An Adaptive Agent Model for the Emergence of Recurring Dream Scripts Based on Hebbian Learning

Valérie de Kemp, Jan Treur

VU University Amsterdam, Agent Systems Research Group
De Boelelaan 1081, 1081 HV, Amsterdam, The Netherlands
Email: v.p.de.kemp@vu.nl, treur@cs.vu.nl URL: http://www.cs.vu.nl/~treur

Abstract. In this paper an adaptive agent model is presented that models how recurrent dreams such as nightmares occur. The approach addresses dreaming as internal simulation incorporating memory elements in the form of sensory representations and their associated emotions. In the agent model recurring dreams emerge as scripts of connected dream episodes in which the connections between the episodes strengthen over time 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], [28-32]. 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. 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. Since a long time these virtual stories and their possible interpretations have been used in a therapeutical context; e.g., [8], [9]. In [26] and [27] computational models for some aspects of dreaming are contributed.

The adaptive agent model presented here adopts basic elements from [26]. However, in contrast to these references, the agent model introduced here generates coherent scripts (virtual stories) for the type of internal simulation that is assumed to take place in dreaming. In [26] for the different dream episodes, the internal simulation incorporates activations of sensory representation states (from memory) providing mental images, and activations of associated feelings, without a direct connection between different episodes. The model presented here does not consider dreams as consisting of isolated episodes as in [26], but models them as coherent scripts with mutually connected mental images and associated feelings to represent the virtual story line, following what is pointed out in [25]. Moreover, the connections between them are strengthened by Hebbian learning, thus developing a recurrent pattern as in recurring nightmares; e.g., [21], [25]. Similar to [26] it incorporates emotion regulation to suppress the feeling levels and the sensory representation states, when the level of fear is too high.

The structure of the paper is as follows. In Section 2 some background literature and the adaptive agent 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 The Adaptive Agent Model for Recurring Dream Scripts

In this section, first it is briefly discussed how in dreaming memory elements with their associated emotions are used as building blocks for an internal simulation of real life. Furthermore, it is pointed out how such internal simulations can lead to dream scripts consisting of fixed sequences of episodes that become recurrent dreams. After this the agent model incorporating these elements is presented.

Within the literature the role of memory elements providing content for dreams is well-recognized; e.g., [21], p. 499-500. The role of emotional aspects in activating such memory elements is emphasized; e.g.: '…elements may be activated as a function of emotional concerns (..) but with the possible introduction of some pseudorandom and incompatible associations.' ([21], p. 500). In particular, it is recognized that the choice for memory elements with some emotional association and (re)combining them into a dream facilitates emotion generation: the emotional associations of the sensory memory elements may make that a person has to cope with high levels of emotions (e.g., fear) felt in the dream; cf. [21], p. 500. *Emotion regulation* mechanisms are used to suppress emotions that are felt as too strong; cf. [11], [13], [14]. Thus dreams are considered as flows of activated sequences of images based on (re)combined memory elements and associated emotions; cf. [21], p. 500. Such flows can be related to the notion of *internal simulation* put forward, among others, by [6], [7], [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. The latter states represent the effects of the prepared actions or bodily changes, without actually having executed them. Being inherently cyclic, the simulation process can go on indefinitely. Internal simulation has been used, for example, to describe (imagined) processes in the external world (e.g., prediction of effects of own actions [3]), or processes in another person's mind (e.g., emotion recognition or mindreading [12]) or processes in a person's own body (e.g., [6]). Although usually internal simulation as briefly described above concerns mental processes for awake persons, it is assumed that it may be applicable as well to describe dreaming.

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* [6]. To describe the generation of emotions and feelings, in [23] a causal chain sensory representation - preparation of emotional response - feeling the bodily effect of the emotional response was introduced: an *as-if body loop* (cf. [6], pp. 155-158; [7], pp. 79-80; [9]). An as-if body loop describes an inner simulation of bodily processes, without actually affecting the body. Note that in [6] an emotion (or emotional response) is distinguished from a feeling (or felt emotion). The emotion and feeling mutually affect each other: an as-if body loop usually occurs in an extended, cyclic form by assuming that the emotion felt in turn also affects the prepared bodily changes, as he points out, for example, in ([8], pp. 91-92; [9], pp. 119-122).

One theory explicitly referring to a purpose of dreaming as internal simulation is the threat simulation theory of the evolutionary function of dreaming (cf. [23], [28]). This theory assumes that dreaming is an evolutionary adaptation to be able to rehearse coping with threatening situations in a safe manner. Others consider the function of dreaming in strengthening the emotion regulation capabilities for fear; e.g., [15], [29], [30]. For this perspective, the purpose of dreaming is to improve the coping with the own fear emotions in real life. For both purposes adequate exercising material is needed for the dreams: fearful situations have to be imagined, built on memory elements suitable for fear arousal.

More specific inspiration for the adaptive agent model for the development of recurrent dreams introduced here was taken from the informal description in [25]. This describes how a nightmare is stored in memory as a *script*: a scary series of events. The probability that the (nightmare) script is activated during the REM sleep depends on the accessibility of the script. If the script is associated with much fear, the accessibility is high. Initially a dream may be neutral, but if there is some association to the nightmare script the script may be activated. To activate associations to the script, a form of resemblance interpretation plays a role. If the dreamer is anxious, neutral dream elements tend to be interpreted as threatening. If an ambiguous stimulus is perceived as threatening it will be perceived as more similar to a threatening script than if it is perceived as neutral. The replaying of the nightmare over and over again causes nightmare distress. The more neurotic (biased towards the negative side) the dreamer is, the more the dreamer gets distressed.

The more the dreamer is distressed, the better the script is consolidated, the more likely it is that the nightmare will become recurrent.

An overview of the agent model is shown in Fig. 1. For an explanation of the symbols used, see Table 1. It reuses some parts of the model described in, [26]. The neuroticism state *ns* is added, which indicates how neurotic the dreamer is. The more neurotic the dreamer is, the more he or she is emotionally affected by the dream, which leads to a higher value for the feeling state fs_b. Moreover, connections between the sensory representations srs_{sk} for different stimuli were added, which makes it possible to activate related stimuli to the ones already active. With strong connections between the sensory representations, the same kind of dream can be replayed, making it possible to have a recurrent nightmare.

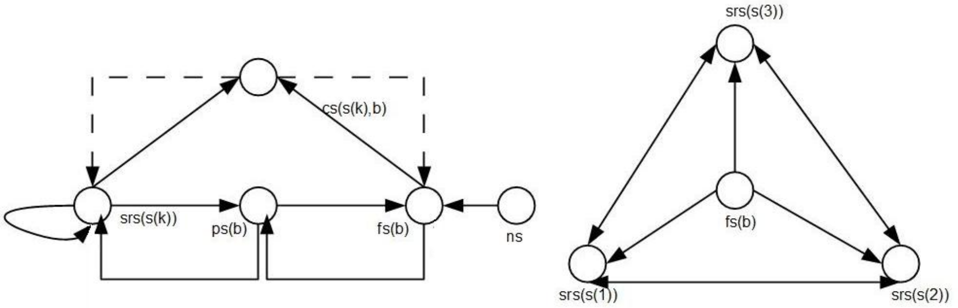

Fig. 1. Agent model for the generation of recurrent dreams

Table 1. Explanation of the states used in the model

state	**explanation**
ps_b	Preparation state for bodily response *b*
fs_b	Feeling state for *b*
srs_{sk}	Sensory representation state for s_k
$cs_{sk,b}$	Control state for regulation of sensory representation of s_k and feeling *b*
es_{sk}	Episode state for s_k
mt_{sk}	Memory trigger for s_k
ns	Neuroticism state

The agent 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:

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

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:

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

Table 2 shows the connection strengths used in the specification of the agent model described below. 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*.

Table 2. Connections and weights used in the model

from states	**to state**	**weights**	**LP**
$srs_{s1}, \ldots, srs_{sn}, fs_b$	ps_b	$\omega_{11}, \ldots, \omega_{1n}, \omega_2$	LP1
$ps_b, cs_{s1,\, b}, \ldots, cs_{sn,\, b}, ns$	fs_b	$\omega_3, \omega_{41}, \ldots, \omega_{4n}, \omega_{12,\, 0}$	LP2
$ps_b, cs_{sk,\, b}, mt_{sk}, srs_{si}$	srs_{sk}	$\omega_{5k}, \omega_{6k}\ \omega_{0k}, \omega_{14,\, ik}$	LP3
srs_{sk}, fs_b	$cs_{sk,\, b}$	ω_{7k}, ω_{8k}	LP4
$srs_{sk}, es_{s1}, \ldots, es_{sn}, cs_{sk,\, b}$	es_{sk}	$\omega_{9k}, \omega_{10,1k}, \ldots, \omega_{10,\, nk}, \omega_{11,\, k}$	LP5

LP1 Preparation state for emotional response *b*
If the sensory representation states of s_k ($k = 1, 2, \ldots$) have level V_{1k}
and the feeling state for *b* has level V_2 and the preparation for *b* has level V_3
then after Δt the preparation state for *b* will have level $V_3 + \gamma\, [th(\Sigma_k \omega_{1k} V_{1k} + \omega_2 V_2) - V_3]\, \Delta t$.
$\mathbf{d}\, ps_b(t)/\mathbf{d}t = \gamma\, [th(\Sigma_k \omega_{1k} srs_{sk}(t) + \omega_2\, fs_b(t)) - ps_b(t)]$

LP2 Feeling state for *b*
If the preparation state for *b* has level V_1
and the control states for s_k and *b* ($k=1, \ldots, n$) have levels V_{2k}
and the neuroticism state has level V_3
and the feeling state for *b* has level V_4
then after Δt the feeling state for *b* will have level $V_4 + \gamma\, [\, th(\omega_3 V_1 + \Sigma_k\, \omega_{4k} V_{2k} + \omega_{12,\, 0} V_3) - V_4]\, \Delta t$.
$\mathbf{d}\, fs_b(t)/\mathbf{d}t = \gamma\, [\, th(\omega_3\, ps_b(t) + \Sigma_k\, \omega_{4k}\, cs_{sk,\, b}(t) + \omega_{12,\, 0}\, ns(t)) - fs_b(t)]$

LP3 Sensory representation state for s_k
If the preparation state for *b* has level V_1
and the control state for s_k and *b* has level V_{2k}
and the memory trigger for s_k has level V_{3k}
and the sensory representation states of s_i ($i=1, \ldots, n$) have level V_{4i}
and the sensory representation state for s_k has level V_{5k}
then after Δt the sensory representation state for *sk* will have
level $V_{6k} + \gamma\, [\, th(\omega_{5k} V_1 + \omega_{6k}\, V_{2k} + \omega_{0k} V_{3k} + \Sigma_i\, \omega_{14,\, ik}\, V_{4i}) - V_{5k}]\, \Delta t$.
$\mathbf{d}\, srs_{sk}(t)/\mathbf{d}t = \gamma\, [\, th(\omega_{5k}\, ps_b(t) + \omega_{6k}\, cs_{sk,\, b}(t) + \omega_{0k}\, mt_{sk}(t) + \Sigma_i\, \omega_{14,\, ik}\, srs_{si}(t)) - srs_{sk}(t)]$

LP4 Control state for s_k **and** *b*
If the sensory representation state for s_k has level V_{1k} and the feeling state for *b* has level V_2
and the control state for s_k and *b* has level V_{3k}
then after Δt the control state for s_k and *b* will have level $V_{3k} + \gamma\, [\, th(\omega_{7k} V_{1k} + \omega_{8k} V_2) - V_{3k}\,]\, \Delta t$.
$\mathbf{d}\, cs_{sk,b}(t)/\mathbf{d}t = \gamma\, [\, th(\omega_{7k}\, srs_{sk}(t) + \omega_{8k}\, fs_b(t)) - cs_{sk,b}(t)]$

At each point in time multiple sensory representation states can be active simultaneously. For cases of awake functioning the *Global Workspace Theory* ([1]) was developed to describe how a single flow of conscious experience can come out of such a large multiplicity of (unconscious) processes. The basic idea is that a *winner-takes-it-all competition* takes place to determine which one will get dominance and be included in the single flow of consciousness (after which it is accessible to all processes). This idea was applied here in the dreaming context to determine which sensory representation element will be included as an episode state es_{sk} in a dream episode. This competition process is decribed in LP5, using inhibiting connections from the episode states es_{si} with $i \neq k$ to es_{sk}. For the suppressing effects the connection weights from the es_{si} with $i \neq k$ to es_{sk} are taken negative. Note that for the sake of notational simplicity $\omega_{10,kk} = 0$ 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 ω_{e3k}. For non-traumatic stimuli this connection is given strength 0.

LP5 Episode state for s_k
If the sensory representation state for s_k has level V_{1k} and the control state for s_k and *b* has level V_{2k}
and the episodic states for *si* ($i = 1, \ldots$) have level V_{3i}
then after Δt the episodic state for s_k will have level $V_{3k} + \gamma\, [th(\omega_{9k} V_{1k} + \omega_{11,k} V_{2k} + \Sigma_i\, \omega_{10,ik} V_{3i}) - V_{3k}]\, \Delta t$.
$\mathbf{d}\, es_{sk}(t)/\mathbf{d}t = \gamma\, [\, th(\omega_{9k}\, srs_{sk}(t) + \omega_{11,k}\, cs_{sk,b}(t) + \Sigma_i\, \omega_{10,ik}\, es_{si}(t)) - es_{sk}(t)]$

Hebbian learning to strengthen connections between sensory representations

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 agent model the mutual connections between the sensory representations for s_k 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):

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

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).

3 Simulation Results

The agent model has been used to conduct a number of simulation experiments. Some of these experiments are discussed here.

3.1 Type of Scenario

In the simulations four stimuli play a role. To make the results more readable the following descriptions are added, which was inspired by [25].

s_1: The dreamer is chased by un unknown person.
s_2: The dreamer walks in an dark environment and sees an unknown person.
s_3: The unknown person is lost and asks the dreamer the way.
s_4: The dreamer can't get away quick enough and the chaser is getting near.

The following type of scenario is used:

- A memory trigger activates the sensory representation state of an emotionally neutral stimulus s_2. The corresponding episode state is triggered and the dream begins.
- Another stimulus, s_1, is associated with fear. There is a strong connection from the sensory representation state of s_2 to the sensory representation state of s_1. This is because the stimulus s_2 evokes an association with s_1, due to resemblance or feelings of fear. Therefore the sensory representation state of s_1 is also triggered.
- The stimulus s_3 is a reassuring stimulus, which does not go together with stimuli which evoke feelings of fear like s_1. The stimuli s_1 and s_3 contradict each other. The sensory representation state of s_2 does also have an excitatory influence on the sensory representation state of s_3. It means that when the sensory representation state of s_2 is activated the sensory representation states of both s_1 and s_3 are both triggered. Only one of the episodes of s_1 and s_3 is activated above threshold at the same time.
- The stimulus s_1 is associated with fear, which means that if the sensory representation state of s_1 is active, the preparation state for bodily response *b* and the feeling state for *b* have higher levels than usual. The more neurotic the dreamer is the higher the level of the feeling state for *b* will be. The higher the activation of the feeling state for *b*, the more it inhibits the sensory representation state of s_3 and the more it excites the sensory representation states of s_3 and s_4.
- The stimulus s_4 is associated with more fear than s_1. When the level of the feeling state for *b* is getting higher the level of the sensory representation state for s_4 catches up with the level of the sensory representation state for s_1 and the episode of s_1 is followed by the episode of s_4. The nightmare becomes really frightening.

3.2 Settings used

As a point of departure a variation on settings as described in [26] were used, which are shown in Table 3 The adjustments, extensions and differentiations of these settings to the new model are shown in Table 4. If a value does not occur in Table 4, the old value from Table 3 is used. All states had an initial value of *0*, except for the sensory representation state for s_2 (srs_{s2}), the memory trigger for s_2 (mt_{s2}) and the neuroticism state (*ns*). Those states had a *1* as initial value. The value of the speed factor γ was *0.5* and the step size Δt was *0.1*.

Table 3. Parameter settings of the model as a variation of what is described in [26]

from state	connection		to state	threshold	steepness
srs_{s_k}	ω_{1k}	1	ps_b	0.5	4
fs_b	ω_2	1			
ps_b	ω_3	1	fs_b	0.5	4
$cs_{s_k,b}$	ω_{4k}	-0.2			
ps_b	ω_{51}	0.5	srs_{s_1}	0.5	8
$cs_{s_1,b}$	ω_{61}	-2			
ps_b	ω_{52}	0.5	srs_{s_2}	0.25	8
$cs_{s_2,b}$	ω_{62}	-0.5			
ps_b	ω_{53}	0.43	srs_{s_3}	0.25	8
$cs_{s_3,b}$	ω_{63}	-0.5			
ps_b	ω_{54}	0.38	srs_{s_4}	0.25	8
$cs_{s_4,b}$	ω_{64}	-0.5			
srs_{s_k}	ω_{7k}	1	$cs_{s_1,b}$	0.7	8
fs_b	ω_{8k}	1	$cs_{s_2,b}$	1.1	8
			$cs_{s_3,b}$	1.4	8
			$cs_{s_4,b}$	1.8	8
srs_{s_k}	ω_{9k}	1	es_{s_k}	0.25	60
es_{s_j}	$\omega_{10,jk}$	-0.4			

Table 4. New parameter settings

from state	to state	connection	strength
srs_{s_1}	ps_b	ω_{11}	1
srs_{s_2}	ps_b	ω_{12}	0.3
srs_{s_3}	ps_b	ω_{13}	0.1
srs_{s_4}	ps_b	ω_{14}	1
es_{s_k}	es_{s_k}	$\omega_{10,kk}$	0
es_{s_1}	es_{s_2}	$\omega_{10,12}$	-1
es_{s_1}	es_{s_3}	$\omega_{10,13}$	-0.6
es_{s_1}	es_{s_4}	$\omega_{10,14}$	-0.2
es_{s_2}	es_{s_1}	$\omega_{10,21}$	-0.2
es_{s_2}	es_{s_3}	$\omega_{10,23}$	-0.2
es_{s_2}	es_{s_4}	$\omega_{10,24}$	-0.4
es_{s_3}	es_{s_1}	$\omega_{10,31}$	-0.6
es_{s_3}	es_{s_2}	$\omega_{10,32}$	-0.8
es_{s_3}	es_{s_4}	$\omega_{10,34}$	-0.8
es_{s_4}	es_{s_1}	$\omega_{10,41}$	-0.8
es_{s_4}	es_{s_2}	$\omega_{10,42}$	-0.8
es_{s_4}	es_{s_3}	$\omega_{10,43}$	-0.8
$cs_{s1,\,b}$	es_{s_1}	$\omega_{11,\,1}$	-0.3
mt_{s_1}, mt_{s_3}, mt_{s_4}	srs_{s_1}, srs_{s_3}, srs_{s_4}	ω_{01}, ω_{03}, ω_{04}	0
mt_{s_2}	srs_{s_2}	ω_{02}	0.5
srs_{s_k}	srs_{s_k}	$\omega_{14,kk}$	0
srs_{s_1}	srs_{s_2}	$\omega_{14,12}$	0
srs_{s_1}	srs_{s_3}	$\omega_{14,13}$	0
srs_{s_1}	srs_{s_4}	$\omega_{14,14}$	0
srs_{s_2}	srs_{s_1}	$\omega_{14,21}$	1
srs_{s_2}	srs_{s_3}	$\omega_{14,23}$	0.7
srs_{s_2}	srs_{s_4}	$\omega_{14,24}$	0
srs_{s_3}	srs_{s_1}	$\omega_{14,31}$	0
srs_{s_3}	srs_{s_2}	$\omega_{14,32}$	0
srs_{s_3}	srs_{s_4}	$\omega_{14,34}$	0
srs_{s_4}	srs_{s_1}	$\omega_{14,41}$	0
srs_{s_4}	srs_{s_2}	$\omega_{14,42}$	0
srs_{s_4}	srs_{s_3}	$\omega_{14,43}$	0
ps_b	srs_{s_1}	ω_{51}	1
ps_b	srs_{s_2}	ω_{52}	0
ps_b	srs_{s_3}	ω_{53}	-1
ps_b	srs_{s_4}	ω_{54}	1

For the simulations with the changing weights for the connections between the different sensory representation states ($\omega_{14,\,ik}$) the learning rate η was *0.05*, and the extinction rate ζ was *0.001*.

3.3 Results of some of the simulation experiments

First some experiments with fixed connections strengths (without learning) have been conducted, next experiments where these connection strengths are learned. For the sake of space limitations, only the latter are presented in this section.

Experiments with learning of dream scripts

Fig. 2 shows the results of the dream simulation of a dreamer who is moderately neurotic ($\omega_{12,\,0}$ = 0.5). State srs_{s2} is triggered from memory and is active from the beginning on. Because of that, the level of the es_{s2} becomes higher. There is a strong connection between *s2* on the one side and *s1* and *s3* on the other side. Therefore *s1* and *s3* are also triggered. Because the connection between *s2* and *s1* is the strongest, the srs_{s1} gets a higher level (*0.66* at time point *2.4*) than the srs_{s3} (*0.44* at time point *1.6*) and the latter drops again. Therefore the es_{s3} stays at a low level and drops again and the es_{s1} follows the es_{s2} up from time point *2.3* on and the nightmare begins. At time point 2.4 the srs_{s1} has reached its peak of 0.66 and drops again. Because of the level of fear the srs_{s4} rises and at time point 3.0 it intersects with srs_{s1}. The episode of *s1* is followed by the episode of *s4* near time point 4. The graph at the bottom of Fig. 2 shows the changes in in the values of the weights $\omega_{14,\,ik}$ from srs_{si} to srs_{sk}. Some weights are not shown: The values of $\omega_{14,\,41}$ are the same as the values of $\omega_{14,\,14}$, the values of $\omega_{14,\,42}$ are the same as the values of $\omega_{14,\,24}$ and the other values $\omega_{14,\,ik}$ do not change during the simulation.

The weights $\omega_{14,\,ik}$ which are reached at the end of the simulation are used as begin values for a new simulation and the results are shown in Fig. 3. The development of the episodes is basically the same as in the original simulation (Fig. 2). The main difference is that the length of the es_{s1} is shorter and its peak is lower and turns earlier in the es_{s4} (the scariest part).

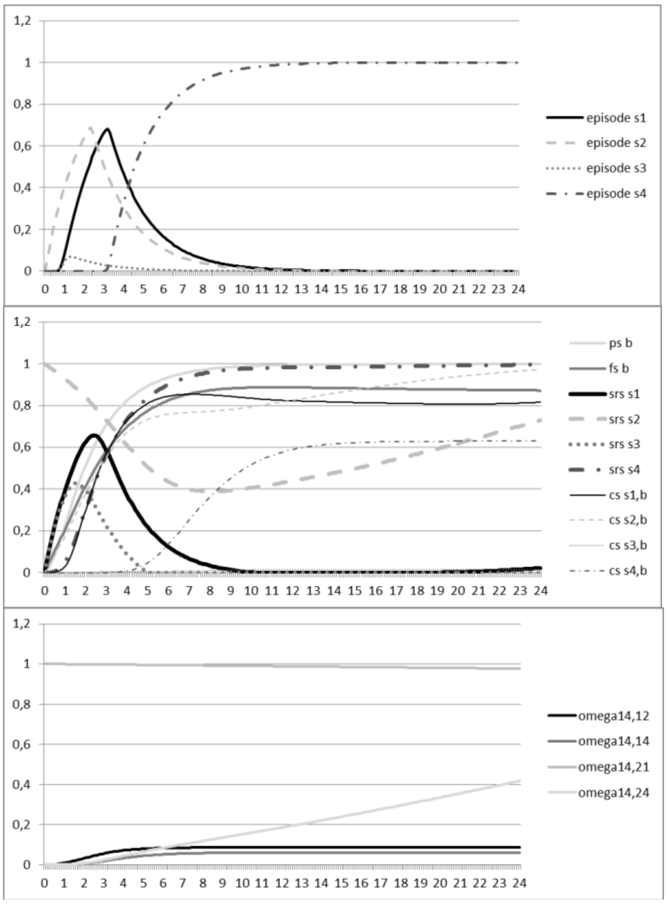

Fig. 2. The different states for a dreamer who is moderate neurotic ($\omega_{12,\,0} = 0.5$); values for $\omega_{14,\,ik}$ are changing

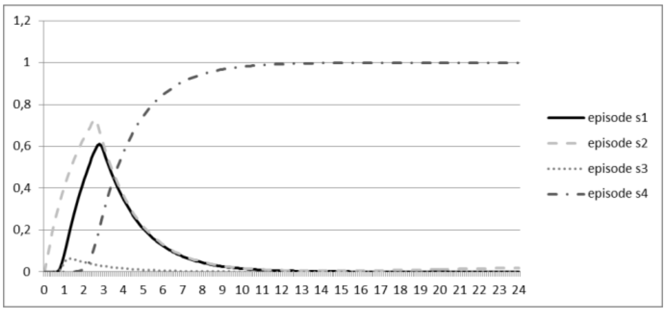

Fig. 3. The episode states with the learned values for $\omega_{14,\,ik}$; the dreamer is moderate neurotic ($\omega_{12,\,0} = 0.5$).

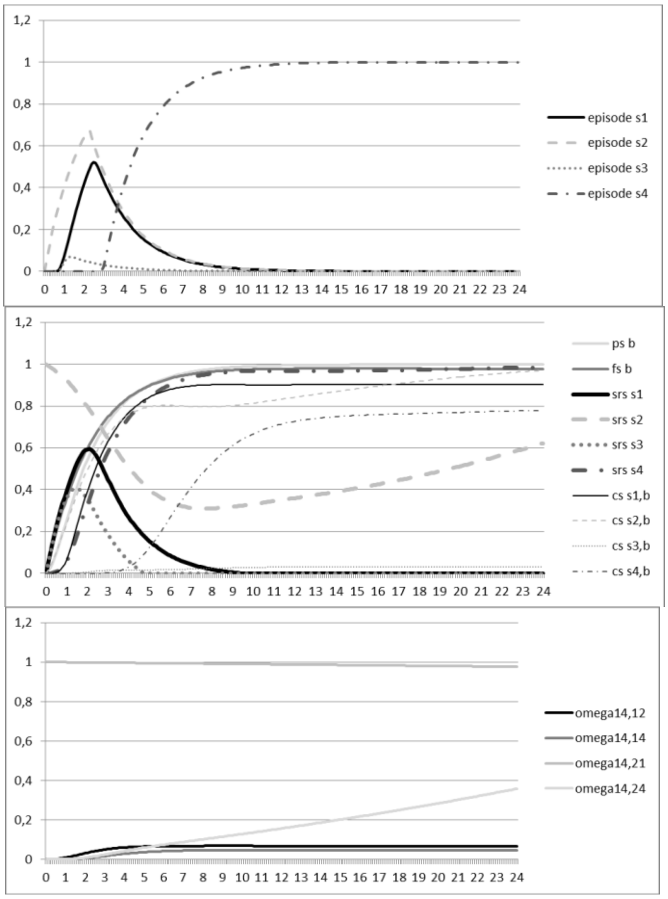

Fig. 4. The different states for a dreamer who is very neurotic ($\omega_{12,\,0} = 1$); changing weights $\omega_{14,\,ik}$

The development of the episodes in Fig. 3 is basically the same as in the original simulation (Fig. 2). The main difference is that the length of episode es_{s1} is shorter and becomes just above threshold and turns earlier in the es_{s4} (the scariest part).

The results of the dream simulation of a dreamer who is very neurotic ($\omega_{12,\,0} = 1$, Fig. 4) resemble the results of the simulation a dreamer who is moderate neurotic ($\omega_{12,\,0} = 0.5$, Fig. 2).

The graph for srs_{s1} intersects with the one for srs_{s4} just after its peak at 2.1 (value 0.59). And the es_{s1} turns into the es_{s4} near time point 4.0. Also the simulation with the learned weights $\omega_{14,\,ik}$ (Fig. 5) resembles the one with the initial weights (Fig. 4).

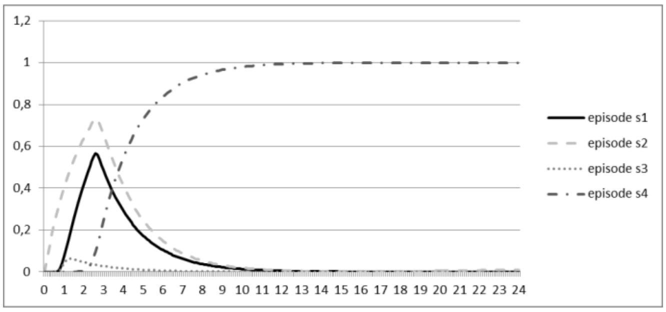

Fig. 5. The episode states for a dreamer who is very neurotic ($\omega_{12,\,0} = 1$); learned values for $\omega_{14,\,ik}$

4 Discussion

Although in the recent cognitive and neurological literature the mechanisms and functions of dreaming have received much attention (e.g., [19-23], [28-32]), only very few computational models are known that address aspects of dreaming; for example, see [26] and [27]. Dreaming generates ‘virtual simulations’ based on memory elements for sensory representations (mental images) and their associated emotions; e.g., [20]. Sometimes dreams emerge that get a recurring character, for example, nightmares; cf. [21], [25].

The presented adaptive agent model shows how recurrent dreams can emerge. The agent model uses adapting connections between different sensory representations and by a converging process obtains a fixed script of dream episodes that can be activated time and time again. The adaptation mechanism is based on a Hebbian learning principle. The model builds further on a previous model for dreaming described in [26]. By this existing model the adaptive scripting process which is the basis of the emergence of recurring dreams and nightmares is not covered. It has been shown that by the adaptive agent model introduced here indeed recurring dreams following a fixed script emerge. In [27] a computational model is decribed that focuses on fear extinction learning during dreaming. In future work an extension of the agent model presented here may be made which also incorporates fear extinction mechanisms as in [27].

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