson, 2000; Gross, 1998, 2001; Ochsner and Gross, 2005; Thompson, 1994), only few contributions address the possibility of developing a computational model of this process. The computational models that have been developed so far either address some very specific aspects of the process at a more detailed (neurological) level, see e.g. (Thayer and Lane, 2000), or they aim at incorporating emotions into software agents, in which case they focus more on emotion generation than on emotion regulation, see e.g. (Bates, 1994). The current paper can be seen as a first attempt to build a bridge between both directions, and to incorporate adaptivity.

Computational models for emotion regulation, like the one described in this paper, can be used for different purposes. In the first place, from a Cognitive Science perspective, such a model can provide insight in the process of emotion regulation. This may be useful for the purpose of developing therapies for persons that have difficulties in regulating their emotions (Burns et al., 2003; Towl and Crighton, 1996), for example, in work with forensic inpatients. In addition, a model for emotion regulation can be used in the field of Artificial Intelligence, see e.g. (Bates, 1994). For example, in the domain of virtual reality it can be used to let virtual agents show human-like behaviour regarding emotion regulation. Similarly, in the gaming industry, there is much interest in manners to let game characters emotionally behave like humans. Finally, computational models for emotion regulation may play a role within the field of Ambient Intelligence (Aarts, Harwig, and Schuurmans, 2001). For instance, in settings where humans have to interact intensively with automated systems, it is useful if the system maintains a model of the emotional state of the user. This can enable the system to adapt the type of interaction to the user's needs.

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