Sleep Advances, 2021, 1–9

doi: 10.1093/sleepadvances/zpab009
Advance Access Publication Date: 17 June 2021
Original Article

ORIGINAL ARTICLE

A neurocomputational theory of nightmares: the role of formal properties of nightmare images

Patrick McNamara[1,2,*], Wesley J. Wildman[3,4], George Hodulik[4] and David Rohr[4]

[1]Department of Psychology, Northcentral University, San Diego, CA, USA, [2]Department of Neurology, Boston University, Boston, MA, USA, [3]Department of Computing and Data Sciences, Boston University, Boston, MA, USA and [4]Center for Mind and Culture, Boston, MA, USA

*Corresponding author. Patrick McNamara, 4935 Knox Ave N, Minneapolis, MN 44530. Email: pmcnamara@ncu.edu; mcnamar@bu.edu.

Abstract

Study Objectives: To test and extend Levin & Nielsen's (2007) Affective Network Dysfunction (AND) model with nightmare disorder (ND) image characteristics, and then to implement the extension as a computational simulation, the Disturbed Dreaming Model (DDM).

Methods: We used AnyLogic V7.2 to computationally implement an extended AND model incorporating quantitative effects of image characteristics including valence, dominance, and arousal. We explored the DDM parameter space by varying parameters, running approximately one million runs, each for one month of model time, varying pathway bifurcation thresholds, image characteristics, and individual-difference variables to quantitively evaluate their combinatory effects on nightmare symptomology.

Results: The DDM shows that the AND model extended with pathway bifurcations and image properties is computationally coherent. Varying levels of image properties, we found that when nightmare images exhibit lower dominance and arousal levels, the ND agent will choose to sleep but then has a traumatic nightmare, whereas, when images exhibit greater than average dominance and arousal levels, the nightmares trigger sleep-avoidant behavior, but lower overall nightmare distress at the price of exacerbating nightmare effects during waking hours.

Conclusions: Computational simulation of nightmare symptomology within the AND framework suggests that nightmare image properties significantly influence nightmare symptomology. Computational models for sleep and dream studies are powerful tools for testing quantitative effects of variables affecting nightmare symptomology. The DDM confirms the value of extending the Levin & Nielsen AND model of disturbed dreaming/ND.

Statement of Significance

Using a computational implementation of Levin and Nielsen's Affective Network Dysfunction model of nightmare symptomology, we demonstrated that specifying the valence, dominance, and arousal properties of given nightmare images can render AND computationally tractable and make novel predictions concerning the role of these image characteristics in production of nightmare symptomology. Targeting these image properties in therapy should be an effective tool in eliminating nightmare distress.

Key words: nightmares, computational models; Affective Network Dysfunction model; fear extinction; disturbed dreaming; REM sleep; valence; dominance; arousal

Submitted: 30 April, 2021; **Revised:** 30 May, 2021

Introduction

The DSM-5 defines Nightmare Disorder (DSM-5 307.47 (F51.5)) as a parasomnia involving repeated awakenings from extremely frightening dreams that do not occur in the context of some other mental disorder. Similarly, the 2016/2017 ICD-10-CM Diagnosis Code F51.5 defines Nightmare Disorder as a sleep disorder characterized by the repeated occurrence of frightening dreams that precipitate awakenings from sleep. Upon awakening, the individual becomes fully alert and oriented and has detailed recall of the nightmare's content, which usually involves imminent danger to the individual. Often the nightmare is so distressful the individual does not want to return to sleep and over time regular sleep insomnia occurs potentially leading to significant sleep debt problems in these persons [1].

Epidemiological studies [2–6] indicate that 2%–6% (about 6.4–15 million people) of the adult American population experience nightmares at least once a week. Up to 85% of adults report at least one nightmare within the past year, 8%–29% report monthly nightmares, and 2%–6% report weekly nightmares [6]. Between 6.7% and 11.3% of children experience recurrent nightmares [7]. Recurrent nightmares in children significantly predict later adolescent and adult psychosis. Indeed, experience of frequent nightmares in both children and adults is associated with a host of neuropsychiatric risk factors and disorders including anxiety, depression, stress, and suicidal ideation [6, 8–14].

There are two types of nightmares: idiopathic and traumatic. Idiopathic nightmares refer to nightmares with unknown etiology that are unrelated to a specific traumatic event or posttraumatic stress disorder (PTSD). Traumatic nightmares refer to dreaming disturbances that are part of the stress reaction following exposure to a traumatic event, either during the acute stress response, or over the course of PTSD. Nightmares are a core feature of PTSD, with up to 90% of individuals with PTSD reporting disturbing dreams with some degree of resemblance to the actual traumatic event. Unlike idiopathic nightmares which occur almost exclusively during REM sleep later in the night, posttraumatic nightmares typically occur earlier in the night and may occur in both REM and NREM sleep phases. This latter point may be clinically important given that the fear extinction process (described below) is more strongly associated with REM than NREM.

Despite the significant clinical dysfunction associated with nightmares, Nightmare Disorder remains under-diagnosed and understudied [15]. We hope to advance the study of nightmares by presenting a neurocomputational theory of nightmare production and symptomology.

Key principles of the neurocomputational model of nightmares offered here were first proposed heuristically and conceptually by Levin and Nielsen in 2007 [17]. Their Affective Network Dysfunction (AND) model of disturbed dreaming and nightmare production suggests that normal dream processes function to facilitate emotional memory consolidation. Consolidation is accomplished when varying dream contexts are created via memory element activation and recombination, and then paired with dreamed emotions appropriate to the context. Stripping a fear memory of its original context and then pairing it with less fearful contextual information is theorized to promote fear extinction via more efficient integration of fear memories and emotions into long-term memory. In short, memory decontextualization and then recontextualization results in new contexts that facilitate fear extinction.

According to AND nontraumatic idiopathic nightmares occur when ongoing affect load due to individual differences factors is high, thus preventing normal completion of the fear extinction process. Trauma-related nightmares, on the other hand, are associated with failure to even initiate the fear extinction process so that the fear memory is never processed and repetitive content results.

In terms of neural processes mediating dream formation, fear extinction, and nightmare production, Nielsen and Levin's AND model and the neurocomputational model we offer here both assign dream context formation to the hippocampus while dream emotion expression, including fear-memory processing, involves mutual inhibitory/activation interactions between the amygdala and the medial prefrontal cortex. Affect distress is mediated by the anterior cingulate cortex (ACC). These neural sites are the key nodes in a specialized fear-memory processing network and interestingly are the same key network nodes activated during REM [18, 19].

Theorists have suggested REM dreaming serves a fear extinction function, and that the awakenings associated with nightmares, but not bad dreams, disrupts this extinction process. When a specific fear memory image is presented to the system it is represented and held in a labile state in working memory stores [20] until it is re-formatted (via decontextualization and recontextualization) and reconsolidated into long-term memory. Consistent with AND, reconsolidation of labile emotional memory traces during REM sleep [21, 22] likely involves decoupling of original contextual information from its emotional valence (called depotentiation) so that the memory image can more easily be integrated into long-term memory systems. If the REM-dependent reconsolidation process fails, fear memories intrude into both dreams and waking consciousness fueling intrusive daytime dysphoric imagery as well as nightmares and anxiety disorders [16, 23].

Extension of the Affective Network Dysfunction model

A rigorous theoretical account of these REM-dependent fear extinction mechanisms should be able to quantitatively model all factors empirical research has discovered to influence the fear-memory extinction process. In addition, we argue that to extend and advance the Levin and Nielsen model we need to introduce formal features of the fear memory image itself. Recent work [24, 25] suggests that nightmare and fear memory image properties load high on formal properties of dominance, arousal, and valence. Imagery dominance is the extent to which the image controls the attention of the participant. Arousal is the extent to which the image moves the participant towards an activated and vigilant state. Valence refers to emotional reaction, and negative valence the extent to which the image elicits a negative dysphoric and distressed emotional reaction. In previous work we [25] have documented that nightmare images are characterized (by people with nightmares and independent raters) as highly arousing, dominant, and unpleasant (e.g. high arousal, high dominance, and high negative valence). In particular, raters were significantly willing to classify high-dominance and arousal images as nightmarish.

These three image properties were not arbitrarily selected. Decades of work on cognitive and psychological effects of image stimuli demonstrated that most psychologically significant imagery can be profitably studied in terms of these three dimensions. The standardized and well-studied International Affective Picture System (IAPS) [26] contains 956 images that have each been rated along the three dimensions of valence, dominance, and arousal. These ratings have been established as reliable [27] and have been corroborated by a variety of assessment procedures [28], a range of psychophysiological measures [29], and functional MRI-measured brain activity patterns [30].

In preparation for development of this neurocomputational model of nightmares, we tested the role of imagery characteristics in the development of nightmare symptomology by targeting image properties in an intervention study using virtual reality (VR) [25]. Use of VR-enabled technology allowed us to isolate effects of image characteristics on nightmare intensity or distress, nightmare related anxiety, and daytime functional effects of nightmares in people with Nightmare Disorder. Over eight sessions across a 4-week intervention trial, participants used manual controls attached to the VR headset to adjust valence, dominance, and arousal properties of images until they subjectively felt less scary or threatening to them. Manually altering images high on dominance and arousal dimensions resulted in significant reductions over the 4-week trial in measures of nightmare symptomology. Anxiety levels declined from Session 1 (mean Anxiety scale score 1.68 [*SD* 1.7]) to Session 8 (Week 4; 0.84 [1.2], t = 2.73, p = .014; two-tailed; Cohen's d 0.63). Similarly, nightmare distress declined from Session 1 (0.60 [.52]) to Session 8 (0.40 [.50], t = 3.29, p = .004, two-tailed; Cohen's d 0.76). Nightmare effects declined from Session 1 (0.59 [.55]) to Session 8 (0.28 [.35], t = 3.93, p = .001, two-tailed; Cohen's d 0.90).

Our next step in testing effects of image properties on nightmare symptomology was to quantitatively evaluate their effects in triggering the fear extinction process, modulating anxiety levels, nighttime awakenings, and daytime effects in a computational model of nightmare symptomology.

Predictions

Based on the AND model we suggest that inefficient fear extinction can occur in at least three ways with respect to nightmare symptomology. First, with regard to non-traumatic idiopathic nightmares, people with a history of nightmares begin the fear-extinction process but terminate it before the fear memory is extinguished, thus waking the sleeper. Second, with regard to trauma-related nightmares, people begin the sleep cycle but are then prevented from even entering the fear-extinction process. The decontextualization of fear memories—the first step of fear-extinction—fails and the dreamer suffers a traumatic nightmare with images that have not been decontextualized, like repetitive event memories. Third, people may attempt to avoid sleep altogether due to perseverating fear memories during waking hours and repetitive nightmares whenever they do sleep, possibly associated with a host of individual-differences variables and trauma. Thus, we introduce new factors to the AND model to account for complex patterns of nightmare symptomology, in the form of six computational bifurcations or choice points, as follows.

- At the threshold between needing and not needing fear extinction, there is a bifurcation between ordinary dreaming and triggering the fear-extinction circuitry. We postulate that degree of negative image valence contributes to triggering fear-extinction circuitry.
- At the threshold between starting and not starting fear extinction, there is a bifurcation between being able to decontextualize event memories to get them ready for recontextualizing in the fear-extinction process, and not being able to decontextualize; the latter results in event memories recurring as traumatic nightmares. We postulate that higher image dominance makes decontextualizing images more difficult.
- At the threshold between fear extinction working and not working, there is a bifurcation between staying in the fear-extinction loop, asleep, and waking with a non-traumatic (idiopathic) nightmare. We postulate that higher image arousal makes waking from a nightmare more likely.
- At the threshold between fear extinction ending and continuing, there is a bifurcation between repeating the fear-extinction loop and achieving depotentiation, which ends the process. If the fear extinction process accomplished its purpose and image memories are recontextualized with less threatening imagery then the loop is closed and the dreamer sleeps soundly. If nightmare imagery remains high on any of the three dimensions then the loop will be re-engaged.
- Another bifurcation is whether to go back to sleep after woken by a nightmare, which is partly a matter of exhaustion and partly a cognitive decision; some people may get up and keep busy to avoid having to experience yet another terrifying nightmare. We postulate that higher image arousal after an awakening makes the decision to attempt to continue sleeping more difficult.
- Finally, as sleep time approaches, there is a bifurcation between going to sleep and sleep-avoidance behaviors, which exacerbate nightmare effects during waking hours but also prevent nightmare distress while trying to sleep. We postulate that high dominance and arousal imagery increases the likelihood of sleep avoidance decisions and behaviors.

Finally, we propose that individual differences can be salient factors in determining how patients navigate the six bifurcations above. The individual differences include trauma history and tendency to affective distress.

To summarize, beginning with Levin and Nielsen's narrative AND model, we added four types of enhancements, as follows:

- individual differences (trauma history, affect distress tendency);
- image characteristics (arousal, dominance, valence);
- a distinction between traumatic nightmares (in which fear-extinction does not begin) and idiopathic (non-traumatic) nightmares (in which fear extinction begins but does not complete); and
- thresholds for the six bifurcations described above.

Methods

We used AnyLogic v7.2 to construct a computational model called the Disturbed Dreaming Model (DDM; see Figure 1) to express the neuropsychology of dreaming and nightmare processing as described in the conceptual extension

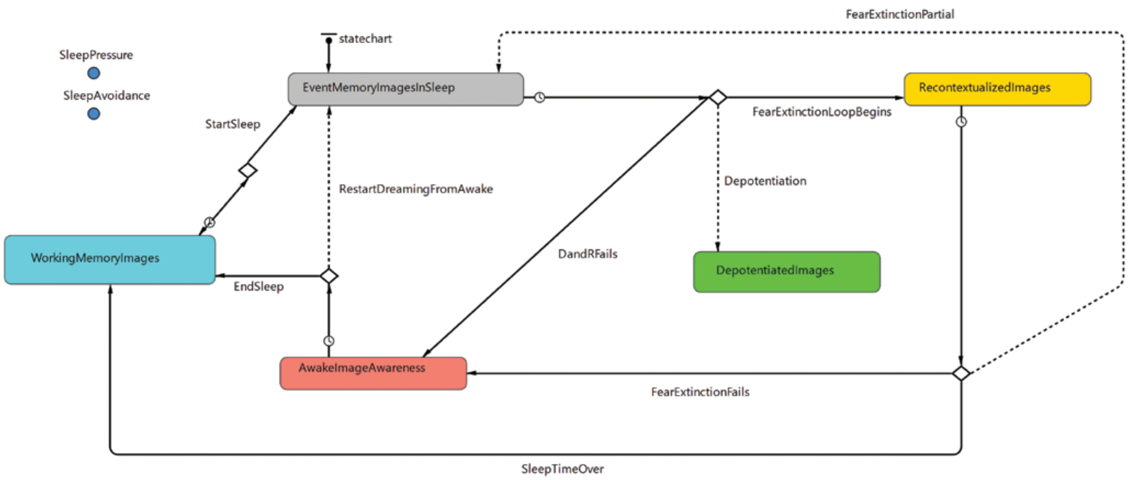

Figure 1. The Disturbed Dreaming Model. Bifurcation points correspond to the diamonds: there are three paths from the diamond between gray and gold, three paths from the diamond between gold and red, two paths from the diamond between red and gray, and a go-no-go choice at the diamond between blue and gray; this yields the six bifurcations described in the text. These bifurcations in turn yield six loops: the Fear-Extinction loop (FE; gray–gold–gray), the Idiopathic Nightmare loop (IN; gray–gold–red–gray), the Idiopathic Nightmare Waking loop 1 (INW1; gray–gold–blue–gray), the Idiopathic Nightmare Waking loop 2 (INW2; gray–gold–red–blue–gray), the Traumatic Nightmare loop (TN; gray–red–gray), and the Traumatic Nightmare Waking loop (TNW; gray–red–blue–gray). SleepPressure and SleepAvoidance (top left) are key variables that impact whether the StartSleep path is taken.

of Levin & Nielsen's AND model above. The DDM represents dreaming in a single artificial mind. The process begins with event memory images challenging the dreaming system (**EventMemoryImagesInSleep**) and ends either when images are depotentiated (**DepotentiatedImages**) or when a model run terminates after a specified number of nights of potential sleep and dreaming. The event memory images have characteristics of valence, dominance, and arousal. The artificial dreamer's ability to process these images depends on individual characteristics such as tendency to distressed affect, trauma history, and general affect load in life when the DDM begins.

Pathways through the model

DDM dynamics are expressed by seven primary paths through the model, of which six are loops, and one ends the simulation run (see Figure 1). Some of these loops involve a daytime process in which nightmare image perseveration can increase sleep-avoidant behavior (**WorkingMemoryImages**). The seven pathways are as follows.

- Depotentiating (D)—ending at green (**DepotentiatedImages**), meaning that fear extinction was never needed or succeeded
- Fear Extinction Loop (FE)—gray–gold–gray (return via **FearExtinctionPartial**)
- Idiopathic Nightmare Loop (IN)—gray–gold–red–gray (return via **FearExtinctionFails** and **RestartDreamingFromAwake**)
- Traumatic Nightmare Loop (TN)—gray–red–gray (via **DandRFails**, meaning that decontextualization and recontextualization does not work, so fear extinction cannot get started, and then **RestartDreamingFromAwake**)
- Idiopathic Nightmare Waking Loop (INW × 2)—there are two loops of this kind: INW1 is gray–gold–blue–gray, in which the patient ends sleep because sleep time is finished; INW2 is gray–gold–red–blue–gray, in which the patient ends sleep before sleep time is finished.
- Traumatic Nightmare Waking Loop (TNW)—gray–red–blue–gray, in which patient ends sleep before sleep time is finished after failing to begin the fear extinction process.

Treatments are possible during daytime hours but treatment options are not implemented in this version of the DDM in order to keep the focus on the theory of disturbed dreaming. Bracketing treatments also simplifies the number of parameters that need to be varied to grasp the dynamics of the model and thus the meaning of the conceptual model of disturbed dreaming that the DDM expresses.

Model parameters

DDM dynamics are tuned by parameters of several kinds. Continuous parameters and variables range from 0 to 1, unless otherwise noted, and parameter defaults are reported in square brackets. Most parameter defaults are set in nominal (mid-range or otherwise plausible) ways. For Threshold parameters, some experimentation was used to locate the regime of interesting model dynamics and defaults we set to land inside that regime. The analysis of the parameter space varies Threshold parameters so those defaults are irrelevant. Full details are in supplemental materials.

Personal factors:

- AffectDistressTendency [0.5]: Individual's tendency to experience high affect distress.
- TraumaHistory [0.5]: Individual's personal history of traumatic events.
- InitialAffectLoad [0.5]: Individual's degree of general affect load at the start of the model. This encompasses general negative life stress as well as negative stress associated with traumatic events and nightmare effects.

Image qualities:

- ImageValence [–0.5; range from –1 to +1]: Emotional valence of event-memory images.

- ImageDominance [0.5]: Attention-arresting quality of event-memory images.
- ImageArousal [0.5]: Physically arousing quality of event-memory images.

Sleep Factors:

- MaxREMCyclesPerNight [4]: Maximum number of REM cycles per night.
- MaxHoursSleepPerNight [8]: Maximum hours of sleep per night.
- IdealHoursSleepPerNight [8]: Ideal hours of sleep per night.
- NormalSleepHour [22:00 or 10 pm]: Normal time to go to sleep.
- INMAffectLoadIncrement [0.005]: Increment to AffectLoad variable each time an idiopathic nightmare occurs.
- TNMAffectLoadIncrement [0.01]: Increment to AffectLoad variable each time a traumatic nightmare occurs.
- FEAffectLoadDecrement [0.005]: Decrement to AffectLoad variable each time the fear-extinction loop is completed.

Thresholds:

- FearExtinctionAttemptThreshold [0.4] and DandRFailureThreshold [0.75]: for negative-valence images and AffectLoad above the FearExtinctionAttemptThreshold, the fear-extinction loop is attempted if Fear is below the DandRFailureThreshold, but if Fear exceeds the DandRFailureThreshold decontextualization and recontextualization does not even begin. If neither condition is met, depotentiation is achieved and the run ends.
- FearExtinctionFailureThreshold [0.25]: the fear-extinction loop does not complete if fear exceeds the FearExtinctionFailureThreshold.
- PostNightmareSleepThreshold [0.5]: the subject can't return to sleep if Fear exceeds the PostNightmareSleepThreshold.

Key model variables

Outcome variables:

- NightmareDistress [0,1]: Distress associated with nightmares during sleeping hours
- NightmareEffects [0,1]: Distress associated with nightmares during waking hours
- DASSAnxiety [0,1]: Anxiety, operationalized in the sense of the Depression, Anxiety, and Stress Scale [28]

Dynamic variables:

- AffectLoad [0,1]: Initialized by InitialAffectLoad parameter, the AffectLoad variable is INCREASED by both idiopathic and traumatic nightmares and decreased by completion of Fear-Extinction loops.
- Fear [0,1]: Average of parameters AffectDistressTendency, TraumaHistory, ImageDominance, ImageArousal and several variables: whether an idiopathic nightmare occurred during the night, whether a traumatic nightmare occurred during the night (weighted × 2), and the cumulative intensity of nightmares in the prior week.
- SleepAvoidance [0,1]: Tendency to avoid sleep in order to minimize nightmare distress.
- SleepPressure [0,1]: Pressure to sleep based on accumulated exhaustion. This impacts both going back to sleep after a nightmare and behavior as sleep time approaches each night, including the feasibility of sleep-avoidance strategies.
- Perseveration [0,1]: Tendency to perseverate over nightmare images during waking hours.

Results

To explore the parameter space of the DDM, we ran approximately a million runs, each for 1 month of model time, varying bifurcation thresholds, image characteristics, and individual-difference variables. We report results here in relation to four dependent variables, as follows:

- the most recent pathway through the model when the run ends (one of the four paths listed above; this is a convenient approximation to the final steady state that the model reaches at or before 1 month),
- nightmare distress (subjective distress due to nightmare occurrence),
- nightmare effects (negative daytime behavioral effects such as image perseveration, obsessiveness, sleep avoidance, sleep deprivation, and REM-deprivation), and
- DASS Anxiety (anxiety as defined by the Anxiety subscale in the Depression, Anxiety, and Stress Scales [31].

In each case, we discuss the region of the parameter space where informative dynamics appear; outside of those regions, parameter changes have few affects.

Most recent pathway through the model

The model has no stochastic elements, so repetition of parameter combinations was not necessary.

Analyzing the parameter space in terms of the most recent pathway through the model showed the conditions under which the most important outcomes occur. Because image dominance and arousal behave similarly when treatments are not activated, we set them to be equal; we did the same for the individual-difference characteristics of trauma history and affect distress tendency for the same reason. We set image valence to be negative and we set most thresholds to moderate values having tested that there was no sensitive dependence on them. Then we varied personal characteristics, image characteristics, and one threshold—the post-nightmare sleep threshold, which is a personal characteristic affecting how willing someone is to go back to sleep after waking from a terrifying nightmare. The parameter space can then be visualized as in Figure 2.

The conditions under which the fear-extinction loop is traversed depends on the image and personal characteristics but is independent of the post-nightmare sleep threshold. As that threshold increases, however, the non-traumatic nightmares (fear extinction starting but not completing) are gradually displaced by traumatic nightmares (fear extinction not even beginning) in an interesting way. Consider the panel with post-nightmare sleep threshold at 0.4 and consider the vertical line determined by holding personal characteristics (trauma history & affect distress tendency) constant at 0.75. As image characteristics (arousal and dominance) increase, the fear-extinction

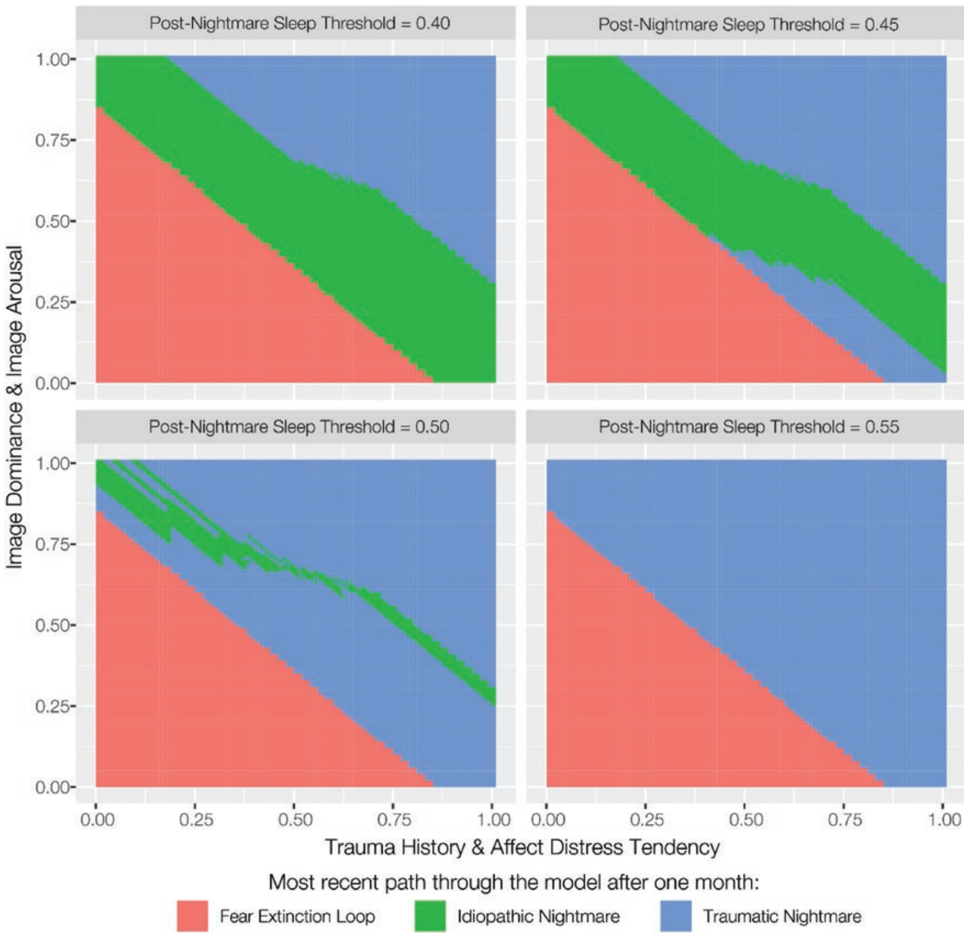

Figure 2. Visualization of the parameter space of the Disturbed Dreaming Model using the image and personal characteristics as independent variables and the most recent path through the model as the dependent variable (note: successful fear extinction is suppressed to focus on the most interesting dynamics).

limit is initially feasible but eventually yields to traumatic nightmares. When images are a little more intimidating, traumatic memories predominate, and eventually they become so scary that only traumatic nightmares occur. The region of nontraumatic nightmares thins further as the willingness to return to sleep after waking from a nightmare climbs, eventually disappearing altogether. This occurs because, when negatively-valenced images are "less scary" (lower dominance and arousal), the agent chooses to sleep and then has a traumatic nightmare; whereas, if the images were a bit scarier (higher dominance and arousal), the non-traumatic "ordinary" nightmare would be frightening enough to keep the agent from sleeping, preventing them from having a traumatic nightmare.

This is a clear instance of a novel prediction generated by implementing an expansion of Levin & Nielsen's model of nightmares in the consistency-enforcing modality of a system dynamics simulation.

Nightmare distress

In the case of nightmare distress, there are two zones where distress is low (see Figure 3). On the one hand, when images are less upsetting (low dominance and low arousal) and personal characteristics are advantageous (low trauma history and low tendency to distressed affect), nightmare distress is naturally low. On the other hand, when personal characteristics are not advantageous, subjects will avoid sleep (more so when images are upsetting), thereby keeping Nightmare Distress low. Outside of those two zones there is higher nightmare distress, with the highest levels when image characteristics are extremely negative and personal characteristics are in the moderate range, so that the subject is willing to go back to sleep and risk further distressing nightmares. The higher the likelihood of going back to sleep after a nightmare, the higher nightmare distress can go.

Nightmare effects

Nightmare effects refers to negative daytime behavioral effects such as image perseveration, obsessiveness, sleep avoidance, sleep deprivation, and REM-deprivation (see Figure 4). Nightmare effects are minimized when image characteristics are least disturbing and personal characteristics optimal (low trauma history and low tendency to distressed affect), which is expected. Also expected, nightmare effects are worst when image and personal characteristics both lead to the worst nightmares and thus provoke the most determined sleep avoidance; the price paid for mitigating nightmare distress (Figure 3) is dangerous nightmare effects (Figure 4). Between these extremes, the main dynamic is increase of severe nightmare effects as the post-nightmare sleep threshold rises. The

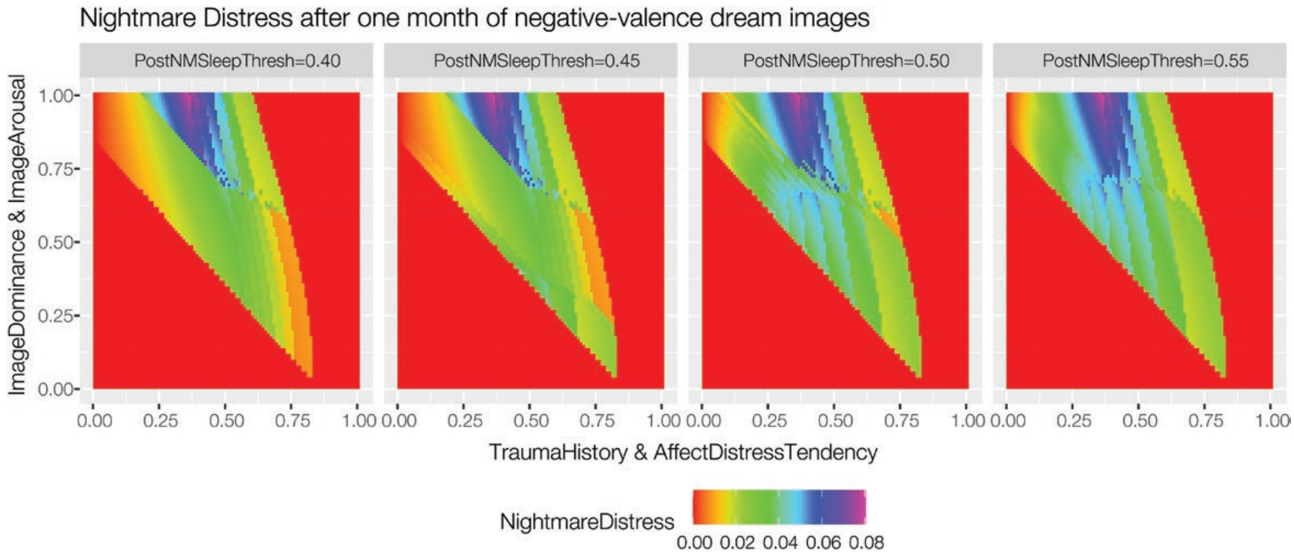

Figure 3. Visualization of the parameter space of the Disturbed Dreaming Model using the image and personal characteristics as independent variables and Nightmare Distress as the dependent variable.

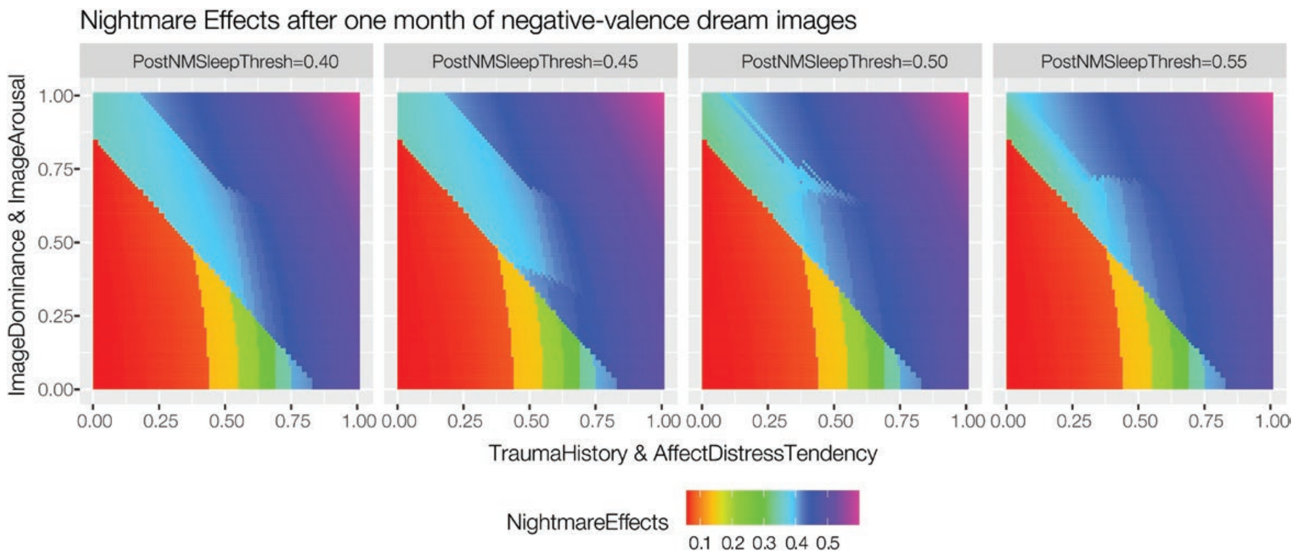

Figure 4. Visualization of the parameter space of the Disturbed Dreaming Model using the image and personal characteristics as independent variables and Nightmare Effects as the dependent variable.

more likely one is to fall back asleep after a nightmare, the more likely nightmare distress will be exacerbated, so the more likely one will try to avoid sleep altogether, thereby worsening nightmare effects.

Anxiety

Finally, the behavior of the DASS Anxiety dependent variable is similar to Nightmare Effects (see Figure 5). The more likely one is to fall asleep after a nightmare (higher PostNMSleepThresh), the more likely anxiety is to be high, but only when image characteristics are unfavorable (high dominance and high arousal). For the subject with unfavorable personal characteristics (high trauma history and high tendency to distressed affect), anxiety is high regardless of the post-nightmare sleep threshold. For people with low to moderate scores on those personal characteristics, by contrast, moderate anxiety is exacerbated into high anxiety as the tendency to go back to sleep increases, because nightmares will be more frequent to the point that sleep avoidance becomes a dominant strategy.

Discussion

Extending the Levin & Nielsen AND model with nightmare image characteristics, and then implementing it as a computational simulation (the Disturbed Dreaming Model, DDM), has significant payoffs.

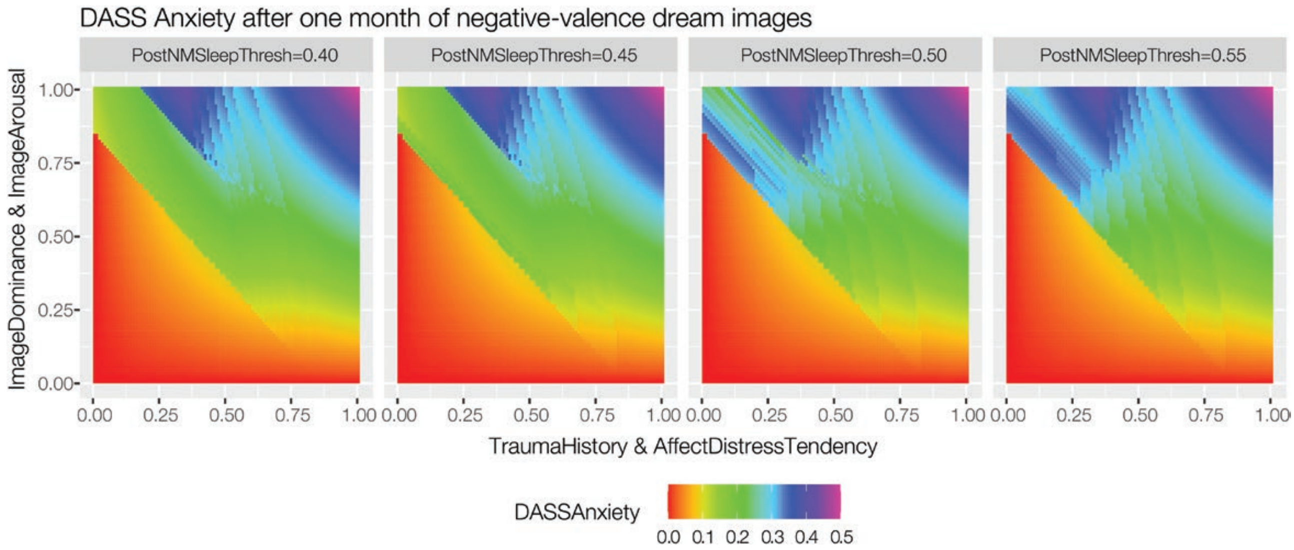

Figure 5. Visualization of the parameter space of the Disturbed Dreaming Model using the image and personal characteristics as independent variables and DASS Anxiety as the dependent variable.

First, the DDM demonstrates that an enhanced version of the AND model is computationally coherent, which a speculative model cannot do. DDM supports the soundness of Levin and Nielsen's original AND model but extends it significantly.

Second, the DDM helps to validate the addition of the role of imagery properties to the AND model because DDM run results and behavior is clinically and behaviorally plausible.

Third, the DDM makes a novel prediction around the balance of nightmare distress and nightmare effects in people with Nightmare Disorder: when nightmare images are "less scary" (lower dominance and arousal relative to group norms), the agent is predicted to choose to sleep but then has a traumatic nightmare, increasing overall nightmare distress; whereas, if the images were a bit scarier (again relative to group averages i.e. higher dominance and arousal), the nightmares would be scary enough to keep the agent from sleeping, triggering sleep-avoidant behavior, thereby lowering nightmare distress at the price of exacerbating nightmare effects during waking hours. In short, the image properties determine both overall nightmare distress and sleep avoidance behaviors.

This both demonstrates the usefulness of computational models for sleep and dream studies and confirms the value of extending the Levin & Nielsen AND model with individual differences effects and nightmare image characteristics.

The DDM model can be adapted for use as a virtual testbed for experimenting with treatment alternatives, probing their benefits and risks relative to individual differences, treatment modalities, and dosage. As noted in our introduction we have already pilot tested an intervention method that directly targets image properties with resultant significant improvement in clinical symptomology.

Results of the DDM simulations also carry implications for the fear extinction process and the functional nature of REM sleep itself as image properties may be crucial in its operations and computational properties. The fear extinction process has been associated with mood regulatory functions of REM sleep. REM sleep is required for effective regulation of emotions and is associated with ongoing consolidation of fear memories [32–35]. Walker and colleagues suggest that REM sleep serves the dual purpose of consolidating the content of emotional memory and diminishing the fear memory's emotional charge [32].

We suggest that REM dreams both reflect and facilitate processing operations that involve far more sophisticated handling of fear memory elements than mere diminishment of the emotional charge of a memory. The DDM suggests that REM involves a complex triaging process of funneling memory types into specialized subsystems as well as the selective de-contextualization and then recombinatory processing of fear memory elements in particular. Humans dream, it appears, in order to remember information content of some memories and to selectively forget associations of other fear memories that impair functioning.

Thus, the REM dreaming system appears to be specialized to "handle" a broad array of image and memory types and elements that are crucial for the organism's optimal functioning. REM's specialized and selective cognitive processing operations require correspondingly complex neurocomputational models to understand and reveal the system's key components, the system's interacting subsystems, the computational resources required for each subsystem, the thresholds required to engage each subsystem, and the bottleneck and breakdown points for these subsystems and the overall REM system itself. The DDM we describe here quantitatively describes each of these system components in a way that allows further testing and refinement in future work.

Supplementary Materials

Supplementary material is available at *SLEEP Advances* online.

References

1. Creamer JL, *et al*. Nightmares in United States military personnel with sleep disturbances. *J Clin Sleep Med*. 2018;**14**(3):419–426.
2. Belicki D, *et al*. Nightmares in a university population. *J Sleep Res*. 1982;**11**:116.

3. Bixler EO, *et al*. Prevalence of sleep disorders in the Los Angeles metropolitan area. *Am J Psychiatry*. 1979;**136**(10):1257–1262.
4. Haynes S, *et al*. Nightmares: etiological, theoretical, and behavioral treatment considerations. *Psychol Rec*. 1975;**25**:225–236.
5. Levin R. Sleep and dreaming characteristics of frequent nightmare subjects in a university population. *Dreaming*. 1994;**4**:127–137.
6. Ohayon MM, *et al*. Prevalence of nightmares and their relationship to psychopathology and daytime functioning in insomnia subjects. *Sleep*. 1997;**20**(5):340–348.
7. Gieselmann A, *et al*. Aetiology and treatment of nightmare disorder: state of the art and future perspectives. *J Sleep Res*. 2019;**28**(4):e12820.
8. Hasler B, *et al*. Correlates and treatments of nightmares in adults. *Sleep Med Clin*. 2009;**4**(4):507–517.
9. Belicki K. Nightmare frequency versus nightmare distress: relations to psychopathology and cognitive style. *J Abnorm Psychol*. 1992;**101**(3):592–597.
10. Hartmann E. *The Nightmare: The Psychology and the Biology of Terrifying Dreams*. New York: Basic Books; 1984.
11. Hartmann E. Nightmare after trauma as paradigm for all dreams: a new approach to the nature and functions of dreaming. *Psychiatry*. 1998;**61**(3):223–238.
12. Hublin C, *et al*. Nightmares: familial aggregation and association with psychiatric disorders in a nationwide twin cohort. *Am J Med Genet*. 1999;**88**(4):329–336.
13. Spoormaker VI, *et al*. Nightmares: from anxiety symptom to sleep disorder. *Sleep Med Rev*. 2006;**10**(1):19–31.
14. Fisher HL, *et al*. Childhood parasomnias and psychotic experiences at age 12 years in a United Kingdom birth cohort. *Sleep*. 2014;**37**(3):475–482.
15. Nadorff MR, *et al*. Nightmares: under-reported, undetected, and therefore untreated. *J Clin Sleep Med*. 2015;**11**(7):747–750.
16. Levin R, Nielsen T. Nightmares: a new neurocognitive model. *Sleep Med Rev*. 2007;**11**(4):295–310.
17. Levin R, *et al*. Disturbed dreaming, posttraumatic stress disorder, and affect distress: a review and neurocognitive model. *Psychol Bull*. 2007;**133**(3):482–528.
18. Maquet P, *et al*. Functional neuroanatomy of human rapid-eye-movement sleep and dreaming. *Nature*. 1996;**383**(6596):163–166.
19. Nofzinger EA. Functional neuroimaging of sleep. *Semin Neurol*. 2005;**25**(1):9–18.
20. Monfils MH, *et al*. Extinction-reconsolidation boundaries: key to persistent attenuation of fear memories. *Science*. 2009;**324**(5929):951–955.
21. Landmann N, *et al*. REM sleep and memory reorganization: potential relevance for psychiatry and psychotherapy. *Neurobiol Learn Mem*. 2015;**122**:28–40.
22. Murkar ALA, *et al*. Consolidative mechanisms of emotional processing in REM sleep and PTSD. *Sleep Med Rev*. 2018;**41**:173–184.
23. Izquierdo I, *et al*. Fear memory. *Physiol Rev*. 2016;**96**(2):695–750.
24. McNamara P, *et al*. Aggression in nightmares and unpleasant dreams and in people reporting recurrent nightmares. *Dreaming*. 2014;**25**(3):190–205.
25. McNamara P, *et al*. Virtual reality-enabled treatment of nightmares. *Dreaming*. 2018;**28**(3):205–224.
26. Lang P, *et al*. *International Affective Picture System (IAPS): Affective Ratings of Pictures and Instruction Manual*. Technical Report A-8. Gainesville, FL: University of Florida; 2008.
27. Lang PJ, *et al*. *International Affective Picture System (IAPS): Affective ratings of pictures and instruction manual*. Technical Report A-6. Gainesville, FL: University of Florida; 2005.
28. Ito TA, *et al*. Eliciting affect using the International Affective Picture System: trajectories through evaluative space. *Personality and Social Psychology Bulletin*. 1998;**24**:855–879.
29. Smith JC, *et al*. Rapid picture presentation and affective engagement. *Emotion*. 2006;**6**(2):208–214.
30. Lang PJ, *et al*. Emotional arousal and activation of the visual cortex: an fMRI analysis. *Psychophysiology*. 1998;**35**(2):199–210.
31. Lovibond S, *et al*. *Manual for the Depression Anxiety & Stress Scales*. 2nd ed. Sydney, Australia: Psychology Foundation; 1995.
32. Walker MP, *et al*. Overnight therapy? The role of sleep in emotional brain processing. *Psychol Bull*. 2009;**135**(5):731–748.
33. Vandekerckhove M, *et al*. The emotional brain and sleep: an intimate relationship. *Sleep Med Rev*. 2010;**14**(4):219–226.
34. Goldstein AN, *et al*. The role of sleep in emotional brain function. *Annu Rev Clin Psychol*. 2014;**10**:679–708.
35. Pace-Schott EF, *et al*. Effects of sleep on memory for conditioned fear and fear extinction. *Psychol Bull*. 2015;**141**(4):835–857.