Dreaming Your Fear Away: a Computational Model for Fear Extinction Learning During Dreaming

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Abstract. In this paper a computational model is presented that models how dreaming is used to learn fear extinction. The approach addresses dreaming as internal simulation incorporating memory elements in the form of sensory representations and their associated fear. During dream episodes regulation of fear takes place, which is strengthened by Hebbian learning. The model was evaluated by a number of simulation experiments for different scenarios.

1 Introduction

In the recent cognitive and neurological literature the mechanisms and functions of dreaming have received much attention; e.g., [19-23], [27-32]. In such literature, usually dreaming is considered a form of internal simulation of real-life-like processes serving as training in order to learn or adapt certain capabilities. Dreaming makes use of memory elements for sensory representations (mental images) and their associated emotions to generate 'virtual simulations'; e.g., [20], pp. 499-500. Taking into account fear emotions that often play an important role in dreams, strengthening of regulation of such emotions is considered an important purpose of dreaming; see, for example, [20, 30]. To this end in dreams adequate exercising material is needed: sensory representations of emotion-loaden situations are activated, built on memory elements suitable for high levels of arousal:

> 'They are recombined or remapped in order to introduce elements that are incompatible with existing fear memories, thus facilitating (among other functions) the acquisition or maintenance of extinction memories. The latter inhibit fear memories (..), and consequently alleviate affect load.' ([20], pp. 500-501)

A comparison can be made to a virtual reality form of exposure therapy ([20], pp. 500-501). Strong fear associations of the sensory memory elements used to make up a dream creates situations in which a person has to cope with high levels of fear. Adopting basic elements from [26] the computational model presented here generates the type of internal simulation that is assumed to take place in dreaming. For the different dream episodes, the internal simulation incorporates interrelated processes of activation of sensory representation states (from memory) providing mental images, and activation of associated feelings. Moreover, it incorporates emotion regulation to suppress the feeling levels and the sensory representation states. The regulation mechanism strengthens the relevant connections by Hebbian learning; e.g., [2, 10, 16].

The structure of the paper is as follows. In Section 2 the computational model is described in more detail. Section 3 presents simulation results providing some dream scenarios. Finally, Section 4 is a discussion, in which also the relation of the model with neurological theories and findings is addressed.

2 A Computational Model for Fear Extinction Learning

The computational model presented here is based on mechanisms suggested in neurological literature; see Fig. 1 for an overview of the states and connections. Some of the (non-adaptive) basic elements were adopted from [26]. In Fig. 1 the basic model for a given stimulus s_k with sensory representation state srs_{s_k} and dream episode state es_{s_k} is shown ($k = 1, ..., n$). An explanation of the states used is shown in Table 1; an overview of the connections is shown in Table 2. Note that in Fig. 1 a sensory representation state and episode state for only one stimulus s_k is depicted. In the specification of the model below an arbitrary number n of such states are taken into account. In Section 4, a simulation scenario with four stimuli s_k is presented.

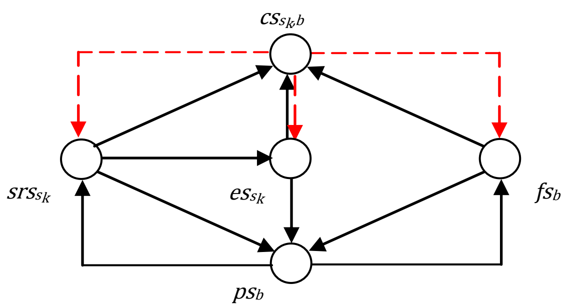

Fig 1. Overview of the states and connections in the model

The inhibiting links for fear regulation are indicated by dotted arrows (in red). The two links between srs_{s_k} and ps_b indicate the bidirectional association between stimulus s_k and emotional response b. The links between ps_b and fs_b indicate a recursive as-if body loop (see below).

Table 1: Overview of the state variables used

state	**explanation**
ps_b	Preparation state for bodily response b
fs_b	Feeling state for b
srs_{s_k}	Sensory representation state for stimulus s_k
$cs_{s_k b}$	Control state for regulation of sensory representation of s_k and feeling b
es_{s_k}	Dream episode state for s_k
mt_{s_k}	Memory trigger for s_k

Table 2: Overview of connections and weights

from states	to state	weights	LP
$srs_{s1}, \ldots, srs_{sn}, fs_b, es_{s1}, \ldots, es_{sn}$	ps_b	$\omega_{1,1}, \ldots \omega_{1,n}, \omega_2, \omega_{12,1}, \ldots \omega_{12,n}$	LP1
$ps_b, cs_{s1,b}, \ldots, cs_{sn,b}$	fs_b	$\omega_3, \omega_{4,1}, \ldots \omega_{4,n}$	LP2
$ps_b, cs_{sk,b}, mt_{sk}$	srs_{sk}	$\omega_{5,k}, \omega_{6,k}, \omega_{0,k}$	LP3
srs_{sk}, fs_b, es_{sk}	$cs_{sk,b}$	$\omega_{7,k}, \omega_{8,k}, \omega_{13,k}$	LP4
$srs_{sk}, es_{s1}, \ldots, es_{sn}, cs_{sk,b}$	es_{sk}	$\omega_{9,k}, \omega_{10,1,k}, \ldots, \omega_{10,n,k}, \omega_{11,k}$	LP5

The model incorporates four connected cycles (see Fig. 1):

- A positive preparation-feeling cycle $ps_b - fs_b$ (right lower part in Fig. 1)
- A positive preparation-sensory representation cycle $ps_b - srs_{sk}$ (left lower part)
- A negative emotion regulation cycle $cs_{sk,b} - fs_b, srs_{sk}, es_{sk}$ (upper part)
- A positive fear extinction learning cycle $cs_{sk,b} - \omega_{7,k}, \omega_{8,k}$ (upper part)

Each of these cycles will be briefly discussed.

The preparation-feeling cycle $ps_b - fs_b$

As indicated in Section 1 above, dreams can be considered as flows of activated imaginations based on (re)combined sensory memory elements with emotional associations. Such flows can be related to the notion of *internal simulation* put forward, among others, by [4, 5, 12, 17, 18]. The idea of internal simulation is that sensory representation states are activated (e.g., mental images), which in response trigger associated preparation states for actions or bodily changes, which, by prediction links, in turn activate other sensory representation states.

sensory representation states $\rightarrow$ preparation states $\rightarrow$ sensory representation states

Internal simulation has been used, for example, to describe prediction of effects of own actions (e.g., [3]), processes in another person's mind (e.g., [12]) or processes in a person's own body (e.g., [4]). The idea of internal simulation has been exploited in particular by applying it to bodily changes expressing emotions, using the notion of *as-if body loop* (cf. [4], pp. 155-158; [5], pp. 79-80; [7]):

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

Damasio [4] distinguishes an emotion (or emotional response) from a feeling (or felt emotion). The emotion and feeling in principle mutually affect each other in a bidirectional manner: an as-if body loop usually occurs in a recursive, cyclic form by assuming that the emotion felt in turn also affects the prepared bodily changes, as he points out, for example, in ([6], pp. 91-92; [7], pp. 119-122):

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

The preparation-sensory representation cycle $ps_b - srs_{sk}$

Sensory representations as stored in memory usually have emotional responses associated to them. This means that as soon as a sensory representation is activated also its associated emotional response preparations are activated, and, conversely, when an emotional response preparation is active, also the sensory representations associated to this type of response become active. This results in a cycle between sensory representations srs_{s_k} and emotional response preparations ps_b shown in the left lower part of Fig. 1. Together with the preparation – feeling cycle discussed above, this provides a state of fear as a complex and cyclic activation state of fear response preparations, fear feelings and fearful sensory representations.

The emotion regulation cycle $cs_{s_k,b}$ – fs_b, srs_{s_k}, es_{s_k}

Fear extinction indicates the process of suppressing fear states. This can be considered a specific type of *emotion regulation* to control emotions that are felt as too strong; cf. [11, 13, 14]. Emotion regulation mechanisms cover *antecedent-focused regulation* (e.g., selection and modification of the situation, attentional deployment, and reappraisal) and *response-focused regulation* (suppression of a response). Regulation of high levels of fear can take place by antecedent-focused emotion regulation, for example, by *attentional deployment* in the form of focusing attention in such a way that situations or aspects of situations in which too strong fear-related stimuli occur are kept out of the attention focus, or by a form of *re-appraisal* decreasing the negative feeling level based on changing the cognitive interpretation of fear-related stimuli into a less negative one. In the upper part of Fig. 1 such an emotion regulation mechanism is depicted. The upward arrows to the control state $cs_{s_k,b}$ take care for monitoring the sensory representations srs_{s_k}, feeling state fs_b and episode state es_{s_k} for the fear state, and when the fear level is too high, this leads to activation of the relevant control states $cs_{s_k,b}$. These control states in turn lead to inhibition of the fear-related states (the downward, dotted arrows in the upper part of Fig. 1).

The fear extinction learning cycle $cs_{s_k,b}$ – $\omega_{7,k}$, $\omega_{8,k}$

The basis of fear extinction learning is that the emotion regulation mechanisms discussed above are adaptive: they are strenghtened over time when they are intensively used. Note that fear extinction learning is *not* a form of unlearning or extinction of acquired fear associations, but it is additional *learning of fear inhibition* in order to counterbalance the fear associations which themselves remain intact (e.g., [20], p. 507). This learning process is modelled by applying a Hebbian learning principle (e.g., [2, 10, 16]) to the upward connections $\omega_{7,k}$ and $\omega_{8,k}$ from sensory representation state srs_{s_k} and feeling state fs_b to the control state $cs_{s_k,b}$ in the upper part of Fig. 1. Note that the dream episode state and its upward link to the control state serve as an amplifier in this Hebbian learning process. The positive cyclic character of this learning process is as follows: the stronger the upward connections become, the higher the activation level of the control state, and this again strengthens the learning process for the connections.

The computational model has been formalised as a set of differential equations. Parameter γ is used as a speed factor, indicating the speed by which an activation level is updated upon received input from other states. During processing, each state has an activation level represented by a real number between 0 and 1. Below, the (temporally) Local Properties (LP) for the dynamics based on the connections between the states in Fig. 1 are described by differential equations. In these specifications a threshold function th is used as a combination function for k incoming connections as follows: the combined input level is $th(\mu_1 V_1 + \ldots + \mu_k V_k)$ with μ_i the connection strength for incoming connection i and V_i the activation level of the corresponding connected state. For this threshold function th different choices can be made. In the simulation experiments (in LP1 to LP4) the following continuous logistic form was used:

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

Here σ is a steepness and τ a threshold parameter. Note that for higher values of $\sigma\tau$ (e.g., σ higher than $20/\tau$) this threshold function can be approximated by the simpler expression; this has been used in LP5:

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

The first property LP1 describes how preparation for response b is affected by the sensory representation and episode states of stimuli s_k (triggering the response), and by the feeling state for b:

LP1 Preparation state for response b

$$\frac{dps_b(t)}{dt} = \gamma \; [\; th(\Sigma_k\, \omega_{1,k} srs_{s_k}(t) + \omega_2\, fs_b(t) + \Sigma_k\, \omega_{12,k} es_{s_k}(t)) - ps_b(t)]$$

The feeling state for b is not only affected by a corresponding preparation state for b, but also by the inhibiting control states for s_k and b. This is expressed in dynamic property LP2. Note that for this suppressing effect the connection weight $\omega_{4,k}$ from the control state for s_k and b to feeling state for b is taken negative, for example $\omega_{4k} = -1$.

LP2 Feeling state for b

$$\frac{dfs_b(t)}{dt} = \gamma \; [\; th(\omega_3\, ps_b(t) + \Sigma_k\, \omega_{4,k}\, cs_{s_k,b}(t)) - fs_b(t)\,]$$

The sensory representation state for s_k is affected by the preparation state for b (fear association) and by the suppressing control state for s_k and b. For this suppressing effect the connection weight ω_{6k} from the control state for s_k and b is taken negative. This is expressed in dynamic property LP3. Moreover, property LP3 is used to describe how the sensory representation of any traumatic s_k is triggered from memory, as a starting point for a dream: in a scenario the memory trigger values are taken 1. For non-traumatic s_k such triggering does not take place: the values are taken 0.

LP3 Sensory representation state for s_k

$$\frac{d\, srs_{s_k}(t)}{dt} = \gamma \; [\; th(\omega_{5,k}\, ps_b(t) + \omega_{6,k}\, cs_{s_k,b}(t) + \omega_{0,k}\, mt_{s_k}(t)) - srs_{s_k}(t)\,]$$

Activation of a control state for a specific sensory representation for s_k and b is based on the level for feeling b and the activation level of the sensory representation and episode states of s_k:

LP4 Control state for s_k and b

$$\frac{d\, cs_{s_k,b}(t)}{dt} = \gamma \; [\; th(\omega_{7,k}\, srs_{s_k}(t) + \omega_{8,k}\, fs_b(t) + \omega_{13,k}\, es_{s_k}(t)) - cs_{s_k,b}(t)]$$

Due to the inherent parallellism in neural processes, at each point in time multiple sensory representation states can be active simultaneously. For cases of awake functioning the *Global Workspace Theory* (e.g., [1]) was developed to describe how a single flow of conscious experience can come out of such a large multiplicity of (unconscious) parallel processes. The basic idea is that based on the various unconscious processes a *winner-takes-it-all competition* takes place to determine which one will get dominance and be included in the single flow of consciousness. This idea was applied here in the dreaming context to determine which sensory representation element will be included as an episode state es_{s_k} in a dream. This competition process is decribed in LP5, using mutual inhibiting connections from episode states es_{s_i} with $i \neq k$ to es_{s_k}. For the suppressing effects the connection weights from the es_{s_i} with $i \neq k$ to es_{s_k} are taken negative, for example $\omega_{10,i,k} = -0.6$ for $i{\neq}k$. Note that for the sake of notational simplicity $\omega_{10,k,k} = 0$ is taken. For traumatic stimuli s_k an additional and strong way of inhibition of the corresponding episode state takes place, blocking the generation of an episode state for this stimulus. It is based on the control state for s_k and b and is assumed to have a strong negative connection strength $\omega_{11,k}$. For non-traumatic stimuli this connection is given strength 0.

LP5 Episode state for s_k

$$\frac{\boldsymbol{d}\, es_{s_k}(t)}{\boldsymbol{dt}} = \gamma\ [\ th(\omega_{9,k}\, srs_{s_k}(t) + \omega_{11,k}\, cs_{s_k,b}(t) + \Sigma_i\, \omega_{10,i,k}\, es_{s_i}(t)) - es_{s_k}(t)]$$

Hebbian learning to strengthen fear extinction

From a Hebbian perspective [16], strengthening of a connection over time may take place when both nodes are often active simultaneously ('neurons that fire together wire together'). The principle goes back to Hebb [16], but has recently gained enhanced interest by more extensive empirical support (e.g., [2]), and more advanced mathematical formulations (e.g., [10]). In the adaptive computational model two upward connections that play a role in monitoring for the emotion regulation cycle are adapted based on a Hebbian learning principle. More specifically, for such a connection from node *i* to node *j* its strength ω_{ij} is adapted using the following *Hebbian learning rule*, taking into account a maximal connection strength 1, a *learning rate* η, and an *extinction rate* ζ (usually taken small):

$$\frac{\boldsymbol{d}\omega_{ij}(t)}{\boldsymbol{dt}} = \eta\ a_i(t)a_j(t)(1 - \omega_{ij}(t)) - \zeta\omega_{ij}(t) = \eta\ a_i(t)a_j(t) - (\eta\ a_i(t)a_j(t) + \zeta)\ \omega_{ij}(t)$$

Here $a_i(t)$ and $a_j(t)$ are the activation levels of node *i* and *j* at time *t* and $\omega_{ij}(t)$ is the strength of the connection from node *i* to node *j* at time *t*. A similar Hebbian learning rule can be found in [10], p. 406. By the factor $1 - \omega_{ij}(t)$ the learning rule keeps the level of $\omega_{ij}(t)$ bounded by 1 (which could be replaced by any other positive number); Hebbian learning without such a bound usually provides instability. When the extinction rate is relatively low, the upward changes during learning are proportional to both $a_i(t)$ and $a_j(t)$ and maximal learning takes place when both are 1. Whenever one of $a_i(t)$ and $a_j(t)$ is 0 (or close to 0) extinction takes over, and ω_{ij} slowly decreases (unlearning). This learning principle has been applied (simultaneously) to the two upward connections from sensory representation and feeling states to the control state in Fig. 1, according to the following instantiations of the general learning rule above:

$$\frac{\boldsymbol{d}\omega_{7,k}(t)}{\boldsymbol{dt}} = \eta\ srs_{s_k}(t)\ cs_{s_k,b}(t)(1 - \omega_{7,k}(t)) - \zeta\omega_{7,k}(t)$$
$$= \eta\ srs_{s_k}(t)\ cs_{s_k,b}(t) - (\eta srs_{s_k}(t)\ cs_{s_k,b}(t) + \zeta)\ \omega_{7,k}(t)$$
$$\frac{\boldsymbol{d}\omega_{8,k}(t)}{\boldsymbol{dt}} = \eta\ fs_b(t)\ cs_{s_k,b}(t)(1 - \omega_{8,k}(t)) - \zeta\omega_{8,k}(t)$$
$$= \eta\ fs_b(t)\ cs_{s_k,b}(t) - (\eta\ fs_b(t)\ cs_{s_k,b}(t) + \zeta)\ \omega_{8,k}(t)$$

In principle, the learning rate η and extinction rate ζ, can be taken differently for the different connections. In the example simulations discussed in Section 4 (shown in Fig. 2) the following values have been used: $\eta = 0.7$ for all $\omega_{7,k}$ and $\eta = 0.4$ for all $\omega_{8,k}$, and $\zeta = 0.001$ for all $\omega_{7,k}$ and $\omega_{8,k}$.

4 Simulations of Fear Extinction Learning in Dream Scenarios

In dream scenarios in which the cycles as discussed play their roles as follows.

Triggering s_1

- A stimulus s_1 is given for which previously a high extent of fear has been experienced, and for which from time to time (in particular during sleep) a sensory representation state is triggered by memory (for the model this is considered an external trigger); note that such a memory trigger was not used for the other stimuli: their activation automatically happens due to the high fear levels induced by triggering s_1, and maintained by the subsequent dream episiodes.
- The activation of the sensory representation of s_1 leads to activation of an enhanced preparation level for a bodily fear response b

The positive preparation-feeling cycle ps_b – fs_b

- By an as-if body loop an enhanced preparation level for b leads to an enhanced fear feeling level for b and vice versa

Blocking s_1

- By a strong form of emotion regulation in particular the sensory representation and episode state of s_1 are strongly suppressed: the activation level of the sensory representation of s_1 becomes low, and no dream episode state for s_1 occurs, as this is blocked

The positive preparation-sensory representation cycle ps_b – srs_{s_k}

- Other fear-associated stimuli s_k for $k \geq 2$ are available for which the person has less strong previous experiences; the sensory representation states for these s_k are activated by links from the high preparation state for b, depending on the strength of these links
- When the sensory representation state of a stimulus s_k is activated, this leads to an enhanced activation level of the preparation state for the emotional fear response

The positive preparation-feeling cycle ps_b –fs_b

- Due to the higher activation level of preparation for fear based on b, via the as-if body loop also the feeling level for b becomes higher: the person experiences more fear

Competition to achieve a dream episode es_{s_k}

- The active sensory representation for some s_k leads to a corresponding dream episode state, according to a competion process by mutual inhibition to get dominance in the episode

The negative emotion regulation cycle $cs_{s_k,b}$ – fs_b, srs_{s_k}, es_{s_k}

- By the control states for emotion regulation for an active sensory representation for s_k both the fear feeling level and the sensory activation level of s_k are suppressed (resp., re-appraisal, attentional deployment)

The fear extinction learning cycle $cs_{s_k,b}$ – $\omega_{7,k}$, $\omega_{8,k}$

- Due to nonzero activation levels of the control states and the fear feeling state for b, and the sensory representation and episode states for s_k Hebbian learning takes place strengthening the connections from feeling state and sensory representation to control state
- Increased connection strengths lead to higher activation levels for the control states

A variety of simulation experiments have been performed according to such scenarios, using numerical software. In the experiments discussed below (see Fig. 2) the settings were as shown in Table 3.

Table 3. Settings used for connection strength, threshold and steepness parameters

from state	connection		to state	threshold	steepness
srs_{s_k}	$\omega_{1,k}$	1	ps_b	0.5	4
fs_b	ω_2	1			
es_{s_k}	$\omega_{12,k}$	1			
ps_b	ω_3	1	fs_b	0.5	4
$cs_{s_k,b}$	$\omega_{4,k}$	-0.2			
ps_b	$\omega_{5,1}$	0.5	srs_{s_1}	0.25	8
$cs_{s_1,b}$	$\omega_{6,1}$	-2			
ps_b	$\omega_{5,2}$	0.5	srs_{s_2}	0.25	8
$cs_{s_2,b}$	$\omega_{6,2}$	-0.5			
ps_b	$\omega_{5,3}$	0.45	srs_{s_3}	0.25	8
$cs_{s_3,b}$	$\omega_{6,3}$	-0.5			
ps_b	$\omega_{5,4}$	0.4	srs_{s_4}	0.25	8
$cs_{s_4,b}$	$\omega_{6,4}$	-0.5			
srs_{s_1}	$\omega_{7,1}$	1	$cs_{s_k,b}$	1	8
fs_b	$\omega_{8,1}$	1			
es_{s_k}	$\omega_{13,k}$	0.3			
srs_{s_k}	$\omega_{9,k}$	1	es_{s_k}	0.25	60
es_{s_j} $(j \neq k)$	$\omega_{10,j,k}$	-0.6			
$cs_{s_k,b}$ $(k \geq 2)$	$\omega_{11,k}$	-0.2			
$cs_{s_1,b}$	$\omega_{11,1}$	-20			

As shown in the left hand side of the table, all noninhibiting connections to preparation, feeling, control, and episode states have strength 1, and all inhibiting connections from control states to feeling, sensory representation states and episode states, and mutually between episode states have strengths -0.2, -0.5, -0.2, and -0.6, respectively, with an exception for the sensory representation and episode states for s_1, which are inhibited by strength -2 and -20 (they are blocked due to a previous traumatic event involving s_1). Small differences in emotional associations for the different s_k are expressed by different strengths from preparation of emotional response to sensory representation states, varying from 0.5 to 0.4. In the scenarios considered, the memory trigger for the sensory representation of s_1 has level 1 and connection strength 0.5. The threshold and steepness values used are shown in the right hand side of Table 3. Relatively low steepness values were used, except for the episode states. The threshold values for preparation and feeling states were taken 0.5; in order to model differences in emotional associations between the s_k, different threshold values were taken for their sensory representation and control states. The initial values of all states were taken 0, and for the adaptive connection strengths 0.1 initially (which also could be taken 0). The speed factor γ was 1, and the step size Δt was taken 0.1. For learning and extinction rates the following values have been used: $\eta = 0.7$ for all $\omega_{7,k}$ and $\eta = 0.4$ for all $\omega_{8,k}$, and $\zeta = 0.001$ for all $\omega_{7,k}$ and $\omega_{8,k}$. The example scenario discussed addresses a case where three dream episodes occur, related to the sensory representations of s_2, s_3, s_4, subsequently. In Fig. 2 time is on the horizontal axis and the activation levels of the indicated states and connections are on the vertical axis. In the first graph it is shown that right from the start the sensory representation for s_1 becomes active (triggered from memory). Immediately the emotional response preparation for b starts to develop, and the related feeling, as shown in the third graph. Also in the third graph it is shown how as a result the control state for s_1 becomes active. Due to the strong suppression, no (full) dream episode develops for s_1, as shown in the second graph. Due to the relatively high emotional response and feeling level, the sensory representations for s_2, s_3, s_4 become active, following that order and strength (first graph).

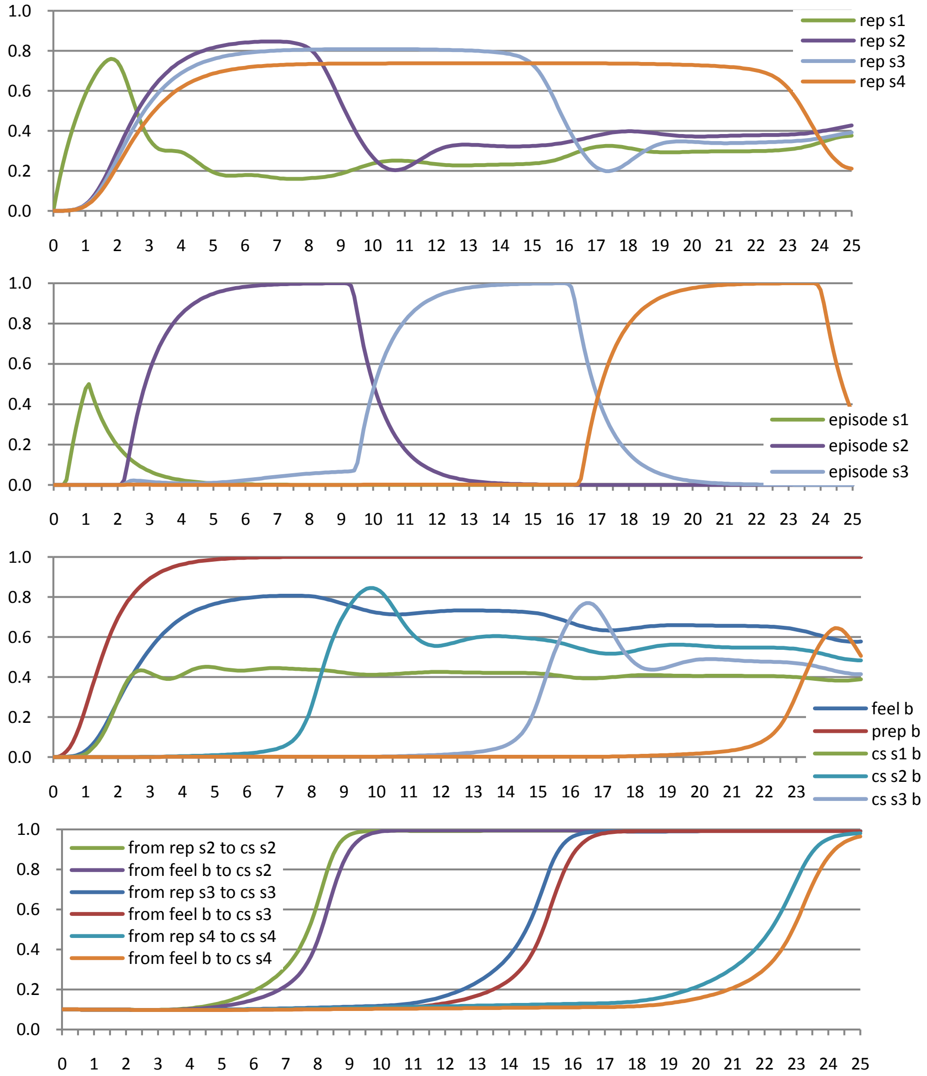

Fig. 2. Dream with three episodes showing extinction learning and reduction of feeling level

In a cyclic process, this further increases the emotional response preparation and feeling levels (third graph). As the sensory representation of s_2 is the strongest, it wins the competition for the dream episode from time point 3 to 9 (second graph).

Given this first episode and the high feeling and sensory representation levels, extinction learning takes place of the connections to the control state for s_2 (see fourth graph), reaching strengths one around *1* at time point 9, and hand in hand with this process the level of the control state for s_2 jumps up from time point 7 on (see third graph). As a result of this, control is exerted, suppressing after time point 9 the feeling level (third graph), the sensory representation of s_2 (first graph), and the related episode (second graph). As the feeling level was only partly reduced, and the sensory representation for s_2 does not compete anymore, from time point 11 on a second episode occurs, based on the sensory representation of s_3 (second graph). Again the whole adaptation process occurs, this time related to s_3. From time point 16 on, this brings the feeling level more down (third graph), and suppresses the sensory representation of s_3 (first graph), and the related episode (second graph). After this, the whole process repeats iteself for a third dream episode, based on the sensory representation of s_4. This leads to another reduction of the feeling level around time 25. Overall, all connections for fear extinction in relation to the most strongly fear-related sensory representations have been learned and have values around *1*, and the feeling level was reduced to below *0.6*.

4 Discussion

The assumption that dreaming, especially when negative emotions are involved, can be considered as a purposeful form of internal simulation is widely supported, in particular, for the purpose of strengthening fear emotion regulation capabilities; cf. [9, 15, 20, 21, 29, 30, 32]. In this paper a computational model was presented that models the generation of dream episodes from an internal simulation perspective, and uses these episodes for fear extinction learning. Building blocks to create such internal simulations are memory elements in the form of sensory representations and their associated emotions. The model exploits a mutual (winner-takes-it-all) competition process to determine sensory representation states that dominate in different dream episodes, comparable to one of the central ideas underlying the Global Workspace Theory of consciousness (cf. [1]). Adaptive emotion regulation mechanisms (cf. [11, 13, 14]) were incorporated to regulate the activation levels of the feeling (by re-appraisal) and the sensory representation states (by attentional deployment). Adaptation in the model is based on Hebbian learning. The computational model was evaluated by a number of simulation experiments for scenarios with different numbers of dream episodes.

In [20] dreaming is related to a network of four main brain components (called the AMPHAC network) and their connections: Amygdala, Medial PreFrontal Cortex (MPFC), Hippocampus, Anterior Cingulate Cortex (ACC). Note that the biological counterparts of the preparation and sensory representation states in the model can be found in the sensory and (pre)motor cortices, indicated in ([20], p. 505) to be 'robustly connected' to the components in the AMPHAC network. One of the roles of the Hippocampus is to store and maintain the relations between sensory memory elements and their emotional associations; in the model these connections are assumed to be fixed and modelled by the (bidirectional) connections between the sensory representations states srs_{s_k} and preparation states ps_b of the emotional response b. The feeling state fs_b in the model can be related to the Amygdala, possibly in combination with some limbic areas involved in maintaining 'body maps'. As discussed in Section 2, the interaction between preparation state ps_b and feeling state fs_b is in line with the neurological theories of Damasio [4-7]. About the role of ACC empirical studies show evidence in different directions (e.g., [20], pp. 505-512); therefore it is not clear yet what exactly its function is in dreaming and how it can be related to the model presented in Section 2.

Especially the interaction between MPFC and Amygdala in fear extinction during dreaming has been extensively studied; e.g. [4, 5, 8, 20, 24, 25]. In various empirical studies it has been found that lower activity of MPFC correlates to less controlled feeling levels, and, moreover, REM sleep is found to strengthen MPFC activation and reduce feeling levels; see, for example, [11, 15, 20, 30, 32]. This regulating role of MPFC with respect to Amygdala activation makes these two neurological components suitable candidates for biological counterparts of the control state $cs_{s_k,b}$ and the feeling states fs_b in the computational model presented in Section 3. Moreover, the reported finding suggests that fear extinction learning affects activation of MPFC; this is in accordance with the modelling choice that the Hebbian learning was applied to the two upward connections from sensory representation and feeling states to the control state. As before, the connections between the two types of states may be related to the Hippocampus. Note that in the computational model the control states $cs_{s_k,b}$ also have a role in suppressing the activation of the corresponding sensory representation state srs_{s_k} which can be justified as being a form of emotion regulation by attentional deployment; cf. [13, 14]; see also Section 2. The episode states es_{s_k} and their competition can be justified by referring to the Global Workspace Theory of consciousness (cf. [1]), as explained in Section 3.

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