BRAIN OSCILLATIONS AND PREDICTIVE CODING: WHAT WE KNOW AND WHAT WE SHOULD LEARN

EDITED BY: Roumen Kirov
PUBLISHED IN: Frontiers in Psychology

frontiers Research Topics

ISSN 1664-8714
ISBN 978-2-88945-161-6
DOI 10.3389/978-2-88945-161-6

About Frontiers

Frontiers is more than just an open-access publisher of scholarly articles: it is a pioneering approach to the world of academia, radically improving the way scholarly research is managed. The grand vision of Frontiers is a world where all people have an equal opportunity to seek, share and generate knowledge. Frontiers provides immediate and permanent online open access to all its publications, but this alone is not enough to realize our grand goals.

Frontiers Journal Series

The Frontiers Journal Series is a multi-tier and interdisciplinary set of open-access, online journals, promising a paradigm shift from the current review, selection and dissemination processes in academic publishing. All Frontiers journals are driven by researchers for researchers; therefore, they constitute a service to the scholarly community. At the same time, the Frontiers Journal Series operates on a revolutionary invention, the tiered publishing system, initially addressing specific communities of scholars, and gradually climbing up to broader public understanding, thus serving the interests of the lay society, too.

Dedication to Quality

Each Frontiers article is a landmark of the highest quality, thanks to genuinely collaborative interactions between authors and review editors, who include some of the world's best academicians. Research must be certified by peers before entering a stream of knowledge that may eventually reach the public - and shape society; therefore, Frontiers only applies the most rigorous and unbiased reviews.
Frontiers revolutionizes research publishing by freely delivering the most outstanding research, evaluated with no bias from both the academic and social point of view.
By applying the most advanced information technologies, Frontiers is catapulting scholarly publishing into a new generation.

What are Frontiers Research Topics?

Frontiers Research Topics are very popular trademarks of the Frontiers Journals Series: they are collections of at least ten articles, all centered on a particular subject. With their unique mix of varied contributions from Original Research to Review Articles, Frontiers Research Topics unify the most influential researchers, the latest key findings and historical advances in a hot research area! Find out more on how to host your own Frontiers Research Topic or contribute to one as an author by contacting the Frontiers Editorial Office: **researchtopics@frontiersin.org**

BRAIN OSCILLATIONS AND PREDICTIVE CODING: WHAT WE KNOW AND WHAT WE SHOULD LEARN

Topic Editor:
Roumen Kirov, Institute of Neurobiology, Bulgarian Academy of Sciences, Bulgaria

Sunset Reflections at the Black Sea: Traces in the Sand and in the Water.
Photo by Roumen Kirov

Predictive coding (PC) is a neurocognitive concept, according to which the brain does not process the whole qualia of external information, but only residual mismatches occurring between incoming information and an individual, inner model of the world. At the time of issue initiation, I expected an essential focus on mismatch signals in the brain, especially those captured by neurophysiologic oscillations. This was because one most plausible approach to the PC concept is to identify and validate mismatch signals in the brain. Announcing the topic revealed a much deeper consideration of intelligible minds of researchers. It turned out that what was of fundamental interest was which brain mechanisms support the formation, maintenance and consolidation of the inner model determining PC. Is PC a dynamic construct continuously modulated by external environmental or internal mental information? The reader will be delighted to get acquainted with the current views and understanding of eminent scholars in the field. It will be challenging to discover the realm of sleep where both physiological, energy preserving and mental qualia principles build on the inner models to shape and transform the self. And where neurophysiologic oscillations may both transmit external information and translate inner models from state to state to preserve the self-continuity and compactness.

Citation: Kirov, R., ed. (2017). Brain Oscillations and Predictive Coding: What We Know and What We Should Learn. Lausanne: Frontiers Media. doi: 10.3389/978-2-88945-161-6

Table of Contents

Sleep and Dreaming: Determinants of the Predictive Coding

REM-Sleep, Dreaming and Predictive Coding: Implications for Psychopathology, Decision Making and Psychoanalysis

Brain Oscillations: Their Role for Predictive Coding in Perception, Consciousness and Memory

frontiers in Psychology

EDITORIAL
published: 11 November 2016
doi: 10.3389/fpsyg.2016.01768

Editorial: Brain Oscillations and Predictive Coding in the Context of Different Conscious States and Sleep-Wake Cycle: Implications for Decision Making and Psychopathology

Roumen Kirov *

Cognitive Psychophysiology, Institute of Neurobiology, Bulgarian Academy of Sciences, Sofia, Bulgaria

Keywords: brain oscillations, predictive coding, REM sleep, dreaming, cognition, psychopathology, evolution

The Editorial on the Research Topic

Brain Oscillations and Predictive Coding in the Context of Different Conscious States and Sleep-Wake Cycle: Implications for Decision Making and Psychopathology

Predictive coding (PC) is a neurocognitive concept, according to which the brain does not process the whole qualia of external information, but only residual mismatches occurring between incoming information and an individual, inner model of the world, thus minimizing the free energy (FE) or brain entropy. The original concept comes from the Helmholtz's view of Bayesian brain or unconscious inference (Helmholz, 1878/1971), and has been elaborated in the last decades by Karl Friston in terms of PC functioning at every level of brain anatomic and functional organization and mind-body interaction (Friston, 2010, 2012). While neurophysiologic evidence is increasingly accumulated in support of the PC concept (Friston, 2012), compelling issues remain open. (1) Is PC an evolutionary pathway which we still underscore? (2) Which neurophysiologic mechanisms support the formation, maintenance and consolidation of the inner model determining PC? (3) Whether and how these may be referenced to the "self" in normal and pathological conditions, thus representing an imperative limit of our free will? (4) Is PC continuously modulated by external environmental or internal mental information? This Research Topic features contributions from several leading scholars addressing these issues.

It is hardly a coincidence that most contributions deal with the neurophysiology of sleep and its dreaming conscious states. Increasing evidence has been provided for the active role of sleep in processes such as metabolic functions and energy balance, synaptic plasticity and memory processing, emotional regulation, and prophylactic cellular maintenance, all of utmost importance for the successful adaptation (Vyazovskiy, 2015). However, a role of sleep for PC is still generally overlooked. Particularly, the bizarre dreaming consciousness upon lack of external input during rapid eye movement (REM) sleep may provide a unique condition for generating the inner model of the world. This may be achieved by incorporating newly encoded memories into consolidated residuals of hypotheses, emotions, basic needs, and individual genetic traits. Such a continuous update of the vital context is thought to determine PC and successful adaptation during wakefulness (Hobson and Friston, 2012; Horne, 2013; Kirov, 2013).

Edited and reviewed by:
Eddy J. Davelaar,
Birkbeck, University of London, UK

Correspondence:
Roumen Kirov
roumen_kirov@yahoo.com

Specialty section:
This article was submitted to
Cognitive Science,
a section of the journal
Frontiers in Psychology

Received: *20 October 2016*
Accepted: *27 October 2016*
Published: *11 November 2016*

Citation:
Kirov R (2016) Editorial: Brain Oscillations and Predictive Coding in the Context of Different Conscious States and Sleep-Wake Cycle: Implications for Decision Making and Psychopathology.
Front. Psychol. 7:1768.
doi: 10.3389/fpsyg.2016.01768

We begin with a scholarly and authoritative hypothesis article by Hobson et al. arguing convincingly that REM sleep and its characteristics, brain oscillations, rapid eye movements and pontine-geniculate-occipital waves, neuromodulation mode, and bizarre dreaming experience, all can support a more complex function of REM sleep than proposed so far. Especially, along with the REM sleep neurobiology, the dreaming conscious state during REM is considered a virtual reality model of surroundings which could determine or modulate the PC. This opening paper also addresses evolutionary and ontogenetic meanings of REM sleep and its key role for complex relationships between primary and secondary consciousness for the successful adaptation. Next, considering the bizarre and hyperassociative nature of REM sleep dreaming, several essentially important implications for REM sleep's neurophysiology and psychology merit a particular attention. According to an insightful model of Llewellyn, REM sleep dreaming generates a prospective code which may identify a personally salient, non-obvious probabilistic pattern in past events that if mobilized into a sensorimotor image as predictive code in wake, could support cognition in wake through sensory input with appropriate action. Notably, the form taken by this prospective code may also relate to ecological contexts for the predictive brain, where REM dreaming evolved to engender-based code which associates temporally discontiguous events in evolutionary terms. The original pilot study by Scarpelli et al. demonstrates that theta electroencephalogram (EEG) oscillations during REM sleep predict successful dream recall in a state-dependent fashion, depending on current psychological states. Along with the impressive review article of Scarpelli et al., this study opens new insights about the role of dreaming for feasible associations between previous experiences and broader biological imperatives that may determine the PC.

From the view point of REM sleep's role for psychopathology, the following papers inspire fresh ideas. First, reconciling REM sleep neurophysiology, Castelnovo et al. bring advantageous perspectives for understanding REM sleep dreaming as a virtual reality model for deviant PC in schizophrenic patients. Second, the search activity concept of REM sleep dreaming proposed by Rotenberg questions adequately and timely possible disadvantages of mental imagery like lucid dreaming (LD). In particular, while LD alters normal brain activation (Voss et al., 2009), its benefits for the natural functions of REM sleep remain unclear. Third, we welcome particularly the hypothesis article of Hopkins which builds on the links between predictive coding and dreaming on one side, and psychopathology and psychoanalytic approaches on the other side. The theoretical and empirical grounds of this important contribution to the topic deserve further attention of expert readers and experimenters.

With regard to the impressive amount of data about brain oscillations and PC during wakefulness, the opinion of Sauseng et al. is an excellent emphasis on cross-frequency EEG coupling as feasible mechanisms for PC in visual search. However, it appears very important to link sleep and wake data regarding the neurophysiology of cognitive and psychopathological aspects of the PC. Thankfully, this gap is targeted by the review of Başar and Düzgün pointing to the role of slow brain oscillations for PC, consciousness, memory, behavior, and psychopathology during sleep and wakefulness.

What we learned from the valuable contributions in this research topic can be summarized as follows: (1) The undermining neurophysiologic and psychological mechanisms of PC are strongly associated with sleep and dreaming features, and particularly with those signifying REM sleep. This in turn can reveal a novel function of sleep which may be of essential importance for the successful adaptation. (2) PC appears as a universal evolutionary pathway which role for cognition and psychopathology we still underscore. What we should learn is whether PC is a genetically determined imperative which limits our free will. Addressing this question mandates further theoretical and experimental developments.

I am personally quite happy with the appearance of such contributions touching on delicate and immensely important neurophysiologic, psychological and psychiatric problems related to veritable philosophical and psychosocial issues, and having the potential to contribute to a wise management of our evolution.

AUTHOR CONTRIBUTIONS

RK drafted the manuscript and is accountable for all aspects of the work.

ACKNOWLEDGMENTS

I am extremely thankful to all Authors for their valuable contributions to this Research Topic and its appearance in the journal Frontiers in Psychology, specialty section Cognitive Science. Also, I would like to thank the Reviewers for their expert and insightful comments on these valuable contributions.

REFERENCES

Friston, K. (2010). The free-energy principle: a unified braint heory? *Nat. Rev. Neurosci.* 11, 127–138. doi: 10.1038/nrn2787

Friston, K. (2012). Prediction, perception and agency. *Int. J. Psychophysiol.* 83, 248–252. doi: 10.1016/j.ijpsycho.2011.11.014

Helmholz, H., (1878/1971). "The fact of perception," in *The Selected Writings of Hermann von Helmholtz*, ed R. Karl (Middletown, CT: *Wesleyan University Press*), 366–408.

Hobson, J. A., and Friston, K. J. (2012). Waking and dreaming consciousness: neurobiological and functional considerations. *Prog. Neurobiol.* 98, 82–98. doi: 10.1016/j.pneurobio.2012.05.003

Horne, J. (2013). Why REM sleep? Clues beyond the laboratory in a more challenging world. *Biol. Psychol.* 92. 152–168. doi: 10.1016/j.biopsycho.2012.10.010

Kirov, R. (2013). REM sleep and dreaming functions beyond reductionism. *Behav. Brain Sci.* 36, 621–622; discussion 634–659. doi: 10.1017/s0140525x13001362

Voss, U., Holzmann, R., Tuin, I., and Hobson, J. A. (2009). Lucid dreaming: a state of consciousness with features of both waking and non-lucid dreaming. *Sleep* 32, 191–200.

Vyazovskiy, V. V. (2015). Sleep, recovery, and metaregulation: explaining the benefits of sleep. *Nat. Sci. Sleep.* 7, 171–184. doi: 10.2147/NSS.S54036

Conflict of Interest Statement: The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in
PSYCHOLOGY

HYPOTHESIS AND THEORY ARTICLE
published: 09 October 2014
doi: 10.3389/fpsyg.2014.01133

Virtual reality and consciousness inference in dreaming

J. Allan Hobson[1], **Charles C.-H. Hong**[2] **and Karl J. Friston**[3]*

[1] Division of Sleep Medicine, Harvard Medical School, Boston, MA, USA
[2] Department of Psychiatry and Behavioral Sciences, Johns Hopkins University, Baltimore, MD, USA
[3] The Wellcome Trust Centre for Neuroimaging, University College London, London, UK

Edited by:
Roumen Kirov, Institute of Neurobiology – Bulgarian Academy of Sciences, Bulgaria

Reviewed by:
Jim Hopkins, University College London, UK
Sue Elizabeth Llewellyn, University of Manchester, UK

***Correspondence:**
Karl J. Friston, The Wellcome Trust Centre for Neuroimaging, University College London, Queen Square, London WC1N 3BG, UK
e-mail: k.friston@ucl.ac.uk

This article explores the notion that the brain is genetically endowed with an innate virtual reality generator that – through experience-dependent plasticity – becomes a generative or predictive model of the world. This model, which is most clearly revealed in rapid eye movement (REM) sleep dreaming, may provide the theater for conscious experience. Functional neuroimaging evidence for brain activations that are time-locked to rapid eye movements (REMs) endorses the view that waking consciousness emerges from REM sleep – and dreaming lays the foundations for waking perception. In this view, the brain is equipped with a virtual model of the world that generates predictions of its sensations. This model is continually updated and entrained by sensory prediction errors in wakefulness to ensure veridical perception, but not in dreaming. In contrast, dreaming plays an essential role in maintaining and enhancing the capacity to model the world by minimizing model complexity and thereby maximizing both statistical and thermodynamic efficiency. This perspective suggests that consciousness corresponds to the embodied process of inference, realized through the generation of virtual realities (in both sleep and wakefulness). In short, our premise or hypothesis is that the waking brain engages with the world to predict the causes of sensations, while in sleep the brain's generative model is actively refined so that it generates more efficient predictions during waking. We review the evidence in support of this hypothesis – evidence that grounds consciousness in biophysical computations whose neuronal and neurochemical infrastructure has been disclosed by sleep research.

Keywords: sleep, consciousness, virtual reality, prediction, free energy, rapid eye movements, pontine-geniculate-occipital waves, neuromodulation

INTRODUCTION

What can sleep and dreaming tell us about consciousness (Windt and Noreika, 2011)? The answer offered in this article regards waking and sleeping consciousness as complementary and necessary for each other. This circular dependency rests upon a view of the brain as an organ of inference, generating virtual realities to explain the waking sensorium – and optimizing generative models during sleep. This view appears to be consistent with the neurobiology of sleep and the phenomenology of dreaming. This article considers the evidence that links active visual (conscious and unconscious) inference in waking and rapid eye movements (REMs) in sleep.

Our waking perception rests on a reconstruction of the world by the brain – a fantasy or hypothesis that explains sensations that are sampled from the world (Gregory, 1980). This article suggests that the capacity to model the world underlies perception in both waking and dreaming. We further propose that dreaming is a crucial prelude to waking perception. In brief, we associate conscious (and unconscious) perception with predictions of sensory inputs during waking – predictions that are generated by an internal model of the world that is embodied by the brain. In sleep, we hypothesize that this model is optimized so that it generalizes to novel situations in waking; thereby furnishing more efficient predictions and (statistical) modeling of sensory data. Crucially, this optimisation in sleep rests on the same neuronal mechanisms (i.e., synaptic activity and plasticity) that are engaged during waking perception. This provides a functional (model optimisation) and phenomenal (perceptual inference) account of dreaming. Because dreaming is highly correlated with REM sleep, the statistical and energetic functions of REM sleep may therefore inform the neurobiology of conscious and unconscious processing. REM sleep frees the brain from sensory enslavement – disclosing its constructive and integrative processes. As noted by Revonsuo (2006, p.75) dreaming "reveals consciousness in a very special, pure, and isolated form." Our premise is that this freedom is necessary for model optimisation, during which the brain can rehearse fictive scenarios that may or may not be encountered in waking.

This article addresses the phenomenology of dreaming, the neurophysiology of REM sleep, its ontogeny, its phylogeny, and its manifestation over the life span – all of which can be interpreted under a virtual reality hypothesis. When a Helmholtzian formulation of the inferential brain is applied to these data, new statistical, and thermodynamic principles emerge, which extend the explanatory power of the virtual reality hypothesis – and may cast new light on the nature of consciousness and its disorders. We will call on promising lines of research that establish the validity of this hypothesis; particularly in relation to the inferential processes that underlie consciousness. The Ego or Self concept that emerges from this treatment owes much to the work of physiologists and philosophers who emphasize the predictive aspects of the brain in grounding (waking and dreaming) consciousness in a first-person explanation of the sensorium (Llinás and Paré, 1991; Revonsuo, 1995; Metzinger, 2009, 2013). In this view, the embodied self is a dynamic construct of the brain that is established during sleep (and *in utero*) and carried forward – fit for purpose – into waking.

Specifically, we propose that REM sleep is an occasion for reiterating and optimizing a generative model of the embodied self with reference to waking experience. This updating rests upon maximizing the statistical – and implicitly thermodynamic – efficiency of generative models of the embodied self. In other words, REM sleep is necessary to minimize their complexity. Our emphasis on the self-as-agent is based on the observation that dreams are almost always first-person. We see this fact as supporting the idea that self-model is a construct of the brain and a central part of a phenomenal experience. In other words, the self is the foundational epicenter of a world from which we sample sensations.

This article comprises two parts: in the first two sections, we overview some important phenomenological and neurobiological aspects of sleep and dreaming. In the remaining (four) sections, we lay out our theoretical framework and then try to account for the empirical facts established in the first two sections. In detail, we first review the phenomenology of dreams, with a special focus on the dreaming associated with REM sleep. We then provide a selective summary of neurobiological findings from sleep research that inform the functional anatomy of REM sleep. Our focus here is on early neurophysiological discoveries and more recent advances using brain imaging and neuropsychology. This section closes with a brief treatment of lucid dreaming that has important implications for hierarchical models in the brain. The third section introduces the Helmholtzian perspective and generative models, linking the virtual reality and Bayesian brain hypotheses. Specifically, we will look at perceptual inference in dreaming and wakefulness from the perspective of predictive coding – and the role of sleep in Bayesian model optimization. The subsequent section pursues optimization; highlighting a fundamental link between the thermodynamic and statistical efficiency afforded by Bayesian model optimization. The penultimate section reviews the empirical evidence for the ensuing role of sleep and dreaming, which is considered from a philosophical perspective in the final section.

THE PHENOMENOLOGY OF DREAMS

In reviewing the phenomenological contrast between waking and dreaming, we will emphasize dream states associated with REM sleep, acknowledging that there are many interesting distinctions (and commonalities) between REM and non-REM sleep. Waking and dreaming have important similarities and marked differences. Chief among the similarities are the vivid and detailed perceptions and marked emotions that characterize both states. These similarities are often interpreted as *copies* of waking by dreaming but might as well be *predictions* of waking by dreaming – as we will argue. Our point here is not to stump for an either/or distinction but rather to explore the idea that waking and dreaming are both leaders and followers. Indeed, one might argue that "not only are dreams experiences but, in a way, all experiences are dreams" (Revonsuo, 2006, p.55). Dreaming tells waking what to expect and waking verifies or refutes those expectations.

Chief among the differences is the fact that dreaming is, by definition, virtual; since its subjective attributes are fabricated internally. The internal fabrication of dreams has been seen as the replay of remembered experience but this cannot be the explanation of much dream imagery, which either has no identifiable mnemonic source or may even run counter to those sources that are readily identified and easily specified in waking. It is this synthetic feature that gives dreaming its deserved pride of place in the psychology of the imagination. Dream synthesis compels us to consider the predictive and creative role that we assign to dreaming.

Other important differences between waking and dreaming are notable: waking memory is greatly enfeebled in dreaming. So is orientation, especially to time and place – as well as to third (but not first) persons. Logical inference is virtually impossible in dreaming. While emotions overlap to some extent, dreaming is associated with a narrower range and a greater depth of emotion than waking – as if dreaming were some proving ground for instinctual feelings. Movement is imagined but not actually enacted in dreaming (with the important exception of eye movements) – as if dreaming were a warm-up exercise for the game of waking.

Many of these observations come from formal analyses of dreaming phenomenology that provides direct access to anatomy of subjective processing. Formal analysis emphasizes the form of the dream as opposed to its content. Formal analysis may be preferred to content analysis (Freud, 1920; Hall and Van de Castle, 1966) in the study of how virtual realities are generated by the brain. To clarify the distinction between formal and content analysis, we will present and analyze a specimen dream recorded by one of us (AH) using both its form and content:

Execution dream (9/23/2011): sometime after 3 AM I had the following vivid dream:

> *I was in a very large and elegant apartment (not mine or any other place that I recognize).*
> *There was to be a series of two or maybe three stereotyped killings that I had arranged or at least approved. Each killing was the shooting, by long rifle, of a victim unknown to me but who deserved to die. In each case, the murder was accomplished by a couple (again people unknown to me). I could clearly see the victim and the murderous couple; feel satisfaction as one member of the couple, usually the man, took careful aim at his victim who did not flinch from fear or apprehension. I don't recall ever hearing a shot, or seeing any victim fall but the series of executions was carried out efficiently at my behest. I was mildly surprised but very satisfied to see it all go so well.*
> *When this had gone on for what I would estimate to be about 5 or maybe 10 min, I began to feel frightened. What if the police came? Would I be arrested?*
> *Suddenly I myself was holding a gun. The weapon was a poorly made rifle with the stock and barrel fastened together with crude screws and nuts. I reasoned that I could dismount this weapon and hide its parts. But where? The police would surely look under the mattresses that I considered as*

possible hiding places. I asked myself, what if the police also realize that I had engineered an earlier crime (of which I was sure I had dreamt before).

FORMAL ANALYSIS (FIRST PERSON)

In terms of its form, this is a typical REM sleep dream with vivid percepts (McCarley and Hoffman, 1981), delusional belief (Hobson et al., 2000), cognitive defects (Hobson and Stickgold, 1994; Stickgold et al., 2001), and both indifference and intense feeling (Merritt et al., 1994). My perceptions were detailed and hallucinatory with strong and clear visual imagery. I never once suspected that I was dreaming, always supposing, erroneously, that I was awake. I was disoriented – having no idea where I was, how I got there, or where I might go next.

In terms of the suggestion that dreaming reinforces the sense of self-as-agent, it is important to stress that I never assumed that I was anyone but me in the dream, yet I had no idea who my hired assassins might be or who the victims were – or even why they were victims. This brutal aggressiveness did not bother me at all in the dream. Other emotions, such as anxiety and apprehension, were strong once I realized what had transpired. My thought processes were grossly impaired, especially with respect to the (almost) complete loss of critical self-reflective awareness and insight.

In the second part of the dream I *did* begin to worry about the consequences of the executions, confirming the assertions of Kahan and LaBerge (2010) that self-reflective awareness is never completely absent from dreams. I was holding a makeshift gun and wondering how to dismantle and hide it lest my part in the murders be discovered by the police. It seems likely that this shift to a more rational, detached observational and reflective stance in the second part of the dream would be accompanied by frontal lobe activation and a reciprocal weakening of REM physiology – as seen in lucid dreaming (Voss et al., 2009).

CONTENT ANALYSIS

A dream content analyst or therapist might well be interested in my murderous impulses and how they relate to my life. Content-wise, this was an unusual dream for me. In my dreams as in my waking life, I am usually engaged and ecstatic, with positive social interaction and affect. I am almost never the dispassionate, detached voyeur of this particular dream scenario. But, I must admit this was my dream – so I need to take responsibility for its content

Many of the formal properties of dreams can be reliably recognized and measured, allowing subjective experience to be correlated with physiological or behavioral responses: for example, in sensory perception (Hong et al., 1997, 2009; Horikawa et al., 2013), visual scanning (Roffwarg et al., 1962; Herman et al., 1984; Hong et al., 1995), motor control (Dresler et al., 2012), language (Hong et al., 1996), multisensory binding (Llinas and Ribary, 1993; Hong et al., 2009), and the organization of intrinsic brain networks (Koike et al., 2011). Furthermore, considerable experience has been accrued using sleep lab reports and home-based data (Hobson, 1988, 1999, 2002; Hobson and Stickgold, 1994; Kahn and Hobson, 1994, 2005; Resnick et al., 1994; Rittenhouse et al., 1994; Stickgold et al., 1994a,b, 2001; Sutton et al., 1994a,b).

In Freudian dream analysis, content is the manifest and latent content of a dream as it is remembered and its hidden meaning respectively, (Freud, 1920). More recent empirical approaches to content analysis have been pioneered by Hall, on the basis of thousands of dream reports. Empirical categories, such as "characters" and "social interactions," were subsequently refined and elaborated by (Hall and Van de Castle, 1966). Most elements in a dream report some fit into one or more categories (e.g., hugging someone is a friendly interaction and a physical activity). Content categories can then be used to create indicators that pertain to the dreamer or cohorts of dreamers. See Schredl (2010), for a contemporary review of content analysis in sleep research.

Virtual reality dream theory asserts that we explore a potentially infinite repertoire of predictive dream scripts. These scripts or scenarios are rehearsed in dreaming to provide an efficient (minimally complex) portfolio of explanations for the waking sensorium. However, the key thing we need to explain is why the phenomenology of dreams is so (apparently) delusional, hallucinatory and formally disordered. We will return to this issue after reviewing the neurobiology of sleep and theories of dreaming.

A SELECTIVE HISTORY OF SLEEP AND DREAM SCIENCE

The discovery of brain activation in sleep by Aserinsky and Kleitman (1953) marked a turning point in the history of consciousness science. The (REM sleep) brain activation they described was qualitatively similar to that of waking – as was the subjective experience of dreaming. These similarities suggested an intimate relationship between brain function in sleep and waking that we will consider in later sections. First, we will look more closely at the nature of REM sleep.

THE NEUROBIOLOGY OF REM SLEEP

The association of brain activation with REMs suggests an endogenous (brain stem) source of neuronal activation – and its role in the internal generation of visual imagery in dreaming. The description of REM sleep muscle atonia by Jouvet and Michel (1959) helped to presage the idea that dreaming was constituted by virtual perception and movement. Real (waking) perception and movement were actively blocked, while the brain was forced to generate a virtual simulacrum of waking consciousness. As the physical basis of the most intense dreaming, REM sleep is generally taken to be the canonical physiological substrate of dream consciousness.

The Aserinsky-Kleitman discovery led to a series of (largely futile) attempts to test psychoanalytic theory, which then dominated the intellectual scene. Because Michel Jouvet was a neurosurgeon, not a psychiatrist or psychoanalyst (and French, not American), he quickly exploited the biological significance of his discovery and proceeded to localize REM sleep control to the pontine brain stem (Jouvet, 1962) and to attempt to characterize REM genesis in neurochemical terms (Jouvet, 1969, 1972). Thus Jouvet was able to add modulation (M) to the already strong evidence for activation (A) and input–output gating (I) – three functions later used to construct a quantitative AIM model of conscious brain states (Hobson et al., 2000).

Other biologically grounded work showed that REM occurred in most mammals and in young birds (Klein et al., 1964; Roffwarg et al., 1966; Allison and Cicchetti, 1976). REM was significantly overrepresented in immature mammals and birds – and was even more evident with prematurity (Dreyfus-Brisac, 1964). At 30 weeks of gestational age, the percent of REM time has been estimated at a hundred percent (Roffwarg et al., 1966; Dawes et al., 1972; Birnholz, 1981). A neurodevelopmental function for REM could therefore be safely assumed.

These facts suggested that to support abundant and vigorous REM sleep, an animal needed to be large-brained and young. These conclusions are relevant to virtual reality dream theory, since they indicate both a neurodevelopmental function and a synthetic strategy for consciousness. Of course, REM sleep is not only present in young developing animals. Rather, its persistence over the life span hints at continued instantiation of intrinsic neuronal programs and the continuous modification by experience. The evidence that sleep favors learning is extensive and REM sleep in particular enhances motor skill acquisition (Walker et al., 2002; Diekelmann and Born, 2010). An intriguing discovery was that mammals and birds that evinced REM were not only dreamers but thermoregulators as well. Crucially, this thermoregulatory (homeothermic) capacity is lost during REM sleep. These discoveries raise interesting questions; for example, what is the functional evolutionary imperative of REM sleep that compensates for the suspension of homeothermy (Hobson and Friston, 2012) – and what is the relationship between thermodynamic and computational costs entailed by the brain activity during REM sleep. We will address these questions later.

THE NATURE OF REM SLEEP AND DREAMING

Many have emphasized the virtual and predictive aspect of dreaming and dream consciousness. For example, Llinás and Paré (1991) considered the idea of dreaming and waking consciousness as predictive models of the world. For example, in their treatment of dreaming and wakefulness they conclude: "These considerations lead us to challenge the traditional Jamesian view of brain function according to which consciousness is generated as an exclusive by-product of sensory input. Instead, we argue that consciousness is fundamentally a closed-loop property, in which the ability of cells to be intrinsically active plays a central role" (Llinás and Paré, 1991).

In a similar vein, Revonsuo presented a Virtual Reality metaphor of consciousness arguing "that the subjective form of dreams reveals the subjective, macro-level form of consciousness in general and that both dreams and the everyday phenomenal world may be thought of as constructed virtual realities" (Revonsuo, 1995). It was later proposed that dreaming is a preparatory, predictive simulation in the Threat Simulation Theory (Valli et al., 2005). Thomas Metzinger and Jennifer Windt have analyzed and refined the idea of dreaming as a model or simulation of the world that transcends waking and dreaming consciousness: "what we call waking life is a form of online dreaming" (Metzinger, 2003; p. 140). From this mix of comparative neurobiology and philosophy grew our concept of protoconsciousness and the virtual reality hypothesis (Hobson, 2009) – under which sensorimotor integration was supposed to be inborn and develop *in utero*. This concept accommodates the fact that dream consciousness *precedes* waking consciousness by months in utero and hours in adult life – it emphasizes self-as-agent, self-acting in a virtual (exteroceptive) space. Later, we will consider implicit virtual reality models as the precursor of generative models; namely, the models that emerge when the brain engages with the job of explaining exteroceptive input (after birth or sleep). We now turn to a promising area of research that has revealed much about the functional anatomy of sleep.

NEUROIMAGING

Brain imaging has revolutionized sleep research and is starting to elucidate the neurobiology of consciousness. Over the past two decades, positron emission tomography (PET) of human subjects has revealed REM sleep activation, above the level of waking, in the following regions:

- The *pontine tegmentum* (Maquet et al., 1996; Braun et al., 1997) confirming the results of Jouvet (1973) in the cat.
- The *amygdala* (Maquet et al., 1996; Braun et al., 1997; Nofzinger et al., 1997) and the *parahippocampal cortex* (Braun et al., 1997; Nofzinger et al., 1997) in keeping with the emotionality of dreaming (Merritt et al., 1994).
- The *parietal operculum* (Maquet et al., 1996; Braun et al., 1997; Nofzinger et al., 1997) a cortical hub for associative integration (Hobson and Stickgold, 1994).

Complementing these positive findings is the singular and unexpected observation of persistent deactivation of the frontal cortex (specifically the dorsolateral prefrontal cortex, Braun et al., 1997; Nofzinger et al., 1997). Note that this is consistent with the cognitive defects revealed by formal analyses of dreams.

The findings of brain imaging are surprisingly consistent and robust. They confirm – and extend to man –neurophysiological findings in experimental animals. As such, they carry with them the theoretical implications already noted from basic research. It seems quite likely that the cellular and molecular mechanisms of brain activation are the same across mammalian species, including humans. These cardinal neuroimaging results are also consistent with brain lesion studies, which we now touch upon.

THE NEUROPSYCHOLOGY OF DREAMING

The neuropsychologist Mark Solms interviewed and obtained computerized axial tomography (CAT) data from several hundred human subjects admitted to a London hospital. His findings complement the PET data: a complete loss of dreaming was reported by victims of stroke damage to either the occipito-temporo-parietal junction or deep frontal white matter. Furthermore, a remarkably astute examination of lobotomy subject records uncovered reports of complete loss of dreaming following surgery.

Thus it seems reasonable to hypothesize (Solms, 1997) that frontal projections are crucial to dreaming (although instrumental awakenings may be required to ensure that dreaming itself – and not just the recollection of dreaming – is impaired by brain lesions). Solms also affirms Epstein (1977) and the PET amygdala activation (Maquet et al., 1996; Braun et al., 1997; Nofzinger et al., 1997) by establishing a possible contribution of the temporal lobe to the hyperemotional, fugue-like and automatic quality of dreams (see dream phenomenology). The temporal lobe is notoriously seizure prone (Epstein, 1977) and its REM sleep brain activation by ponto-geniculo-occipital (PGO) wave excitation (Calvo et al., 1992) is relevant to the hypothesis of a seizure-like process in normal sleep.

LUCID DREAMING

Dreams, such as the specimen dream above, are normally delusional as to the state of consciousness in which they unfold. The dreamer supposes him or herself to be awake when he or she is, in fact, fast asleep. This delusion is easily resolved by awakening the dreamer, whose brain then becomes a more accurate (sensory-bound) instrument. The delusion can also be recognized and dispelled by introducing waking awareness into the dream. This creates lucidity, which can be defined as the conscious (doxastic) awareness that one is dreaming instead of believing, falsely, that one is awake.

Lucid dreaming is of central importance to the virtual reality hypothesis, because it clearly demonstrates the validity of three foundational assumptions:

(1) *There are two states of consciousness: one is waking and the other is dreaming.*
(2) *Waking and dreaming consciousness are normally separate and distinct, but,*
(3) *They can coexist as a hybrid state, in which both are present.*

The hybrid state of lucid dreaming – however, rare and evanescent – can be scientifically investigated as shown by Steven LaBerge, whose pioneering sleep lab studies proved that lucid dreaming – a first-person experience – always arises out of REM sleep and can be identified by a third person observer (LaBerge, 1990). Similarly, Ursula Voss has demonstrated that waking, non-lucid and lucid dreaming have quantitatively distinct EEG power signatures and that frontal lobe activation was lowest in non-lucid dreaming, highest in waking, and intermediate in lucid dreaming (Voss et al., 2012). Finally, Martin Dresler used fMRI to show that a distinct brain circuit was activated in lucid dreaming – a circuit that might mediate this curious state (Dresler et al., 2012).

The upshot of this work is that the brain mediates at least three states of consciousness, each in precise and distinctive ways. The crucial variable here is activation: both regional and global brain activation can be spontaneously and voluntarily changed to enhance one state of consciousness or another. The incidence of spontaneous lucidity peaks at about age nine (Voss et al., 2012), while volitional lucid dreaming can be cultivated most easily in young adults, under the age of thirty (Hobson, 2010).

Why age should be so crucial in determining dream lucidity is a question for future investigation. Most studies of dreaming have been conducted using young adult subjects – a limitation easily overcome using journalistic and home-based recording methods (Stickgold et al., 2001). Another interesting question concerns the apparently divided "self" of lucid dreamers: one watches, while the other dreams. Furthermore, the watching self can influence dream continuation and command changes in dream content. We speak of "being of two minds" and this is literally true in the case of lucid dreaming. We also speak of "talking to ourselves" – often in an encouraging way – as if we were indulging in autosuggestion.

Emergence of the observing self is associated with frontal lobe activation (Voss et al., 2009), a fact that accords well with executive functions attributed to this region. We know that dreaming is a brainstem-posterior forebrain affair (Jouvet, 1973; Maquet et al., 1996) and that frontal lobe activation is suppressed in REM (Braun et al., 1997; Nofzinger et al., 1997). The functionally "split brain" of sleep may thus become a rich source of data for studies of volition and metaconsciousness.

Having reviewed the functional anatomy of REM sleep and dreaming, we now turn to more formal models of conscious perception. Our hope is to explain the neurobiology and phenomenology of the dreaming in theoretical terms that call on generative models of the world.

VIRTUAL REALITY AND THE BAYESIAN BRAIN

Our thesis is that dreaming and REM sleep may hold the key for understanding the nature of conscious inference and its neurophysiological underpinnings. This understanding rests upon viewing the phenomenology of dreams and their neurophysiology in terms of perceptual synthesis – using a generative model of the sensorium. This section considers the special role that dreaming has in optimizing virtual reality models in the brain. In brief, we propose that dreaming and REMs are natural consequences of model optimization – in which the model is optimized to minimize redundancy or complexity. This will become crucial from the point of view of metabolism and energy efficiency – and its association with sleep – considered in the next section.

In what follows, we will refer to the brain as performing inference. Inference is usually thought of as reasoning on the basis of evidence; for example, inferring the probability of rain when deciding to take a raincoat. Almost universally, inference can be cast in terms of Bayesian inference, in which prior beliefs (April showers are common) are combined with sensory evidence (dark clouds over the horizon) to produce a posterior belief (it is likely to rain). This posterior belief is the expectation that maximizes Bayesian model evidence. We will take inference to be any process that increases the Bayesian model evidence associated with posterior expectations. Crucially, this inference may or may not be consciously articulated – but can always be defined mathematically and functionally.

THE BAYESIAN BRAIN

The notion that perception occupies the realm of a virtual reality dates back to Plato and his allegorical cave – in which are sensory impressions were likened to shadows cast by firelight on a cave wall. Perception makes sense of these impressions and, necessarily, entails some form of inference or modeling. This was most clearly articulated by Helmholtz (1866/1962) in terms of unconscious inference and the generation of explanations for sensory impressions:

> "*Objects are always imagined as being present in the field of vision as would have to be there in order to produce the same impression on the nervous mechanism*" – von Helmholtz

Over the last century, this insight has been treated in several guises – from Gregory's notion of perception as hypothesis testing (Gregory, 1980) to current formulations of the Bayesian brain (Knill and Pouget, 2004). They all appeal to an underlying generative model from which predictions or hypotheses are drawn. One might ask what why we equate (phenomenal) virtual realities with (inferential) generative models.

The concept of virtual reality is often used to refer to the subjective experiences of a self immersed in a world that appears real (Revonsuo, 1995, 2006). The generative models that underlie the Bayesian brain hypothesis may, at first glance, fail to emphasize the subjective aspect of virtual reality model. However, virtual reality and generative models are formally equivalent – in the sense that generative models generate predictions of sensory contact with a world that is perceived through sensations. However, there is an important distinction between virtual reality and generative models: the purpose of a generative model is to account for (sensory) data. This means that when exposed to sensory information, the generative model – embodied by the brain – is trying to recapitulate reality through sensory exchanges with the world. It is therefore constrained by reality. Only when asleep, is the brain freed from sensory constraints to generate fictive predictions or a virtual reality proper. In short, we may be born with a virtual reality model but sensory exchanges with the real world quickly mould it into a generative model – with nightly reprises from predicting sensations during sleep. Note that the generative model is quintessentially subjective or first-person because the sensory predictions are unique to the self-as-agent in a sampled world.

The most neurobiological plausible instance of this predictive sampling is known as predictive coding; particularly of a hierarchical sort (Srinivasan, Laughlin and Dubs, 1982; Rao and Ballard, 1999; Bastos et al., 2012; Clark, 2013; Hohwy, 2013). Predictive coding involves the updating of expectations about hidden states of the world generating sensory data. This updating is driven by sensory information that cannot be explained by current expectations or beliefs entertained by the brain. This information is known as prediction error and is simply the difference between sensory input and top-down or descending predictions of that input. When generalized to hierarchical models, the same reciprocal exchange of descending top-down predictions and ascending or bottom-up prediction errors emerges. This provides a nice metaphor for the recurrent message passing between levels of the cortical hierarchy – and accounts for many anatomical and physiological aspects of extrinsic (long-range) connections in the brain (Lee and Mumford, 2003; Friston, 2008; Bastos et al., 2012). The idea here is that prediction errors inform expectations at higher levels of the hierarchy so that they can send better predictions to lower levels – and thereby suppress prediction error. If one can suppress prediction error at all levels of the cortical hierarchy, then the implicit expectations – encoded neuronally – provide a plausible explanation for sensory input at multiple levels of description or abstraction.

Clearly, this reciprocal message passing or hierarchical predictive coding rests upon a model that can generate top-down predictions. It is this hierarchical model – entailed by cortical hierarchies – which we associate with the virtual reality model of dream theory. The principle that drives recurrent neuronal exchanges is to minimize prediction error and thereby make (Bayes) optimal predictions that underlie perceptual *inference* or synthesis. In this setting, minimizing prediction error corresponds to maximizing Bayesian model evidence. Exactly the same prediction error minimization underlies changes in synaptic efficacy – through associative or experience-dependent plasticity – enabling the brain to acquire models of increasing hierarchical depth. This is referred to as perceptual *learning*.

There is now a large body of circumstantial evidence for predictive coding in the brain, both in terms of hierarchical cortical architectures and the canonical microcircuits required to construct predictions (Bastos et al., 2012; Adams et al., 2013a). In brief, current thinking suggests that prediction errors are encoded by firing rates of superficial pyramidal cells in the upper layers of the cortex. The predictions, in turn, are conveyed by top-down or descending backward connections from deep pyramidal cells encoding expectations or beliefs about (hidden) states in the world causing sensory impressions (Mumford, 1992; Bastos et al., 2012). But what has this view of neuronal processing to do with sleep and dreaming?

To understand this, we have to step back from predictive coding – and the minimization of prediction errors – and think about the underlying quantity that is being optimized during perception. From a statistical perspective, this quantity is the (Bayesian model) evidence for the generative model. In other words, the model is optimized or adjusted until the probability of sensations – over an extended period of time – is the most probable under all models that could be entertained. Practically, Bayesian model evidence is very difficult to compute, so a proxy is generally used both in statistics and – we suggest – the brain. This proxy is called variational free energy (Hinton and van Camp, 1993; Beal, 2003), leading to the variational free energy formulation of perceptual inference and learning (Dayan et al., 1995; Friston et al., 2006).

From the point of view of sleep, the key thing to appreciate is that maximizing model evidence (or minimizing variational free energy) does not just rest upon minimizing prediction errors but also requires that they are minimized as parsimoniously as possible. Technically speaking, the (logarithm of the) Bayesian model evidence can be decomposed into *accuracy* and *complexity*; where log evidence increases with accuracy (small prediction errors) but decreases with complexity – the degrees of freedom required to make predictions (Penny et al., 2004). This means that there is an imperative to minimize the complexity of generative models to maximize their evidence.

COMPLEXITY AND SLEEP

Complexity is a measure of how complicated a generative model is. In other words, complexity reflects the degrees of freedom – or numbers of parameters – that are required to provide an accurate prediction of sensory data. Minimizing complexity under the constraint of maintaining accurate predictions is nothing more than the principle of Occam's razor; formulated in terms of Bayesian model selection (Penny et al., 2004). Technically speaking, complexity is measured as the difference between prior beliefs (expressed as a probability distribution) and posterior beliefs – after the prior beliefs have been updated on observing sensory outcomes. We have previously discussed the physiological basis for this complexity reduction in terms of eliminating redundant parameters or synapses during sleep (Hobson and Friston, 2012). This is exactly consistent with the synaptic homoeostasis hypothesis and the role of sleep in pruning unnecessary and exuberant synaptic connections (Gilestro et al., 2009). This pruning minimizes the redundancy (complexity) of the model and endows it with a parsimony and hierarchical simplicity that is essential for efficient and generalizable perceptual inference during waking (i.e., precludes overfitting). In summary, the very notion of a model induces the concept of model complexity and an associated cost function that has to comply with Occam's principle. Physiologically, we have suggested that sleep is necessary to minimize complexity in order to ensure that our models are optimal during waking. But what is special about sleep from point of view of model optimization?

According to the AIM hypothesis, REM sleep is the quintessential state of perceptual processing in which the brain is sequestered from sensory perturbations. This modulatory input gating is crucial for minimizing complexity – because we can ignore the accuracy part of model evidence (because there are no sensations for which an accurate explanation is required). This means that the brain can focus on minimizing complexity, using exactly the same hierarchical prediction error minimization that it uses during wakefulness. Indeed, statistical schemes that operate along these lines can be found in powerful machine learning algorithms such as the wake-sleep algorithm (Hinton et al., 1995).

Notice here, it is the synaptic connections *learning* associations and contingencies that are optimized, not the synaptic activity *inferring* current states of the world. In other words, brain activity is freed from explaining sensory input and is used to generate fictive predictions that produce prediction errors at each level of the hierarchy. These prediction errors then drive activity-dependent plasticity to minimize complexity (by minimizing prediction error). We have here the first glimpse of a functional explanation for the formal phenomenology of dreams. The distinction between inference and learning is central to our arguments – and the distinction between waking and dreaming perception. Inference corresponds to optimizing neuronal or synaptic activity at a fast timescale over hundreds of milliseconds, while learning corresponds to a slow optimization of synaptic connections over minutes to hours. In waking, inference is enslaved by sensory input and learning is driven vicariously by (experience dependent) plasticity. In contrast, during sleep there is no sensory entrainment – and learning (synaptic plasticity) can only reduce model complexity; in other words, make the generative model internally consistent. This means the perceptual content of dreams – encoded by synaptic activity – is fictive in the sense that it corresponds to real-world scenarios that never actually occur. Put simply, the content of dreams is not a prediction of what will happen but an exploration of what could (or could not) happen that is necessary to minimize model complexity – rendering it a more efficient model of the experienced world on waking.

COMPLEXITY MINIMISATION AND DREAM PHENOMENOLOGY

In the absence of sensory constraints, the vivid percepts (McCarley and Hoffman, 1981), delusional beliefs (Hobson et al., 2000) and cognitive defects (Hobson and Stickgold, 1994; Stickgold et al., 2001) cease to be delusional or defective – because these attributes are only defined in relation to sensory evidence. However, in sleep, there is no sensory evidence and the only imperative is to adjudicate and select among unconstrained scenarios that can be entertained by the sleeping brain. The implicit (protoconscious) self-supervision may also explain frontal deactivation and the temporary suspension of top-down constraints on lower-level representations – representations or beliefs that compete for "synaptic resources." As noted above, this functional hypofrontality may preclude the veridical self-awareness and doxastic attributions that characterize dreaming.

In this view, dream content corresponds to expectations or beliefs encoded by endogenous neuronal activity that both causes, and is caused by, changes in synaptic connectivity. Both neuronal activity and connectivity minimize prediction errors, even in the absence of sensory input – because prediction errors are prevalent throughout the depth of cortical and subcortical hierarchies. The only difference between dreaming and waking is that the precision (neuromodulatory gain) of prediction errors at the lowest (sensory) levels and deepest (executive) is reduced – leaving intermediate levels to sculpt themselves into a parsimonious and self-consistent architecture, that will be more efficiently entrained by the waking sensorium.

Interestingly, Jesse Prinz (2000) has argued that there is something special about processes that operate upon "intermediate-level representations." A natural speculation is that inferences that are geared to action-selection predominate at intermediate levels – apt for the selection and control of embodied action. We will pursue this in setting of oculomotor control below. However, the notion of intermediate cortical levels generating a virtual reality – that is freed from both (bottom-up) sensory constraints and (top-down) contextual constraints from prefrontal narratives – may also have something to say about dream content.

If the purpose of dreaming is to simplify our model of the world, why are dreams so diverse and, if anything, more complex than the world itself? Hofstadter (1979) touches on this issue: by exploring themes common to the works of the logician Gödel, artist Escher and composer Bach, Hofstadter discusses how self-reference allow systems to generate meaning. His treatment rests on recursion and self-reference, in a way that is very reminiscent of hierarchical inference and reciprocal message passing in the brain. Hofstadter asserts that dreams are unpredictably diverse and infinitely creative. How does this fit with complexity minimisation? The key thing to note is that complexity is an attribute of a model, not the content of (fictive) inferences afforded by a model. As noted above, the function of complexity minimisation is to ensure that the model can generalize. In other words, minimizing the complexity of synaptic connections enables efficient inferences about a greater diversity of sensory scenarios – scenarios that may be rehearsed during dreaming. It is the very diversity of dream content that complexity minimisation aspires to accommodate. In this sense, dreaming may prepare the brain for the unpredictable diversity of scenarios it encounters during waking. Complexity minimisation therefore furnishes a plausible perspective on the diversity of dream content but what about its creative aspects?

Clearly, freed from the top-down (prefrontal) constraints of narratives and perspective-taking, dream content can take on a fantastical aspect that can entertain violations of temporal and perspectival contiguity. But how does this relate to creativity? A potential answer to this question may lie in daydreaming and mind-wandering (McMillan et al., 2013). Several lines of research have linked mind-wandering to creativity, especially in problems that have been encountered recently (Baird et al., 2012). Using an incubation task and a validated creativity task – the Unusual Use Task – Baird et al. (2012) showed that creative problem solving can be enhanced by performing an undemanding distraction task during an incubation period (c.f., eureka moments that come out of the blue). In short, the ability to realize creative (generalizable) associations rests on a temporary suspension of cognitive and attentional set – of the sort associated with the prefrontal cortex (Christoff et al., 2009). This fits comfortably with the suspension of high level (prefrontal) constraints that we suppose helps optimize associative connection strengths during sleep.

In summary, our explanation for the function of sleep suggests that the brain is essentially doing the same thing in sleep and waking; with one key difference – there is no sensory input during sleep. However, the recurrent hierarchical message passing is still in process; with continually changing expectations and hierarchical predictions that constitute dream content. Physiologically, it appears that cholinergic discharges enable the promulgation of ascending prediction errors at intermediate levels of the cortical hierarchy, while aminergic neuromodulation suppresses or gates ascending sensory input at the sensory level (Hobson and Friston, 2012). This means that, from the brain's point of view, the world is still unfolding with deep hierarchical structure and perceptual content – the only thing that has changed is that this content is no longer enslaved by sensory information.

Having said this, the brain is still compelled to minimize (extrasensory) prediction errors and implicitly complexity. Heuristically, one can imagine how this proceeds by considering prediction errors as reporting inconsistent or over-parameterized models. As the models are revised during dreaming, different hierarchical representations become internally consistent producing – on average – fewer hierarchical prediction errors. The endpoint of this process is a hierarchical model that can generalize to the diversity of sensory scenarios it encounters during waking. This offers an explanation for the function of sleep. But how does it explain the physiology of sleep?

ACTIVE INFERENCE AND RAPID EYE MOVEMENTS

According to the AIM model, the transitions from wakefulness to sleep rest upon a selective gating of sensory inputs that is entirely consistent with the neurochemistry of the wake-sleep cycle (Hobson, 2009). The selective pressure for this diurnal gating can now be motivated in terms of model optimization or complexity minimization. Furthermore, the advantage afforded by parsimonious but hierarchically deep models may explain the association between REM sleep and higher levels of consciousness in comparative sleep research (see above and Hobson, 2009).

One interesting aspect of this formulation is the special status of eye movements during sleep. All perceptual inference is at some level active – in the sense that we actively sample our sensorium to create our own sensations (Wurtz et al., 2011; Brown et al., 2013). This embodied perspective is referred to as *active inference* (Friston et al., 2011). This is important because higher levels of the model are necessarily producing multilateral top-down predictions of both visual (and other exteroceptive) input *and the proprioceptive consequences of actively sampling that input*. Indeed, under active inference, the descending proprioceptive predictions become motor commands that are fulfilled by peripheral reflexes in the spinal-cord and pontine nuclei (Adams et al., 2013a). In this formulation, classical reflexes simply minimize (proprioceptive) prediction error.

This is important because – unlike the striatal muscle of the motor plant – it is possible to move the eyes without changing posture. In other words, proprioceptive predictions descending within the central nervous system can engage the oculomotor system with impunity. In turn, this means model optimization during sleep (and *in utero*) can include predictions about visual and oculomotor sensations that engage the full depth of the hierarchy – spanning the visual (geniculo-occipital) system and the (pontine) oculomotor system. Physiologically, this means that we would expect to see classical oculomotor reflexes fulfilling proprioceptive predictions – and producing eye movements in sleep that are not dissimilar to saccadic eye movements. At the same time, descending visual predictions will fall upon deaf ears (sic) as they encounter the (gated) sensory level at the lateral geniculate or early visual cortex. This provides a simple explanation for REMs in REM sleep and – electrophysiologically – for their association with PGO waves.

In summary, the generative or virtual model entertained by the brain requires maintenance – in the sense it has to account for a vast amount of sensory input during waking and can only do this if it generalizes to every context encountered. This generalization rests upon minimizing model complexity (to avoid overfitting sensory data), which is equivalent to minimizing variational free energy in the absence of sensory input. The neurophysiological validity of variational free energy minimization – in terms of predictive coding and associative plasticity – has already been established in terms of neuronally plausible mechanisms (Friston et al., 2006; Bastos et al., 2012). Furthermore, we have discussed at length the role of sleep in enabling this optimization (Hobson and Friston, 2012). This perspective provides a simple and mechanistically grounded account of the neuromodulatory gating of cortical and subcortical systems, the selective expression of eye movements in sleep and their association with PGO waves. In the penultimate section, we will expand upon the role of virtual reality models in conscious inference. In the next section, we consider the relationship between complexity minimization, energy regulation and sleep.

REM SLEEP, MODEL COMPLEXITY AND THERMODYNAMIC EFFICIENCY

We have hinted at an intimate association between homoeothermic regulation and REM sleep in terms of comparative physiology. There are some further fascinating links between thermoregulation and REM sleep that we now pursue in light of complexity (variational free energy) minimization during sleep.

A remarkable fact about REM sleep is that homeothermy is suspended and temperature sensitive neurons in the hypothalamus become temperature insensitive in REM (Parmeggiani, 2003). The predictive coding formulation above provides a simple explanation for the implicit loss of temperature control during sleep: if aminergic modulation suppresses the sensitivity of principal cells reporting sensory (interoceptive) prediction errors, then it will preclude the signaling of thermoreceptors along unmyelinated C-fibers and delta-fibers. In short, the brain will be impervious to fluctuations in temperature and will not respond to suppress thermal prediction errors, resulting in a suspension of homeothermy. So what evolutionary imperatives endorse this risky physiology? The answer that emerges from the above arguments is that sleep is an optimization process that is disclosed by the nightly removal of sensory perturbations; in other words, the brain can take itself off-line with impunity, so that synaptic plasticity and homoeostasis (Gilestro et al., 2009) can reduce the complexity it has accrued during wakefulness. In evolutionary terms, the adaptive cost of nightly suspensions of homeothermy is offset by the reduction of complexity costs afforded by sleep – provided environmental temperature does not fluctuate too much during sleeping (or *in utero*).

As noted in Hobson and Friston (2012), the imperative to reduce complexity during sleep may be greater for the (complicated) brains of mammals (and birds). The failure to restore complexity to minimal levels would, in principle, mean that experience-dependent learning during the day would not be tempered; leading to a colloquial and context-bound model of the world that becomes increasingly complex and redundant. In statistics, the equivalent pathology is known as "over-fitting" and leads to suboptimal models that fail to generalize beyond the data on which they were trained. In short, taking the brain off-line to prune exuberant associations established during wakefulness may be a necessary price we pay for having a sophisticated virtual reality model that can distil complex and subtle associations from the sensorium. But is this the complete story?

In fact, there is a more fundamental link between complexity minimization and thermoregulation that provides a thermodynamic perspective on minimizing complexity costs. The arguments here are subtle but simple (a detailed discussion can be found in Sengupta et al., 2013). The premise is that minimizing complexity implicitly maximizes the thermodynamic efficiency of information processing in the brain. This premise can be verified by noting that when the brain minimizes complexity it also minimizes its thermodynamic free energy (and the work needed to attain that state). In short, a minimally complex brain state is also in an energetic minimum:

Any system – including the brain – will minimize its *thermodynamic* free energy when isolated from external forces or perturbations. However, when isolated from sensory perturbations, a system that is trying to minimize model evidence (or *variational* free energy) will minimize complexity – which means the state of minimum complexity is also the state of minimum thermodynamic free energy. More generally, simpler models are less costly both in terms of statistical or model complexity and the thermodynamic work entailed by applying them to (sensory) data. Quite literally, our might brains run a tiny bit hotter after a sleepless night – as they try to inefficiently over-fit sensory data.

The notion – that a failure to minimize information-theoretic free energy in sleep entails a failure to minimize thermodynamic free energy – seems borne out by the fate of Rechtschaffen et al.'s (1989) rats (Jim Hopkins – personal communication). As Rosalind Cartwright reports (Cartwright, 2010, pp37–8) these sleep-deprived rats died as a consequence of metabolic burn-out. This apparently resulted from a failure to lower (or down-regulate) their core body temperature (NREM and REM sleep had different effects but REM deprivation alone was sufficient). The mechanisms remain unclear but – in the present context – speak to a failure of (interoceptive) predictive coding, resulting (fatal) failures to minimize both information theoretic and thermodynamic free energy.

Note that we are not saying the sleeping brain finds some equilibrium steady-state of minimum energy consumption. Rather, we are saying that the drive toward simpler models implicit in synaptic regression – and other physiological mechanisms – during sleep, renders the brain's non-equilibrium steady-state functioning less metabolically expensive when averaged over both sleep and wakefulness. In the next section, we will consider neuroimaging evidence that large portions of the brain reduce their metabolic rates during REM sleep – but other regions show activation during REM sleep. Interestingly, the particular systems showing REM-locked activation are those involved in intermediate hierarchical representations and the enabling of message passing among those levels.

In summary, we have seen that the imperative to minimize model complexity is equivalent to optimizing the thermodynamic efficiency of information processing in the brain. Given that the previous section established sleep as necessary for complexity minimization, it follows that sleep is also necessary to optimize the metabolic efficiency of operating the virtual reality model in wakefulness. We now consider empirical evidence for the theoretical considerations above, with a special focus on the neuronal systems generating and searching fictive visual scenes.

EMPIRICAL EVIDENCE FOR PREDICTIVE CODING DURING SLEEP

In this section, we review recent functional magnetic resonance imaging and electrophysiological evidence that is consistent with the computational architecture implied above. Our focus is on the correlates of REMs and the modulation of fast synchronous (gamma) activity by (cholinergic) gating mechanisms in REM sleep.

REM-LOCKED ACTIVATION IN THE BRAIN

We recently reported an fMRI study of the neural correlates of REMs in sleep (Hong et al., 2009). REMs were identified from video recordings that detects about four times as many REMs than conventional electrooculographic (EOG) approaches that are usually used in fMRI studies (Wehrle et al., 2005; Miyauchi et al., 2009). This is because removing MRI scanner artifacts from the EOG also removes small amplitude eye movements. In contrast, video monitoring reveals small eye movements, which is important because both small and large eye movements can be detected with fMRI (Kimmig et al., 2001).

Our key findings can be summarized as follows: REM-locked activation is distributed but regionally specific. Peak activation is clearly localized in primary visual and non-visual sensory cortex and regions implicated in perceptual binding or synthesis: namely, the thalamic reticular nucleus, claustrum, and basal cholinergic forebrain. The reticular nucleus of the thalamus and claustrum have been identified as structures that are crucial for binding information distributed within and across different sensory modalities (Crick, 1984; Crick and Koch, 2005). The role of the claustrum in binding and salience detection has also been considered by Smythies et al. (2012) and Remedios et al. (2010), respectively. Furthermore, electrical stimulation of the claustrum has been shown to produce reversible arrest of volitional behavior and unresponsiveness (Koubeissi et al., 2014). REM-locked activation was also found in multisensory cortical areas indentified in waking studies (Calvert and Thesen, 2004). These include superior temporal gyrus – a key region for audiovisual integration (Hein and Knight, 2008) – and the right retrosplenial cortex.

REM-locked activation overlaps with brain regions expressing or modulating gamma oscillations (Gross and Gotman, 1999; Jouny et al., 2000); i.e., the thalamocortical sensory system (Llinas and Ribary, 1993), mesopontine tegmentum (Steriade et al., 1991) and basal forebrain (Szymusiak, 1995; Mesulam, 2004; Perry and Perry, 2004). These findings are consistent with a role for REMs in hierarchical multisensory integration that may be evident before birth (Hobson, 2009) and through the life span (Bremner et al., 2012).

NEUROMODULATORY GATING AND ELECTROPHYSIOLOGICAL OSCILLATIONS

The basal forebrain cholinergic system can induce gamma band synchronization, which is a potential mechanism for the binding of distributed neuronal processes (Engel and Singer, 2001) – and regional enhancement of cortical sensory processing (Szymusiak, 1995; Mesulam, 2004; Perry and Perry, 2004). From the perspectives of the AIM model and predictive coding, cholinergic modulation may play an important role in modulating and gating prediction errors signals – a role that has been associated with the deployment of attention in waking (Feldman and Friston, 2010) and the neurochemical modulation of hierarchical cortical processing during sleep (Hobson and Friston, 2012).

Crucially, the rapid integration or binding of distributed neuronal groups is thought to be required for conscious experience. It has been proposed that "rapid integration is achieved through the process of reentry, the ongoing, recursive, highly parallel signaling within and among brain areas" (Tononi and Edelman, 1998). This fits comfortably with the reciprocal message passing mandated by predictive coding. Furthermore, the REM-locked activation of brain regions commonly associated with binding and high-frequency (gamma) synchronization is consistent with the cholinergic boosting of superficial pyramidal cells at intermediate levels in the cortex during REM sleep. Typically, superficial cortical layers show greater coherence and activity in the gamma range; for example, the superficial layers of cortex show neuronal synchronization and spike-field coherence predominantly in the gamma frequencies, while deep layers prefer lower (alpha or beta) frequencies (Roopun et al., 2006; Maier et al., 2010; Buffalo et al., 2011). This is potentially important because – as noted above – superficial pyramidal cells are thought to encode prediction error (Bastos et al., 2012).

Rapid eye movement-locked activation in the primary sensory (olfactory or somatosensory) cortex does not necessarily correspond to an olfactory or somatosensory dream experience (Hong et al., 2009). In dreaming, people rarely smell (Zadra et al., 1998) or feel touch (McCarley and Hobson, 1979). Instead, REM-locked multisensory recruitment may reflect top-down priming of sensory cortex (Tallon-Baudry and Bertrand, 1999; Calvert and Thesen, 2004; Hong et al., 2009).

REMs are accompanied by PGO waves (Nelson et al., 1983). REM-locked multisensory recruitment suggests that top-down predictions – eliciting REM and PGO waves – involve visual and non-visual components of the cortical hierarchy (Hobson and Friston, 2012). Furthermore, brain activation time-locked to REM (and PGO waves) is widespread; as predicted by the activation-synthesis hypothesis (Hobson and McCarley, 1977). However, while this activation is distributed, it is also highly system-specific, engaging exactly those systems that are deployed for hierarchical perceptual synthesis during visual palpation in waking.

In short, these results are compatible with virtual reality dream theory in that they demonstrate the activation of the brain in REM sleep recapitulates that of waking. Given the phenomenology of dreams, this is no great surprise – supporting the idea that dreaming and waking mirror each other. Instead of arguing that dreaming precedes rather than follows waking, one might argue that waking and dreaming are two sides of the same coin – interacting in a complementary and reciprocal fashion. Our two states of consciousness are mutually enhancing rather than divisively competitive.

DO REMs SCAN DREAM IMAGERY OR GENERATE IT?

A correlation between the density of REMs in sleep and reports of visual experience in dreaming may indicate that REMs "scan" the dream scene (Roffwarg et al., 1962; Herman et al., 1984; Hong et al., 1995; Hong et al., 1997). Alternatively, it may indicate that REMs play a role in generating dream images (Hong et al., 2009). This issue is important because, in active inference, eye movements are both cause and consequence of perception. This is meant in the sense that a percept entails both visual and proprioceptive predictions – and the latter induce movement through oculomotor reflexes in sleep (REM) and wakefulness (saccades).

Are REMs driven by dream imagery or do they generate it (or both)? Studies in human subjects suggest that REMs are visually targeted eye movements – commanded by the forebrain – in response to visual dream images (Roffwarg et al., 1962; Herman et al., 1984; Hong et al., 1995, 2009). In contrast, single cell recording studies in animals have established that PGO waves that are coupled with REMs (Nelson et al., 1983). PGO waves have been interpreted as corollary discharges associated with brain stem oculomotor commands. We originally proposed that this discharge might be associated with the generation of visual images in dreams (Hobson et al., 2000). Indeed, from the perspective of predictive coding, this corollary discharge corresponds to descending visual predictions (of a virtual scene) that are an integral part of perceptual inference – inference that determines dream content.

In short, two lines of research that initially appeared to contradict each other now converge on the view that REMs are involved in both the scanning and generation of dream imagery (Hong et al., 2009). In other words, eye movements are both cause and consequence of perceptual content – a notion that is becoming increasingly dominant in the visual neurosciences. This "active vision" perspective (Wurtz et al., 2011) is consistent with active inference during waking, where perceptual content is used to generate top-down predictions of oculomotor sensations and their consequences. This provides a nice model for saccadic eye movements that are essential for waking perception (Yarbus, 1967) and sequential updating of sensory samples (Friston et al., 2012). Saccadic searches of the visual world in wakefulness are necessary for testing models of the world and serially updating the ensuing hypotheses with data sampled through scanning. This has been simulated in terms of active inference (Friston et al., 2012) – and has been pursued in the context of abnormalities seen in schizophrenia (Adams et al., 2012). Recordings of saccadic eye movements show that they are attracted to parts of the visual scene that have salient or precise information; e.g., the eyes and lips (Yarbus, 1967). These saccadic searches are performed automatically and quickly: about four to eight eye movements per second, which is interestingly about the same frequency of PGO waves and bursts of REM in sleep. It therefore appears that both waking saccadic searches and REMs are an integral part of active vision (Wurtz et al., 2011) – in much the same way that we infer the nature of an object in the dark by palpitating it.

However, there is no visual world to be scanned by a fetus. REM sleep is nonetheless preponderant in the third trimester of pregnancy. How can we interpret this fact? The answer is simple: although there are no precise visual (exteroceptive) consequences of movement, there are proprioceptive consequences that have to be learnt – and can be learned *in utero*. If this observation is right, REMs would be essential to enable the brain to model the (proprioceptive) consequences of eye movements that will be necessary during active visual searches. Crucially, REM sleep deprivation in immature rats suggests that endogenously generated visual activation during REM sleep plays a necessary role in development of the visual system (Shaffery et al., 2002).

Waking imagery studies (Brandt and Stark, 1997; Laeng and Teodorescu, 2002) suggest that information pertaining to saccadic sequences is maintained together with the visual representation – and is used as spatial index for the proper arrangement of image components during image generation (in dreaming) and perceptual synthesis (in waking). Again, we conclude that REMs are involved both in saccadic searches of the dream image and in its generation. In the setting of active inference, REMs are the peripheral expression of top-down proprioceptive predictions based upon active visual palpation of a virtual scene generated in the cortical hierarchy. It is therefore sensible – from the virtual reality perspective – that dream perception and its proprioceptive manifestation share a common visual theme.

Further evidence supports the view that REMs are involved in the generation of a virtual reality. First, REM-locked activation is greater in the posterior left hemisphere (Hong et al., 2009) that appears to be crucial for generation of dream imagery (Farah, 1984). Second, REM-locked activation in language areas speaks to the involvement of association (semantic) cortex (Hong et al., 2009) and its reciprocal interaction with lower (sensory) cortex (e.g., Tallon-Baudry and Bertrand, 1999). Finally, REM-locked activation is seen in primary somatosensory cortex, premotor cortex, vestibular cortex, insula, anterior cingulate cortex, putamen, and superior temporal gyrus (Hong et al., 2009). These regions have all been implicated in representing the embodied self (Blanke, 2012) – suggesting that REMs may be involved in the generation of (bodily) self images in dreaming.

SOME CLUES FROM ELECTROPHYSIOLOGY

There are two key neurobiological candidates for modulating synaptic gain that are implicated in both REM sleep and attentional gating: synchronous gain (Chawla et al., 1999) mediated by fast oscillatory or synchronized activity (Womelsdorf and Fries, 2006) and classical neuromodulatory (e.g., cholinergic) neurotransmission (Schroeder et al., 2001; Hirayama et al., 2004). Furthermore, both of these gating mechanisms influence each other: as noted above, gamma oscillations are profoundly affected by acetylcholine, which is released into sensory cortex from nuclei in the basal forebrain. Acetylcholine acts through both fast ion channel (nicotinic) receptors and slow metabotropic (muscarinic) receptors (Hasselmo and Giocomo, 2006). Acetylcholine appears to increase synaptic gain directly by, for example, reducing spike-frequency adaptation. It may also facilitate the induction of gamma oscillations by reducing adaptation in pyramidal cells or decreasing activity of inhibitory interneurons (Börgers et al., 2005).

Human intracranial EEG shows that cortical gamma power is enhanced during phasic REM sleep (but not tonic REM sleep associated with generalized atonia). Similarly, rat hippocampus shows increased gamma synchrony during phasic REM sleep, while gamma power and firing rates decrease during tonic REM sleep (Montgomery et al., 2008). Therefore, gamma power may be preferentially expressed during phasic REM sleep, enabling message passing among intermediate levels of the cortical hierarchy (and explaining the relatively low gamma–REM association found by Le Van Quyen et al., 2010).

Interestingly, there is reduced EEG coherence in the gamma band between cortical areas during REM sleep (Castro et al., 2013). This is not inconsistent with the functional disconnection or suspension of top-down constraints implied by the exploratory nature of fictive predictive coding during complexity minimization. Indeed, "The virtual absence of gamma frequency coherence during REM sleep may underlie the unique cognitive processing that occurs during dreams, which is principally a REM sleep-related phenomenon" (Castro et al., 2013).

Another important electrophysiological hallmark of predictive coding is the mismatch negativity (MMN), elicited as an event related potential difference by oddball or deviant stimuli. These responses have often been associated with prediction errors. There is some evidence that an analog of the MMN can be elicited in REM sleep "despite the gross suppression of both executive top-down processing and external input transmission (Atienza et al., 2000; Ibáñez et al., 2009)" (Yordanova et al., 2012). Interestingly, no MMN has been recorded during non-REM sleep and slow wave sleep (Yordanova et al., 2012), suggesting that there may be something special about the activated brain state in REM sleep that enables descending predictions (necessary to produce the mismatch response).

In summary, much of the empirical evidence pertaining to the neurophysiology of REM sleep – as obtained through invasive and non-invasive studies – implicates the functional anatomy that underlies perceptual synthesis and binding. Furthermore, many of the neurophysiological correlates of REMs in sleep are consistent with neuronal implementations of predictive coding based on virtual reality or generative models. In particular, the involvement of brain systems that underlie active visual inference account for both the prevalence of visual content in dreaming perception and the prominence of REMs – and their associated PGO waves. In the next section, we consider the implications of the virtual reality model for understanding conscious inference – and the special role that dreaming may play in disclosing the anatomy of consciousness.

VIRTUAL REALITY DREAM THEORY AND CONSCIOUSNESS

There are clear echoes in active inference of Kant's search for the *a priori* conditions for the possibility of experience (Kant, 1999/1781). The prenatal evidence of highly organized brain activity of the fetal brain *in utero* (Birnholz, 1981) is a cogent of modern findings in this regard. The post-natal prevalence of REM sleep is also relevant but it could be argued that neonatal infants have an abundance of novel experiential data to assimilate into their generative models during sleep. In both cases, it seems likely that important statistical and thermodynamic processes are at work at this point in neurodevelopment.

We have already shown that several issues in consciousness research (Chalmers, 1996; Wegner, 2003) can be addressed when the brain is treated as an organ of inference (Hobson and Friston, 2014). In what follows, we briefly review how appealing to the process of inference, implicit in the deployment of virtual reality models, may provide plausible answers to metaphysical questions.

CONSCIOUS AND UNCONSCIOUS INFERENCE

In the preceding sections, we have seen how the virtual reality model underlies inference in the brain – and how statistical imperatives persist during sleep. The neurobiological generation and refining of perceptual fantasies during dreaming was considered in light of predictive coding and the neuromodulatory gating effects of sleep. The previous section reviewed the empirical neurophysiological evidence in support of this formulation. Here, we return to our assertion that sleep and dream research can cast light upon some aspects of consciousness.

In Hobson and Friston (2014), we put forward the simple argument that consciousness can – at some level – be equated with inference. The idea here is that the dualism implied by the *res cogitans* and *res extensa* (realm of the mind and realm of extensive physical reality: Manuel, 2001, p. 97) can be resolved through the biophysical act of inference; namely, neuronal message passing in the sleeping and waking brain. This dual aspect monism follows from the fact that the biophysical state of the brain encodes probabilistic beliefs that minimize prediction error (or variational free energy). In other words, the dynamics of synaptic activity and efficacy are driven by quantities (variational free energy) that are functions of beliefs (probability distributions) encoded by those biophysical quantities. For example, population activity at the neuronal level may encode the expectation or mean of a Gaussian probability distribution over some hidden state of the world. The very fact that dynamical forces on the physical brain are produced by (functions of) probability distributions links the physical (*res extensa*) to the mindful (beliefs or *res cogitans*) in a fundamental way. Another perspective on this bridge over the Cartesian divide is that it provides a (wide sense) realization relationship (Wilson, 2001; Gillett, 2002). In other words, the process of inference affords a unique mapping between physical (neuronal) states and the properties (probabilistic beliefs) they realize (c.f., Bechtel and Mundale, 1999).

In short, we cast perception in terms of inference, where inference is associated with a distinctive functional property or role (i.e., hierarchical message passing). This functional role is realized by neuronal populations that encode probability distributions. This makes this theory a functionalist theory, which links mental to physical states as roles to realizers. As far as metaphysics goes, this is then a theory that is consistent with (i) a thoroughgoing reductive physicalism, if we identify mental states with the physical states that realize the roles, or (ii) a non-reductive physicalism, if all and only physical states play the functional roles (in the actual world), and/or (iii) with a property dualism, if realizers and roles are considered distinct properties. Property dualism is the modern type of dual aspect theory.

Many of the interesting insights offered by equating consciousness with the process of inference rest on the hierarchical nature of generative or virtual reality models. In hierarchical models, inference can be decomposed into multiple levels, with progressively higher or deeper levels of representational abstraction or explanation. This leads to the distinction between inferences at low levels of sensory hierarchies – that can be associated with unconscious inference in the sense of Helmholtz (1866/1962) – and at higher levels that could be associated with conscious percepts and concepts.

To illustrate the importance of hierarchical inference consider a concrete example, starting at the lowest level of the hierarchy; namely, a reflex. A peripheral reflex counters deviations from a proprioceptive equilibrium point set by descending corticopontine or corticospinal projections. One can associate this equilibrium point with the set point of a thermostat. From a statistical perspective, the neuronal activity encoding the equilibrium point corresponds to the expected (or mean) proprioceptive input and the gain of peripheral motor neurons encodes the inverse variance (or precision) (Adams et al., 2013a). Does this neuronal encoding of a probability distribution constitute consciousness? In the sense that it encodes a probabilistic belief, one might argue that even a simple knee-jerk reflex embodies some form of unconscious (motor) belief. However, things get more interesting if the descending proprioceptive predictions (motor commands) arise from a higher hierarchical level with autonomous dynamics (e.g., a central pattern generator). At the higher level, one can interpret neuronal activity (and gain) as encoding expectations (and precision) of movement trajectories, framed in terms of proprioceptive input.

These are beliefs about motion that entail both past and future; immediately freeing beliefs from the instant in time that they are fulfilled. Consider now a further hierarchical level that predicts (and selects) the particular trajectory that is enacted. This level may generate top-down predictions of proprioceptive trajectories and their visual consequences. In other words, we have moved beyond simple motor representations to a hierarchical level where expectations (neuronal activity and their associated beliefs) are quintessentially sensorimotor in nature. At this level, the multimodal nature of descending predictions (aka corollary discharge) renders the expectations amodal. Would these constitute conscious experience?

One could argue that these high-level, dynamically structured beliefs are much closer to phenomenal consciousness. Furthermore, if we now equip our hierarchical model with models that distinguish between the consequences of self-made acts and the acts of others, we start to get closer to conceptual expectations of the sort that may underlie subjective consciousness. Crucially, at all hierarchical levels, the biophysical drives underlying neuronal activity are physically lawful in that they minimize variational free energy – in exactly the same way that gravitational forces conform to Hamilton's principle of least action.

HIERARCHICAL INFERENCE AND DREAMING

The notion of hierarchical representation comes to the fore in the context of dreaming. First, we have the hierarchical distinction between sensory and higher levels. This is important because modulatory gating during REM sleep has opposing effects on the two levels – effectively suppressing the sensory level and augmenting message passing among higher levels through selective activation of ascending cholinergic systems. This means that Bayesian belief updating is implicit in the sleeping brain in a way that is formally equivalent to predictive coding of (non-gated) sensory input during wakefulness. However, the nature of conscious inference is fundamentally different in the sense that beliefs – encoded by neuronal activity and plasticity – are unconstrained by sensory information, permitting fantastical constructions.

Second, in the setting of hierarchical models, each hierarchical level or system makes inferences about others. This is exactly the conclusion reached from analysis of the phenomenology of lucid dreaming. Recall from above that the notion of watching oneself implies a partition of consciousness into the "watcher" and the "watched." This is consistent with a hierarchical decomposition of inference during sleep. It could even be argued that the same hierarchical decomposition or meta-representational interpretation applies during wakefulness – and emerges as meta-cognition (awareness of being aware).

Recently, it has been shown that transcranial alternating current stimulation, at low gamma frequencies, induces lucidity and self-reflective awareness in REM dreaming (Voss et al., 2014). The authors assume that "lower gamma band activity is mediated by activation of fast spiking interneurons that are known to generate gamma oscillations." The ensuing oscillations have been proposed to increase the synchronous gain of neuronal message passing. This suggests that lucid dreaming may be associated with an increase in the precision of prior beliefs (in prefrontal cortex) that underlie personal narratives (Kiebel et al., 2008) – priors that are quiescent in normal REM sleep. We again see the importance of neuromodulation in contextualizing the relative contribution (of higher, intermediate and sensory) hierarchical processing in the induction of conscious states. See **Figure 1**.

In summary, the inferential perspective on conscious processes creates a hierarchically composed theater for conscious experience that accommodates the distinction between waking and dreaming consciousness (through a dissociation of sensory and non-sensory hierarchical levels) and dissociation within higher levels that would be necessary for lucid dreaming. Within this framework, many of the formal characteristics of perception and cognition during dreaming start to make sense – in terms of a free-running inference machine that is untethered from the sensorium.

CONCLUSION

Conceiving of the mind as a physical force – tied to the structure and function of the brain – is not novel but giving it a detailed instantiation formalizes its scientific status. We have suggested that many of the formal properties of dreams (e.g., internally generated visual imagery, delusional beliefs about the waking state, cognitive deficits in self-reflective awareness, disorientation, impaired volition, recent memory loss, and hyper-emotionality) are delirium, by definition. If the explanations on offer are true, one can now supply the cellular and chemical basis for this (entirely normal) delirium. In doing so, we move the conscious states of dreaming and waking into their long-sought relation to brain activity. Virtual reality dream theory does not have to solve the brain–mind problem, but may contribute to the solution. This contribution raises interesting questions for example; is REM sleep necessary for consciousness?

According to the arguments in this paper, REM sleep enables the optimisation (complexity minimisation) of deep hierarchical models and may therefore be necessary for the conscious (inference) processes that are unique to deep models. Having said this, REM sleep is clearly not necessary for the emergence of embodied virtual reality models in species that do not evidence REM sleep and – to the extent that these species are conscious – it is not necessary for consciousness. Perhaps answers to these sorts of questions are not as important as the fact that these questions can be addressed formally, using the notion of hierarchical inference and virtual reality models that are grounded in neurobiological and evolutionary processes.

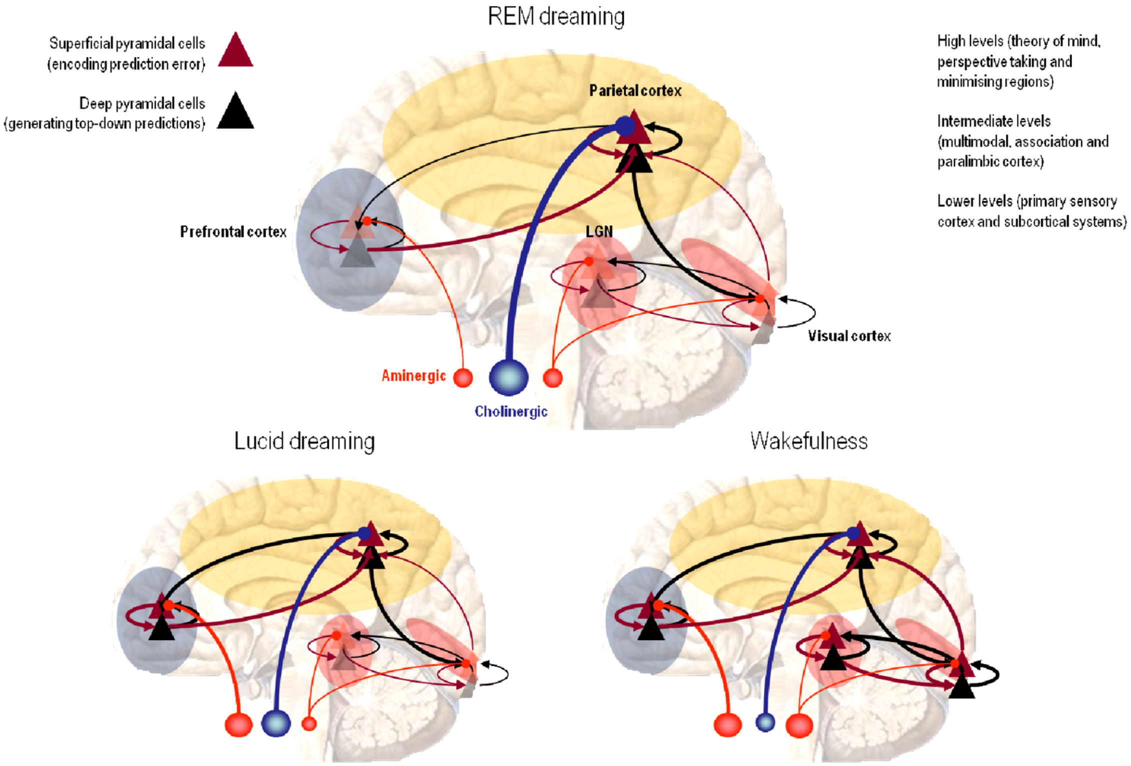


FIGURE 1 | The schematic illustrates the neuromodulatory gating of hierarchical message passing in the brain during rapid eye movement (REM) sleep (top), wakefulness (right), and the hybrid state of lucid dreaming (left). The anatomy of this schematic should not be taken too seriously: it is just meant to differentiate between different levels of the cortical hierarchy in terms of low (sensory) levels, intermediate (extrasensory and multimodal) levels and – for the purposes of this paper – high (meta-representational) levels. Here, we have associated higher levels with theory of mind areas that are engaged in mentalizing and perspective taking tasks. Within each level we have depicted representative cortical microcircuits in terms of superficial (red triangles) and deep (black triangles) pyramidal cells. In predictive coding formulations of neuronal message passing, superficial pyramidal cells encode prediction error that is passed up the hierarchy to update the activity of deep pyramidal cells encoding expectations (red connections). These reciprocate top-down predictions that are compared with the expectations by prediction error units in the level below (black connections). In REM sleep, the idea is that cholinergic modulation (blue projections) of superficial pyramidal cells at intermediate levels of the cortical hierarchy preferentially enables these levels, while suppressing ascending prediction errors from primary sensory cortex. In lucid dreaming, aminergic (e.g., dopaminergic: pink projections) neuromodulation sensitizes prediction errors in the prefrontal cortex, enabling top-down predictions from the highest or deepest levels of the hierarchy – endowing processing in intermediate levels with a narrative or context. In waking, aminergic (e.g., noradrenergic) neuromodulation boosts sensory prediction errors that are now able to entrain hierarchical inference in higher cortical levels for perceptual synthesis.

In short we have a mechanistic account of processes underlying conscious and unconscious inference, where this mechanism is fully embedded in a causal nexus of neuronal machinery. Potential beneficiaries of this account are our concepts of psychopathology; for example, psychosomatic disorders. If the mind is a causal physical force, then mental states can be orderly (as in physical and mental health) or disorderly (as in physical and so-called mental disease). Many have assumed that this must be so – and indeed have fruitfully pursued predictive coding in this context (Fletcher and Frith, 2009; Edwards et al., 2012; Adams et al., 2013b; Hohwy, 2013). The general point that we wish to make is that clinical psychology and psychiatry are in a position to change – and arm themselves with insights from sleep and dream science.

Clearly, there are many fascinating issues that we have not considered – issues that could be pursued from the Bayesian brain perspective offered in this article. One intriguing issue (noted by our reviewers) is the role of prediction in active inference: in other words, the role of hierarchical inference in prescribing predictions about how we will move or what we will do next. Currently, we have just focused on perceptual inference and making sense of the sensorium. It is intriguing to consider that dreaming and model optimization may also apply to inferences about our actions and how we sample outcomes from the world during wakefulness.

ACKNOWLEDGMENTS

We would like to thank Nicholas Tranquillo for invaluable help in preparing this manuscript. Charles C.-H. Hong was funded by the Johns Hopkins Institute for Clinical and Translational Research (ICTR), which is funded in part by Grant Number UL1 TR 000424-06 from the National Center for Advancing Translational Sciences (NCATS) a component of the National Institutes of Health (NIH), and NIH Roadmap for Medical Research. Karl J. Friston is funded by the Wellcome trust (Ref: 088130/Z/09/Z). We are indebted to Andy Clark and several anonymous reviewers of previous version of this manuscript for guidance and ideas.

REFERENCES

Adams, R. A., Perrinet, L. U., and Friston, K. (2012). Smooth pursuit and visual occlusion: active inference and oculomotor control in schizophrenia. *PLoS ONE* 7:e47502. doi: 10.1371/journal.pone.0047502

Adams, R. A., Shipp, S., and Friston, K. J. (2013a). Predictions not commands: active inference in the motor system. *Brain Struct. Funct.* 218, 611–643. doi: 10.1007/s00429-012-0475-5

Adams, R. A., Stephan, K. E., Brown, H. R., Frith, C. D., and Friston, K. J. (2013b). The computational anatomy of psychosis. *Front. Psychiatry* 4:47. doi: 10.3389/fpsyt.2013.00047

Allison, T., and Cicchetti, D. V. (1976). Sleep in mammals: ecological and constitutional correlates. *Science* 194, 732–734. doi: 10.1126/science.982039

Aserinsky, E., and Kleitman, N. (1953). Regularly occurring periods of ocular motility and concomitant phenomena during sleep. *Science* 118, 361–375. doi: 10.1126/science.118.3062.273

Atienza, M., Cantero, J., and Gómez, C. (2000). Decay time of the auditory sensory memory trace during wakefulness and REM sleep. *Psychophysiology* 37, 485–493. doi: 10.1111/1469-8986.3740485

Baird, B., Smallwood, J., Mrazek, M. D., Kam, J. W., Franklin, M. S., and Schooler, J. W. (2012). Inspired by distraction: mind wandering facilitates creative incubation. *Psychol. Sci.* 23, 1117–1122. doi: 10.1177/0956797612446024

Bastos, A. M., Usrey, W. M., Adams, R. A., Mangun, G. R., Fries, P., and Friston, K. J. (2012). Canonical microcircuits for predictive coding. *Neuron* 76, 695–711. doi: 10.1016/j.neuron.2012.10.038

Beal, M. J (2003). *Variational Algorithms for Approximate Bayesian Inference.* PhD. thesis, University College London.

Bechtel, W. J., and Mundale, J. (1999). Multiple realizability revisited linking cognitive and neural states. *Philos. Sci.* 66, 175–207. doi: 10.1086/392683

Birnholz, J. C. (1981). The development of human fetal eye movement patterns. *Science* 213, 679–681. doi: 10.1126/science.7256272

Blanke, O. (2012). Multisensory brain mechanisms of bodily self-consciousness. *Nat. Rev. Neurosci.* 13, 556–571. doi: 10.1038/nrn3292

Börgers, C., Epstein, S., and Kopell, N. J. (2005). Background gamma rhythmicity and attention in cortical local circuits: a computational study. *Proc. Natl. Acad. Sci. U.S.A.* 102, 7002–7007. doi: 10.1073/pnas.0502366102

Brandt, S. A., and Stark, L. W. (1997). Spontaneous eye movements during visual imagery reflect the content of the visual scene. *J. Cogn. Neurosci.* 9, 27–38. doi: 10.1162/jocn.1997.9.1.27

Braun, A. R., Balkin, T. J., Wesenten, N. J., Carson, R. E., Varga, M., Baldwin, P., et al. (1997). Regional cerebral blood flow throughout the sleep–wake cycle. *Brain* 120, 1173–1197. doi: 10.1093/brain/120.7.1173

Bremner, A. J., Lewkowicz, D. J., and Spence, C. (2012). "The multisensory approach to development," in *Multisensory Development*, eds A. J. Bremner, D. J. lewkowicz, and C. Spence (Oxford: Oxford University Press), 1–26.

Brown, H., Adams, R. A., Parees, I., Edwards, M., and Friston, K. (2013). Active inference, sensory attenuation and illusions. *Cogn. Process.* 14, 411–427. doi: 10.1007/s10339-013-0571-3

Buffalo, E. A., Fries, P., Landman, R., Buschman, T. J., and Desimone, R. (2011). Laminar differences in gamma and alpha coherence in the ventral stream. *Proc. Natl. Acad. Sci. U.S.A.* 108, 11262–11267. doi: 10.1073/pnas.1011284108

Calvert, G. A., and Thesen, T. (2004). Multisensory integration: methodological approaches and emerging principles in the human brain. *J. Physiol. Paris* 98, 191–205. doi: 10.1016/j.jphysparis.2004.03.018

Calvo, J. M., Datta, S., Quattrochi, J., and Hobson, J. A. (1992). Cholinergic microstimulation of the peribrachial nucleus in the cat. II. Delayed and prolonged increases in REM sleep. *Arch. Ital. Biol.* 130, 285–301.

Cartwright, R. D. (2010). *The Twenty-four Hour Mind: The Role of Sleep and Dreaming in Our Emotional Lives.* Oxford: Oxford University Press, 37–38.

Castro, S., Falconi, A., Chase, M. H., and Torterolo, P. (2013). Coherent neocortical 40-Hz oscillations are not present during REM sleep. *Eur. J. Neurosci.* 37, 1330–1339. doi: 10.1111/ejn.12143

Chalmers, D. J. (1996). *The Conscious Mind: In Search of a Fundamental Theory.* New York: Oxford University Press.

Chawla, D., Lumer, E. D., and Friston, K. J. (1999). The relationship between synchronization among neuronal populations and their mean activity levels. *Neural. Comput.* 11, 1389–1411. doi: 10.1162/089976699300016287

Christoff, K., Gordon, A. M., Smallwood, J., Smith, R., and Schooler, J. W. (2009). Experience sampling during fMRI reveals default network and executive system contributions to mind wandering. *Proc. Natl. Acad. Sci. U.S.A.* 106, 8719–8724. doi: 10.1073/pnas.0900234106

Clark, A. (2013). Whatever next? Predictive brains, situated agents, and the future of cognitive science. *Behav. Brain Sci.* 36, 181–204. doi: 10.1017/S0140525X12000477

Crick, F. (1984). Function of the thalamic reticular complex: the searchlight hypothesis. *Proc. Natl. Acad. Sci. U.S.A.* 81, 4586–4590. doi: 10.1073/pnas.81.14.4586

Crick, F. C., and Koch, C. (2005). What is the function of the claustrum? *Philos. Trans. R. Soc. Lond. B Biol. Sci.* 360, 1271–1279. doi: 10.1098/rstb.2005.1661

Dawes, G. S., Fox, H. E., Leduc, B. M., Liggins, G. C., and Richards, R. T. (1972). Respiratory movements and rapid eye movement sleep in the foetal lamb. *J. Physiol.* 220, 119–143.

Dayan, P., Hinton, G. E., and Neal, R. (1995). The Helmholtz machine. *Neural Comput.* 7, 889–904. doi: 10.1162/neco.1995.7.5.889

Diekelmann, S., and Born, J. (2010). The memory function of sleep. *Nat. Rev. Neurosci.* 11, 114–126. doi: 10.1038/nrn2762

Dresler, M., Wehrle, R., Spoormaker, V. I., Koch, S. P., Holsboer, F., Steiger, A., et al. (2012). Neural correlates of dream lucidity obtained from contrasting lucid versus non-lucid REM sleep: a combined EEG/fMRI case study. *Sleep* 35, 1017–1020. doi: 10.5665/sleep.1974

Dreyfus-Brisac, C. (1964). "The electroencephalogram of the premature infant and full-term newborn. Normal and abnormal development of waking and sleeping patterns," in *Neurological and Electroencephalographic Correlative Studies in Infancy*, eds P. Kellaway and I. Petersen (London: Grune & Stratton), 186–207.

Edwards, M. J., Adams, R. A., Brown, H., Pareés, I., and Friston, K. J. (2012). A Bayesian account of "hysteria." *Brain* 135(Pt 11), 3495–3512. doi: 10.1093/brain/aws129

Engel, A., and Singer, W. (2001). Temporal binding and the neural correlates of sensory awareness. *Trends cogn. sci.* 5, 16–25. doi: 10.1016/S1364-6613(00)01568-0

Epstein, A. W. (1977). Dream formation during an epileptic seizure: implications for the study of the "unconscious." *J. Am. Acad. psychoanal.* 5, 43–49.

Farah, M. J. (1984). The neurological basis of mental imagery: a componential analysis. *Cognition* 18, 245–272. doi: 10.1016/0010-0277(84)90026-X

Feldman, H., and Friston, K. J. (2010). Attention, uncertainty, and free-energy. *Front. Hum. Neurosci.* 4:215. doi: 10.3389/fnhum.2010.00215

Fletcher, P. C., and Frith, C. D. (2009). Perceiving is believing: a Bayesian approach to explaining the positive symptoms of schizophrenia. *Nat. Rev. Neurosci.* 10, 48–58. doi: 10.1038/nrn2536

Freud, S. (1920). *A General Introduction to Psychoanalysis: VII Manifest Dream Content and Latent Dream Thought.* New York: Boni & Liveright.

Friston, K. (2008). Hierarchical models in the brain. *PLoS Comput. Biol.* 4:e1000211. doi: 10.1371/journal.pcbi.1000211

Friston, K., Adams, R. A., Perrinet, L., and Breakspear, M. (2012). Perceptions as hypotheses: saccades as experiments. *Front. Psychol.* 3:151. doi: 10.3389/fpsyg.2012.00151

Friston, K., Kilner, J., and Harrison, L. (2006). A free energy principle for the brain. *J. Physiol. Paris* 100, 70–87. doi: 10.1016/j.jphysparis.2006.10.001

Friston, K., Mattout, J., and Kilner, J. (2011). Action understanding and active inference. *Biol. Cybern.* 104, 137–160. doi: 10.1007/s00422-011-0424-z

Gilestro, G. F., Tononi, G., and Cirelli, C. (2009). Widespread changes in synaptic markers as a function of sleep and wakefulness in *Drosophila. Science* 324, 109–112. doi: 10.1126/science.1166673

Gillett, C. (2002). The dimensions view of realization: a critique of the Standard view. *Analysis* 64, 316–323. doi: 10.1093/analys/62.4.316

Gregory, R. L. (1980). Perceptions as hypotheses. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* 290, 181–197. doi: 10.1098/rstb.1980.0090

Gross, D. W., and Gotman, J. (1999). Correlation of high-frequency oscillations with the sleep-wake cycle and cognitive activity in humans. *Neuroscience* 94, 1005–1018. doi: 10.1016/S0306-4522(99)00343-7

Hall, C. S., and Van de Castle, R. L. (1966). *The Content Analysis of Dreams.* New York: Appleton-Century-Crofts.

Hasselmo, M. E., and Giocomo, L. M. (2006). Cholinergic modulation of cortical function. *J. Mol. Neurosci.* 30, 133–135. doi: 10.1385/JMN:30:1:133

Hein, G., and Knight, R. T. (2008). Superior temporal sulcus–It's my area: or is it? *J. Cogn. Neurosci.* 20, 2125–2136. doi: 10.1162/jocn.2008.20148

Helmholtz, H. (1866/1962). "Concerning the perceptions in general," in *Treatise on Physiological Optics*, 3rd Edn (New York: Dover).

Herman, J. H., Erman, M., Boys, R., Peiser, L., Taylor, M. E., and Roffwarg, H. P. (1984). Evidence for a directional correspondence between eye movements and dream imagery in REM sleep. *Sleep* 7, 52–63.

Hinton, G. E., Dayan, P., Frey, B. J., and Neal, R. M. (1995). The "wake-sleep" algorithm for unsupervised neural networks. *Science* 268, 1158–1161. doi: 10.1126/science.7761831

Hinton, G. E., and van Camp, D. (1993). "Keeping neural networks simple by minimizing the description length of weights," in *Proceedings of COLT-93*, 5–13.

Hirayama, J., Yoshimoto, J., and Ishii, S. (2004). Bayesian representation learning in the cortex regulated by acetylcholine. *Neural Netw.* 17, 1391–1400. doi: 10.1016/j.neunet.2004.06.006

Hobson, J. A. (1988). *The Dreaming Brain.* New York: Basic Books.

Hobson, J. A. (1999). *Dreaming as Delirium.* Cambridge: The MIT Press.

Hobson, J. A. (2002). *Dreaming: An Introduction to Sleep Science.* Clarendon: Oxford University Press.

Hobson, J. A. (2009). REM sleep and dreaming: towards a theory of protoconsciousness. *Nat. Rev. Neurosci.* 10, 803–813. doi: 10.1038/nrn2716

Hobson, J. A. (2010). Lucid dreaming wakes up: response to commentaries. *IJODR* 3, 98–99.

Hobson, J. A., and Friston, K. J. (2012). Waking and dreaming consciousness: neurobiological and functional considerations. *Prog. Neurobiol.* 98, 82–98. doi: 10.1016/j.pneurobio.2012.05.003

Hobson, J. A., and Friston, K. J. (2014). Consciousness, dreams, and inference: the cartesian theatre revisited. *J. Conscious. Stud.* 21, 6–32.

Hobson, J. A., and McCarley, R. W. (1977). The brain as a dream state generator: an activation-synthesis hypothesis of the dream process. *Am. J. Psychiatry* 134, 1335–1348.

Hobson, J. A., Pace-Schott, E. F., and Stickgold, R. (2000). Dreaming and the brain: toward a cognitive neuroscience of conscious states. *Behav. Brain Sci.* 23, 793–842. doi: 10.1017/S0140525X00003976

Hobson, J. A., and Stickgold, R. (1994). Dreaming: a neurocognitive approach. *Conscious Cogn.* 3, 1–15. doi: 10.1006/ccog.1994.1001

Hofstadter, D. R. (1979). *Gödel, Escher, Bach: An Eternal Golden Braid.* New York: Basic Books.

Hohwy, J. (2013). *The Predictive Mind.* Oxford: Oxford University Press.

Hong, C. C.-H., Gillin, J. C., Dow, B. M., Wu, J., and Buchsbaum, M. S. (1995). Localized and lateralized cerebral glucose metabolism associated with eye movements during REM sleep and wakefulness: a positron emission tomography (PET) study. *Sleep* 18, 570–580.

Hong, C. C.-H., Harris, J. C., Pearlson, G. D., Kim, J.-S., Calhoun, V. D., Fallon, J. H., et al. (2009). fMRI evidence for multisensory recruitment associated with rapid eye movements during sleep. *Hum. Brain Mapp.* 30, 1705–1722. doi: 10.1002/hbm.20635

Hong, C. C.-H., Jin, Y., Potkin, S. G., Buchsbaum, M. S., Wu, J., Callaghan, G. M., et al. (1996). Language in dreaming and regional alpha power. *Sleep* 19, 232–235.

Hong, C. C.-H., Potkin, S. G., Antrobus, J. S., Dow, B. M., Callaghan, G. M., and Gillin, J. C. (1997). REM sleep eye movement counts correlate with visual imagery in dreaming: a pilot study. *Psychophysiology* 34, 377–381. doi: 10.1111/j.1469-8986.1997.tb02408.x

Horikawa, T., Tamaki, M., Miyawaki, Y., and Kamitani, Y. (2013). Neural decoding of visual imagery during sleep. *Science* 340, 639–642. doi: 10.1126/science.1234330

Ibáñez, A., Martín, R., Hurtado, E., and López, V. (2009). ERPs studies of cognitive processing during sleep. *Int. J. Psychol.* 44, 290–304. doi: 10.1080/00207590802194234

Jouny, C., Chapotot, F., and Merica, H. (2000). EEG spectral activity during paradoxical sleep: further evidence for cognitive processing. *Neuroreport* 11, 3667–3671. doi: 10.1097/00001756-200011270-00016

Jouvet, M. (1962). Research on the neural structures and responsible mechanisms in different phases of physiological sleep. *Arch. Ital. Biol.* 100, 125–206.

Jouvet, M. (1969). Biogenic amines and the states of sleep. *Science* 163, 32–41. doi: 10.1126/science.163.3862.32

Jouvet, M. (1972). The role of monoamines and acetylcholine-containing neurons in the regulation of the sleep-waking cycle. *Ergeb. Physiol.* 64, 166–307. doi: 10.1007/3-540-05462-6_2

Jouvet, M. (1973). Essai sur le rêve. *Arch. Ital. Biol.* 111, 564–576.

Jouvet, M., and Michel, F. (1959). Electromyographic correlations of sleep in the chronic decorticate and mesencephalic cat. *C. R. Seances. Soc. Biol. Fil.* 153, 422–425.

Kahan, T. L., and LaBerge, S. P. (2010). Dreaming and waking: similarities and differences revisited. *Conscious. Cogn.* 20, 494–514. doi: 10.1016/j.concog.2010.09.002

Kahn, D., and Hobson, J. A. (1994). Self-organization theory of dreaming. *Dreaming* 3, 151–178. doi: 10.1037/h0094378

Kahn, D., and Hobson, J. A. (2005). State-dependent thinking: a comparison of waking and dreaming thought. *Conscious. Cogn.* 14, 429–438. doi: 10.1016/j.concog.2004.10.005

Kant, I. (1999/1781). *Critique of Pure Reason*, eds P. Guyer and A. Wood. Cambridge: Cambridge University Press.

Kiebel, S. J., Daunizeau, J., and Friston, K. J. (2008). A hierarchy of timescales and the brain. *PLoS Comput. Biol.* 4:e1000209. doi: 10.1371/journal.pcbi.1000209

Kimmig, H., Greenlee, M. V. V., Gondan, M., Schira, M., Kassubek, J., and Mergner, T. (2001). Relationship between saccadic eye movements and cortical activity as measured by fMRI: quantitative and qualitative aspects. *Exp. Brain Res.* 141, 184–194. doi: 10.1007/s002210100844

Klein, M., Michel, F., and Jouvet, M. (1964). Polygraphic study of sleep in birds. *C. R. Seances Soc. Biol. Fil.* 158, 99–103.

Knill, D. C., and Pouget, A. (2004). The Bayesian brain: the role of uncertainty in neural coding and computation. *Trends Neurosci.* 27, 712–719. doi: 10.1016/j.tins.2004.10.007

Koike, T., Kan, S., Misaki, M., and Miyauchi, S. (2011). Connectivity pattern changes in default-mode network with deep non-REM and REM sleep. *Neurosci. Res.* 69, 322–330. doi: 10.1016/j.neures.2010.12.018

Koubeissi, M. Z., Bartolomei, F., Beltagy, A., and Picard, F. (2014). Electrical stimulation of a small brain area reversibly disrupts consciousness. *Epilepsy Behav.* 37, 32–35. doi: 10.1016/j.yebeh.2014.05.027

LaBerge, S. (1990). "Lucid dreaming: psychophysiological studies of consciousness during REM sleep," in *Sleep and Cognition*, eds R. R. Bootzen, J. F. Kihlstrom, and D. L. Schacter (Washington, DC: American Psychological Association). 109–126.

Laeng, B., and Teodorescu, D.-S. (2002). Eye scanpaths during visual imagery reenact those of perception of the same visual scene. *Cogn. Sci.* 26, 207–231. doi: 10.1207/s15516709cog2602_3

Le Van Quyen, M., Staba, R., Bragin, A., Dickson, C., Valderrama, M., Fried, I., et al. (2010). Large-scale electrode recordings of high-frequency gamma oscillations in human cortex during sleep. *J. Neurosci.* 30, 7770–7782. doi: 10.1523/JNEUROSCI.5049-09.2010

Lee, T. S., and Mumford, D. (2003). Hierarchical Bayesian inference in the visual cortex. *J. Opt. Soc. Am. A Opt. Image Sci. Vis.* 20, 1434–1448. doi: 10.1364/JOSAA.20.001434

Llinas, R., and Ribary, U. (1993). Coherent 40-Hz oscillation characterizes dream state in humans. *Proc. Natl. Acad. Sci. U.S.A.* 90, 2078–2081. doi: 10.1073/pnas.90.5.2078

Llinás, R. R., and Paré, D. (1991). Of dreaming and wakefulness. *Neuroscience* 44, 521–535. doi: 10.1016/0306-4522(91)90075-Y

Maier, A., Adams, G. K., Aura, C., and Leopold, D. A. (2010). Distinct superficial and deep laminar domains of activity in the visual cortex during rest and stimulation. *Front. Syst. Neurosci.* 4:31. doi: 10.3389/fnsys.2010.00031

Manuel, B. D. J. (2001). *Philosophy of Man: Selected Readings.* Philippines: Goodwill Trading Co.

Maquet, P., Péters, J., Aerts, J., Delfiore, G., Degueldre, C., Luxen, A., et al. (1996). Functional neuroanatomy of human rapid-eye-movement sleep and dreaming. *Nature* 383, 163–166. doi: 10.1038/383163a0

McCarley, R. W., and Hobson, J. A. (1979). "The form of dreams and the biology of sleep," in *Handbook of Dreams: Research, Theories and Applications,* ed. B. B. Wolman (New York: Van Nostrand Reinhold Company), 76–130.

McCarley, R. W., and Hoffman, E. (1981). REM Sleep dreams and the activation-synthesis hypothesis. *Am. J. Psychiatry* 138, 904–912.

McMillan, R. L., Kaufman, S. B., and Singer, J. L. (2013). Ode to positive constructive daydreaming. *Front. Psychol.* 4:626. doi: 10.3389/fpsyg.2013.00626

Merritt, J. M., Stickgold, R. A., Pace-Schott, E. F., Williams, J., and Hobson, J. A. (1994). Emotion profiles in the dreams of young adult men and women. *Conscious. Cogn.* 3, 46–60. doi: 10.1006/ccog.1994.1004

Mesulam, M.-M. (2004). The cholinergic innervation of the human cerebral cortex. *Prog. Brain Res.* 145, 67–78. doi: 10.1016/S0079-6123(03)45004-8

Metzinger, T. (2003). *Being No One. The Self-Model Theory of Subjectivity.* Cambridge: MIT Press.

Metzinger, T. (2009). *The Ego Tunnel: The Science of the Mind and the Myth of the Self.* New York: Basic Books.

Metzinger, T. (2013). Why are dreams interesting for philosophers? The example of minimal phenomenal selfhood, plus an agenda for future research. *Front. Psychol.* 4:746. doi: 10.3389/fpsyg.2013.00746

Miyauchi, S., Misaki, M., Kan, S., Fukunaga, T., and Koike, T. (2009). Human brain activity time-locked to rapid eye movements during REM sleep. *Exp. Brain Res.* 192, 657–667. doi: 10.1007/s00221-008-1579-2

Montgomery, S. M., Sirota, A., and Buzsáki, G. (2008). Theta and gamma coordination of hippocampal networks during waking and rapid eye movement sleep. *J. Neurosci.* 28, 6731–6741. doi: 10.1523/JNEUROSCI.1227-08.2008

Mumford, D. (1992). On the computational architecture of the neocortex. II. *Biol. Cybern.* 66, 241–251. doi: 10.1007/BF00198477

Nelson, J. P., McCarley, R. W., and Hobson, J. A. (1983). REM sleep burst neurons, PGO waves, and eye movement information. *J. Neurophysiol.* 50, 784–797.

Nofzinger, E. A., Mintun, M. A., Wiseman, M. B., Kupfer, D. J., and Moore, R. Y. (1997). Forebrain activation in REM sleep: an FDG PET study. *Brain Res.* 770, 192–201. doi: 10.1016/S0006-8993(97)00807-X

Parmeggiani, P. L. (2003). Thermoregulation and sleep. *Front. Biosci.* 8:s557–s567. doi: 10.2741/1054

Penny, W. D., Stephan, K. E., Mechelli, A., and Friston, K. J. (2004). Comparing dynamic causal models. *Neuroimage* 22, 1157–1172. doi: 10.1016/j.neuroimage.2004.03.026

Perry, E. K., and Perry, R. H. (2004). Neurochemistry of consciousness: cholinergic pathologies in the human brain. *Prog. Brain Res.* 145, 287–299. doi: 10.1016/S0079-6123(03)45020-6

Prinz, J. J. (2000). A neurofunctional theory of visual consciousness. *Conscious. Cogn.* 9, 243–259. doi: 10.1006/ccog.2000.0442

Rao, R. P., and Ballard, D. H. (1999). Predictive coding in the visual cortex: a functional interpretation of some extra-classical receptive-field effects. *Nat. Neurosci.* 2, 79–87. doi: 10.1038/4580

Rechtschaffen, A., Bergmann, B. M., Everson, C., Kushida, C. A., and Gilliland, M. A. (1989). Sleep deprivation in the rat: X. Integration and discussion of the findings. *Sleep* 12, 68–87.

Remedios, R., Logothetis, N. K., and Kayser, C. (2010). Unimodal responses prevail within the multisensory claustrum. *J. Neurosci.* 30, 12902–12907. doi: 10.1523/JNEUROSCI.2937-10.2010

Resnick, J., Stickgold, R., Pace-Schott, E., Williams, J., and Hobson, J. A. (1994). Self-representation and bizarreness in children's dreams. *Conscious. Cogn.* 3, 30–45. doi: 10.1006/ccog.1994.1003

Revonsuo, A. (1995). Consciousness, dreams and virtual realities. *Philos. Psychol.* 8, 35–58. doi: 10.1080/09515089508573144

Revonsuo, A. (2006). *Inner Presence: Consciousness as a Biological Phenomenon.* Cambridge: MIT Press.

Rittenhouse, C., Stickgold, R., and Hobson, J. A. (1994). Constraint on the transformation of characters, objects, and settings in dream reports. *Conscious. Cogn.* 3, 100–113. doi: 10.1006/ccog.1994.1007

Roffwarg, H. P., Dement, W. C., Muzio, J. N., and Fisher, C. (1962). Dream imagery: relationship to rapid eye movements of sleep. *Arch. Gen. Psychiatry* 7, 235–258. doi: 10.1001/archpsyc.1962.01720040001001

Roffwarg, H. P., Muzio, J. N., and Dement, W. C. (1966). Ontogenetic development of the human sleep-dream cycle. *Science* 152, 604–619. doi: 10.1126/science.152.3722.604

Roopun, A. K., Middleton, S. J., Cunningham, M. O., LeBeau, F. E., Bibbig, A., Whittington, M. A., et al. (2006). A beta2-frequency (20–30 Hz) oscillation in nonsynaptic networks of somatosensory cortex. *Proc. Natl. Acad. Sci. U.S.A.* 103, 15646–15650. doi: 10.1073/pnas.0607443103

Schredl, M. (2010). Dream content analysis: basic principles. *Int. J. Dream Res.* 3, 65–73.

Schroeder, C. E., Mehta, A. D., and Foxe, J. J. (2001). Determinants and mechanisms of attentional modulation of neural processing. *Front. Biosci.* 6:D672–D684. doi: 10.2741/Schroed

Sengupta, B., Stemmler, M. B., and Friston, K. J. (2013). Information and efficiency in the nervous system-a synthesis. *PLoS Comput. Biol.* 9:e1003157. doi: 10.1371/journal.pcbi.1003157

Shaffery, J. P., Sinton, C. M., Bissette, G., Roffwarg, H. P., and Marks, G. A. (2002). Rapid eye movement sleep deprivation modifies expression of long-term potentiation in visual cortex of immature rats. *Neuroscience* 110, 431–443. doi: 10.1016/S0306-4522(01)00589-9

Smythies, J., Edelstein, L., and Ramachandran, V. S. (2012). Hypotheses relating to the function of the claustrum. *Front. Integr. Neurosci.* 6:1–16. doi: 10.3389/fnint.2012.00053

Solms, M. (1997). *The Neuropsychology of Dreams: A Clinico-Anatomical Study.* Hillsdale: Erlbaum.

Srinivasan, M. V., Laughlin, S. B., and Dubs, A. (1982). Predictive coding: a fresh view of inhibition in the retina. *Proc. R. Soc. Lond. B Biol. Sci.* 216, 427–459. doi: 10.1098/rspb.1982.0085

Steriade, M., Dossi, R. C., Paré, D., and Oakson, G. (1991). Fast oscillations (20–40 Hz) in thalamocortical systems and their potentiation by mesopontine cholinergic nuclei in the cat. *Proc. Natl. Acad. Sci. U.S.A.* 88, 4396–4400. doi: 10.1073/pnas.88.10.4396

Stickgold, R., Malia, A., Fosse, R., Propper, R., and Hobson, J. A. (2001). Brain-mind states: I. Longitudinal field study of sleep/wake factors influencing mentation report length. *Sleep* 24, 171–179.

Stickgold, R., Pace-Schott, E., and Hobson, J. A. (1994a). A new paradigm for dream research: mentation reports following spontaneous arousal from REM and NREM sleep recorded in a home setting. *Conscious. Cogn.* 3, 16–29. doi: 10.1006/ccog.1994.1002

Stickgold, R., Rittenhouse, C., and Hobson, J. A. (1994b). Dream splicing: a new technique for assessing thematic coherence in subjective reports of mental activity. *Conscious. Cogn.* 3, 114–128. doi: 10.1006/ccog.1994.1008

Sutton, J., Rittenhouse, C., Pace-Schott, E., Merritt, J., Stickgold, R., and Hobson, J. A. (1994a), emotion and visual imagery in dream reports: a narrative graphing approach. *Conscious. Cogn.* 3, 89–99. doi: 10.1006/ccog.1994.1006

Sutton, J., Rittenhouse, C., Pace-Schott, E., Stickgold, R., and Hobson, J. A. (1994b). A new approach to dream bizarreness: graphing continuity and discontinuity of visual attention in narrative reports. *Conscious. Cogn.* 3, 61–88. doi: 10.1006/ccog.1994.1005

Szymusiak, R. (1995). Magnocellular nuclei of the basal forebrain: substrates of sleep and arousal regulation. *Sleep* 18, 478–500.

Tallon-Baudry, C., and Bertrand, O. (1999). Oscillatory gamma activity in humans and its role in object representation. *Trends Cogn. Sci.* 3, 151–162. doi: 10.1016/S1364-6613(99)01299-1

Tononi, G., and Edelman, G. M. (1998). Consciousness and complexity. *Science* 282, 1846–1851. doi: 10.1126/science.282.5395.1846

Valli, K., Revonsuo, A., Pälkäs, O., Ismail, K. H., Ali, K. J., and Punamäki, R. L. (2005). The threat simulation theory of the evolutionary function of dreaming: evidence from dreams of traumatized children. *Conscious. Cogn.* 14, 188–218. doi: 10.1016/S1053-8100(03)00019-9

Voss, U., Frenzel, C., Koppehele-Gossel, J., and Hobson, A. (2012). Lucid dreaming: an age-dependent brain dissociation. *J. Sleep Res.* 21, 634–642. doi: 10.1111/j.1365-2869.2012.01022.x

Voss, U., Holzmann, R., Hobson, A., Paulus, W., Koppehele-Gossel, J., Klimke, A., et al. (2014). Induction of self-awareness in dreams though low current stimulation of gamma activity. *Nat. Neurosci.* doi: 10.1038/nn.3719 [Epub ahead of print].

Voss, U., Holzmann, R., Tuin, I., and Hobson, J. A. (2009). Lucid dreaming: a state of consciousness with features of both waking and non-lucid dreaming. *Sleep* 32, 1191–2000.

Walker, M. P., Brakefield, T., Morgan, A., Hobson, J. A., and Stickgold, R. (2002). Practice with sleep makes perfect: sleep-dependent motor skill learning. *Neuron* 35, 205–211. doi: 10.1016/S0896-6273(02)00746-8

Wegner, D. M. (2003). The mind's best trick: how we experience conscious will. *Trends Cogn. Sci.* 7, 65–69. doi: 10.1016/S1364-6613(03)00002-0

Wehrle, R., Czisch, M., Kaufmann, C., Wetter, T. C., Holsboer, F., Auer, D. P., et al. (2005). Rapid eye movement-related brain activation in human sleep: a functional magnetic resonance imaging study. *Neuroreport* 16, 853–857. doi: 10.1097/00001756-200505310-00015

Wilson, R. A. (2001). Two Views of Realization. *Philos. Stud.* 104, 1–31. doi: 10.1023/A:1010358523824

Windt, J. M., and Noreika, V. (2011). How to integrate dreaming into a general theory of consciousness – a critical review of existing positions and suggestions for future research. *Conscious. Cogn.* 20, 1091–1107. doi: 10.1016/j.concog.2010.09.010

Womelsdorf, T., and Fries, P. (2006). Neuronal coherence during selective attentional processing and sensory-motor integration. *J. Physiol. Paris* 100, 182–193. doi: 10.1016/j.jphysparis.2007.01.005

Wurtz, R. H., McAlonan, K., Cavanaugh, J., and Berman, R. A. (2011). Thalamic pathways for active vision. *Trends Cogn. Sci.* 15, 177–184. doi: 10.1016/j.tics.2011.02.004

Yarbus, A. L. (1967). *Eye Movements and Vision.* New York: Plenum Press.

Yordanova, J., Kolev, V., and Kirov, R. (2012). Brain oscillations and predictive processing. *Front. Psychol.* 3:416. doi: 10.3389/fpsyg.2012.00416

Zadra, A. L., Nielsen, T. A., and Donderi, D. C. (1998). Prevalence of auditory, olfactory, and gustatory experiences in home dreams. *Percept. Mot. Skills* 87, 819–826. doi: 10.2466/pms.1998.87.3.819

Conflict of Interest Statement: The reviewer Jim Hopkins declares that, despite being affiliated to the same institution as the author Karl Friston, the review process was handled objectively and no conflict of interest exists. The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Received: 09 August 2014; paper pending published: 03 September 2014; accepted: 18 September 2014; published online: 09 October 2014.
Citation: Hobson JA, Hong CC-H and Friston KJ (2014) Virtual reality and consciousness inference in dreaming. Front. Psychol. ***5****:1133. doi: 10.3389/fpsyg.2014.01133*
This article was submitted to Cognitive Science, a section of the journal Frontiers in Psychology.

frontiers in Psychology

HYPOTHESIS AND THEORY
published: 05 January 2016
doi: 10.3389/fpsyg.2015.01961

Dream to Predict? REM Dreaming as Prospective Coding

Sue Llewellyn *

Faculty of Humanities, University of Manchester, Manchester, UK

The dream as prediction seems inherently improbable. The bizarre occurrences in dreams never characterize everyday life. Dreams do not come true! But assuming that bizarreness negates expectations may rest on a misunderstanding of how the predictive brain works. In evolutionary terms, the ability to rapidly predict what sensory input implies—through expectations derived from discerning patterns in associated past experiences—would have enhanced fitness and survival. For example, food and water are essential for survival, associating past experiences (to identify location patterns) predicts where they can be found. Similarly, prediction may enable predator identification from what would have been only a fleeting and ambiguous stimulus—without prior expectations. To confront the many challenges associated with natural settings, visual perception is vital for humans (and most mammals) and often responses must be rapid. Predictive coding during wake may, therefore, be based on unconscious imagery so that visual perception is maintained and appropriate motor actions triggered quickly. Speed may also dictate the form of the imagery. Bizarreness, during REM dreaming, may result from a prospective code fusing phenomena with the same meaning—within a particular context. For example, if the context is possible predation, from the perspective of the prey two different predators can both mean the same (i.e., immediate danger) and require the same response (e.g., flight). Prospective coding may also prune redundancy from memories, to focus the image on the contextually-relevant elements only, thus, rendering the non-relevant phenomena indeterminate—another aspect of bizarreness. In sum, this paper offers an evolutionary take on REM dreaming as a form of prospective coding which identifies a probabilistic pattern in past events. This pattern is portrayed in an unconscious, associative, sensorimotor image which may support cognition in wake through being mobilized as a predictive code. A particular dream illustrates.

Keywords: prediction, prospective coding, REM dreaming, pattern, unconscious

Edited by:
Roumen Kirov,
Bulgarian Academy of Sciences,
Bulgaria

Reviewed by:
Karl Friston,
University College London, UK
Caroline L. Horton,
Bishop Grosseteste University, UK

***Correspondence:**
Sue Llewellyn
sue.llewellyn@manchester.ac.uk

Specialty section:
This article was submitted to
Cognitive Science,
a section of the journal
Frontiers in Psychology

Received: *29 October 2015*
Accepted: *07 December 2015*
Published: *05 January 2016*

Citation:
Llewellyn S (2016) Dream to Predict?
REM Dreaming as Prospective
Coding. Front. Psychol. 6:1961.
doi: 10.3389/fpsyg.2015.01961

INTRODUCTION

There is a long standing idea that, based on prior experience, the brain generates predictions (or expectations) to interpret and, thereby, identify sensory input (Helmholtz, 1909; Gregory, 1980). Equally, the notion that expectations link perception and action is an old one (James, 1890). These revived ideas have excited current interest in the predictive brain across multiple areas (Bubic et al., 2010). Specifically, in the brain as a "Bayesian inference machine" (Knill and Pouget, 2004; Yuille and Kersten, 2006; Friston, 2010), in bi-directional "hierarchical generative models" (Dayan et al., 1995; Rao and Ballard, 1999; Friston, 2012; Clark, 2013), and in predictive (Friston, 2005;

Friston and Kiebel, 2009) and prospective coding (Rainer et al., 1999; Ferbinteanu and Shapiro, 2003; Schütz-Bosbach and Prinz, 2007). Against this background, Yordanova et al. (2012) call for a major research focus on the predictive brain during altered states of consciousness, suggesting REM sleep may be of particular consequence.

This paper focuses on the *form* coding may take, hypothesizing that, a REM dream constitutes a form of prospective image-based code which identifies an associative pattern in past events and, therefore, portrays associations *between* past experiences (rather than the experiences as such). This image-based code may be retained at an unconscious level and mobilized to predict the immediate sensory environment and interpret the causes of sensory input during wake.

In relation to this hypothesis, two points are worthy of note. First, there is agreement with Stickgold (2002) who argues that, in the absence of sensory input, reactivated memories must be the source material for dreams. Albeit this paper hypothesizes that REM dreams portray only those elements of reactivated memories which identify an associative pattern in past events. Second, Horne (2013) presents evidence that REM sleep prepares for wake, here this proposal is extended to REM dreams also- in the sense that REM dreams are argued to create prospective codes which impact on perception and action in subsequent waking states.

Patterns, Predictions, and Unconscious Inference

In evolutionary terms, any animal which can move must predict where food, predators, and mates can be found (Schultz et al., 1997). Prediction can preclude possible futures and, thus, would have enhanced fitness and survival (Gilbert and Wilson, 2011). For example, if memory of a predator sighting interprets sensory input as indicative of a predator, the animal can take avoiding action and preclude being killed on this occasion. This perspective on memory as inherent to sense-making extends to an enactivist ontology, where the world, as experienced, is sculpted by expectations which project meaning and propel willed actions (Varela et al., 1991; Di Paolo, 2009).

Predictions, on the basis of memories of past events, are only possible if events are patterned in some way (Panichello et al., 2012). Memory is fundamentally associative in both structure and process (Fuster, 1997, 1999). Associative structure and process may have evolved to embed patterns in memory. In turn, associative activation of memories generates the patterns which form predictions (Bar, 2007, 2011; Aminoff et al., 2008; Buckner, 2010). Patterns may be deterministic, generated by fixed regularities, co-occurrences or associations. For example, night with associated dark follows and is associated with day, with its associated light. On the other hand, the patterns generated by the behavior of living beings will be probabilistic, based on regularities or associations which have a tendency to co-occur (see later discussion). Probabilistic patterns may be difficult to discern because they are based on memories of infrequent, complex or non-obvious co-occurrences or associations.

Animals are thought able to discern patterns in events because they are capable of inference (Tolman, 1948; Pfeiffer and Foster, 2013), through using configural, as opposed to elemental, associations (Honey et al., 2014) and can link common elements across different experiences (Wood et al., 1999; Hampson et al., 2004) to discern patterns in events. Humans too associate common experiential elements in a combined representation (Zeithamova and Preston, 2010), such integrated representations portray memory elements in "prospectively useful formats" (Zeithamova et al., 2012).Animals lack sophisticated language skills, however. Both animals and early humans would have "thought" non-verbally through images (Baumeister and Masicampo, 2010). The primary function of mental imagery may be to generate predications (Moulton and Kosslyn, 2009). An image-based code may portray the associations which reflect experiential patterns. These associations drive expectations for sensory input during wake. Clearly, at any point in time in wake, the sensorium is infinite and, in consequence, must be sampled. Image-based predictions may drive "active sampling of sensory data" to identify its expected causes (Friston et al., 2012). Expectations about causes can only be on the basis of inferring a causal pattern in the world.

Helmholtz (1909) proposed that unconscious inference is the foundation for perception. For humans and most other mammals, maintaining visual perception is crucial. Unconscious image-based predictions would not interfere with visual perception. They would also facilitate rapid action and be particularly relevant in situations of threat and potential danger. Dangers require fast processing and rapid action (Öhman et al., 2000; Carretié et al., 2005). In evolutionary terms, early humans had to visit particular places (associated with survival). Such landmark places held rewards but also dangers. For example, a waterhole where "sit and wait" predators, like lions, may seek to ambush prey in the surrounding vegetative cover (Hopcraft et al., 2005). On approach to a waterhole, unconscious image-based predictions, based on prior predator sightings, may drive active sampling of color and movement in the vegetative cover- if a predator was judged to be a plausible explanation for sensory input. Visual perception has been found to be predictive and probabilistic rather than passive, incoming visual input is interpreted and fine-tuned unconsciously with reference to memories, including memories of prior beliefs (Kersten et al., 2004; Knill and Pouget, 2004).

Congruent with the idea that expectations link perception and action, an unconscious image-based code may also portray memories of action appropriate to the circumstances. The activation of mnemonic images enables unconscious bodily responses which reflect the situation i.e., mnemonic images are fundamentally efferent processes, the image is essential for the motor actions, for review, see Cuthbert et al. (1991). Indeed, motor directives can be integrated into sensory perceptions to facilitate rapid action, for review see Bubic et al. (2010). Predictive coding enables the motor system to "select appropriate responses" before an anticipated event is realized (Schütz-Bosbach and Prinz, 2007).

Prospective Coding and Predictive Coding

Bubic et al. (2010) comment that the terms "predictive" and "prospective" are not consistently used in the same way but, on the other hand, are not always clearly differentiated, a situation that can lead to confusion, they suggest that "predictive coding" is taken to mean that, during the wake state the brain anticipates upcoming sensory inputs and actively samples external stimuli to identify their causes, rather than registering stimuli in a passive manner. In this article predictive coding in wake is hypothesized to rely upon unconscious, internally generated prospective codes. Prospective coding is understood here as the off-line creation of prospective codes which are oriented toward the future and can be mobilized as predictive codes to interpret the immediate environment during wake.

A key aspect of prospective codes is that because they portray associative visual patterns *between* prior events (rather than the events *per se*), therefore, they engender representations that are quintessentially fictive or counterfactual. In this sense, this paper equates prospective coding with the encoding of counterfactual representations which can inform in the future, which is one step further than classical predictive coding theory (that only furnishes predictions of the current outcome given their hypothetical causes).

REM dreaming is argued to be conducive to prospective coding. Such coding may require the core characteristics which REM dreaming shares with the wake state: active consciousness during which a world appears with (almost always) an embodied, agential self at its center (Llinás, 2002; Metzinger, 2009).

REM SLEEP AND DREAMING AS PROSPECTIVE CODING

During off-line states, people contemplate the past to anticipate the future (Bar, 2007, 2011; Schütz-Bosbach and Prinz, 2007). Sleep is clearly off-line. As a whole, sleep preferentially reactivates memories associated with future rewards (Fischer and Born, 2009) and memories expected to be relevant to future behavior (Wilhelm et al., 2011). Hobson et al. (2014) argue the virtual realities engendered in REM dreams refine predictions. A REM dream image may be the result of prospective coding which refines predictions through hyperassociating elements of different past events during the identification of a personally significant pattern which arises from these elements of past events.

Dreaming hyperassociates different memories (Hobson, 2002; Llewellyn, 2013; Horton and Malinowski, 2015; Malinowski and Horton, 2015). Whole memories are hardly ever replayed in dreams (Fosse et al., 2003; Malinowski and Horton, 2014), rather elements of experiential memories are associated in visual scenes (Hobson, 1988; Hartmann, 1996; Walker and Stickgold, 2010). Memory trace reactivation in REM was associated with the extraction of patterns in higher order information (Peigneux et al., 2003). Using fMRI, Chow et al. (2013) found brain connectivity during REM to be consistent with the extraction of patterns from past events. REM sleep selectively processes personally-significant material (van Rijn et al., 2015). The extraction of any personally meaningful pattern in past experiences would enable expectations about future, personally significant, events.

Personally significant, past and future events will be emotionally charged. Indeed, anticipatory affect may be an integral aspect of prediction (Barrett and Bar, 2009; Anderson et al., 2011). Emotional memory is enhanced in REM sleep (Cahill and McGaugh, 1998; Wagner et al., 2001; Nishida et al., 2009) and heightened emotional tone strengthens memory associations (Cahill et al., 1996; Hamann et al., 1999). REM sleep may preferentially reactivate emotionally significant memories (Sterpenich et al., 2007, 2009). About 75–95% of dreams depict emotional events, such dreams are largely during REM sleep (Hobson et al., 1998, 2000). REM dreams are characterized by fear and anxiety (Smith et al., 2004). Sleep deprivation (whole night) leads to preferential retention of negative (rather than positive) memories (Walker and Stickgold, 2006; Sterpenich et al., 2007; Yoo et al., 2007; Walker, 2008) and REM sleep even counteracts the suppression of unwanted memories (Fischer et al., 2011). The preferential retention of negative, rather than positive memories, after sleep deprivation, may have an evolutionary explanation. Animals face many survival challenges in natural environments, early humans, too, would have experienced such testing conditions. An ability to predict threats to survival would have been adaptive, therefore, evolution may have prioritized negative over positive memories—*under conditions of sleep deprivation*.

Evolutionary explanations for REM sleep functions have been suggested. Evolutionarily ancient brain networks are preferentially engaged in REM sleep, for review see (Doricchi et al., 2007). In humans and most mammals, brain processes in REM indicate behaviors such as exploration, foraging, eating, and spatial navigation and the ability to deal with fear and anxiety, suggesting that REM serves ecological purposes and had an evolutionary imperative (Horne, 2013, 2015).

As noted earlier, in evolutionary terms, the rewards of food or water were often only obtained under situations of risk because places, such as waterholes and dependable food sites, where many species congregated, both provoked competitive interactions and also attracted predators. In such circumstances, simple predator and competitor avoidance was not possible. To obtain food and water the animal would have been exposed to risk. Predicting the patterns of behavior of both competitors and predators would have reduced risk and increased the chances of securing the rewards.

Rewards, dangers and competitive interactions were emotive and of high personal significance. Wallas (1926) identified an evolutionary imperative to recognize "resemblance in difference" i.e., "hidden" or non-obvious likenesses between, for example, different kinds of scraps which are all associated because they are all food and animals from different species which are all associated because they are all competitors or predators. Likenesses, whether obvious or non-obvious, constitute patterns in events, so do place-object associations. With regard to predators, it is not only necessary to predict "Is this a predator"—to identify it from what may be ambiguous sensory input but also to predict "How does the predator behave" and "Where and when can it be found"—to take appropriate action to avoid it.

Predator sightings (the object) in, for example, three out of ten approaches to a waterhole (the place) would have been a personally significant pattern which could give rise to a probabilistic prediction. Even if the pattern of sightings of a predator was regular, for example on the third, sixth and ninth visits, predictions about the behavior of this predator, would still be probabilistic because patterned behavior can always vary. A pattern of predator sightings on three out of ten approaches to a waterhole may be driven by another non-obvious, meaningful association. For example, the predator only visits this waterhole when it anticipates that prey will be abundant. In such a circumstance, identifying an association between "waterhole" and "abundance of prey" and "presence of a predator" would enhance survival because the animal could visit at less populous times. As mentioned earlier, unconscious predictions are particularly relevant in situations of potential danger.

However, unconscious predictions are also important whenever speed is crucial for success. For example, identifying a probabilistic pattern in the presence of mates at a landmark place would enhance reproduction and speed would be necessary to secure a mate against competitors. Unconscious learning of probabilistic patterns to predict future events benefits from sleep (Djonlagic et al., 2009) and is REM sleep dependent (Barsky et al., 2015).

Several studies indicate that REM sleep enables the identification of meaningful patterns. Walker et al. (2002) found a 32% increase in the number of anagrams solved after REM awakenings, as compared to non-REM (NREM). There is also evidence that the patterns identified in REM may be "loose" or non-obvious. For example, when awakened from REM sleep, subjects demonstrated more priming in response to looser, non-obvious primes (e.g., thief-wrong) as compared to stronger, obvious primes (e.g., hot-cold), whereas after NREM awakenings subjects showed more responsiveness to the stronger, obvious primes (Stickgold et al., 1999). REM, as compared to quiet rest in wake and NREM sleep, increased subjects' abilities to think of a word linked with three test words that seemed unrelated, for example, "surprise," "line," and "birthday" do not seem associated but "party" is connected with all three (Cai et al., 2009). Looking for non-obvious patterns in past events involves making creative (i.e., non-obvious or loose) associations between experiences. Sterpenich et al. (2014) found that reactivating memories during REM sleep engendered new creative associations amongst them.

Cognitive control and tight, analytic reasoning depend upon the prefrontal cortex (Nathaniel-James and Frith, 2002; Goel and Dolan, 2004; Ridderinkhof et al., 2004; Reverberi et al., 2005a), which is deactivated during REM sleep (Maquet et al., 1996; Braun et al., 1997; Maquet, 2000). For a non-obvious insight task, 82% of patients with focal damage to the frontal lateral cortex solved the task whereas only 43% of healthy participants did so (Reverberi et al., 2005b), indicating that prefrontal areas actually impede non-obvious associative insights—possibly through exercising cognitive control which biases toward more obvious associations. Similarly, Limb and Braun (2008) argued that de-activation of the frontal cortex may generate "spontaneous unplanned associations," see also (Liu et al., 2012).

Association between memories is driven by inferring their meaning. Experiences (or things) are associated in the mind/brain when their meaning is the same or similar. For humans, meanings may be culturally shared (Bruner, 1990) but meaning is often personally specific i.e., what does this mean *to me*. Carruthers and Ziolkowski (2002) point out that associational meaning, is often individualized rather than universal, dependent on one's prior experiences, and personal needs, desires and goals. For example, "hospital" may be most meaningfully associated to "eye" to me but "recovery" to another or even "career" to some. Meaning can also imply concrete significance for needs, desires or goals (Clore and Ortony, 2000) i.e., what does this mean *for me*?

Such personal meanings may have evolved from the relational "affordances" which link animals and their environment (Chemero, 2003). From a relational view, environmental affordances only become resources if there are animals to take advantage of them, for example, fruit only means food *for* fruit eating animals, see Turvey (1992). To exploit what the environment affords *for me* it is sometimes necessary to avoid threats, archetypically, from competitors and predators.

In a natural environment, a lion means "fundamental threat for my goal of survival." The presence of a competitor means "rivalry for resources." Memories of possible predator sightings on approach to waterholes would have been associated because they all meant and implied the same motor actions of rapid flight or freezing. Equally, memories of competitors at dependable food sites all meant potential struggle. Or memories of mating at a particular place all meant satisfaction of instinctive drives. In their entirety, memories of visits may have been completely different but with respect to the element "predator sighting," "competitor present" or "mating opportunity," respectively, they were the same. In consequence, a prospective code, created in REM dreaming, which identifies a pattern in "predator sightings," "competitors present," or "mating opportunities" may discard much that is already predictable about the visits to associate only memory elements relevant to "predator sightings," "competitors present," or "mating opportunities."

As mentioned above, if a conscious image-based predictive code was mobilized in wake it would interfere with visual perception, and be detrimental in situations where rapid action is essential. If any insights into patterns are acquired unconsciously in wake before sleep, REM sleep stabilizes them at an unconscious level (Yordanova et al., 2008). Implicit learning seems to be especially sensitive to REM sleep deprivation (Smith, 1995; Plihal and Born, 1997) and REM sleep benefits implicit visual memories (Wagner et al., 2003).

Indeed, throughout evolutionary time, "vision for action" may have relied on unconscious mental imagery (Goodale and Milner, 1992, 2013; Milner and Goodale, 2008). Congruent with the idea that the predictive brain links expectations with perception and action (see above), the imagery during REM dreaming is sensorimotor in nature and action-oriented (Hobson, 2002; Llinás, 2002). As discussed above, REM dreaming is emotionally charged, particularly with the primary emotions of elation, fear and anxiety (Hobson, 1988, 2002). Such emotions may have evolved from securing rewards in situations of risk. From an evolutionary perspective, emotions are action depositions and reflect two fundamental opposed action sets: approach, following positive evaluations and avoidance, after negative evaluations (Lang et al., 1990; Lang, 1995; Elliot and Church, 1997; Carver et al., 2000; Elliot, 2006). These evaluations of positive or negative consequences can be unconscious (Chen and Bargh, 1999; Neumann et al., 2003; Bargh and Morsella, 2008).

Memory reactivations in post-training REM sleep optimize visuo-motor responses (Laureys et al., 2001), suggesting that REM dreaming may rehearse the motor actions necessary for the approach or avoidance behaviors appropriate to the identified pattern in events [c.f. the "dream as rehearsal" of motor programs for instinctive, particularly threatening experiences in wake (Jouvet, 1999; Revonsuo, 2000)]. Such processing may enable the integration between expectation, perception and action which is thought to characterize predictive coding in wake.

Visual Processing, REMs and Prospective Coding

Certain visual processing abilities e.g., identifying embedded figures and recognizing images in unfocussed pictures are the best predictors of solving problems requiring insight into patterns (Schooler and Melcher, 1995; Bowden et al., 2005). In evolutionary terms, an ability to identify embedded figures would, clearly, be required to distinguish any partially camouflaged predators (Llewellyn and Hobson, 2015). Moreover, the visual sense is the only modality which readily enables non-obvious associations to be made, incorporated into a whole and readily communicated (Paivio, 1990, 2013). Indeed, as noted earlier, the prime function of mental imagery may be to make predications. Ever since the Aserinsky and Kleitman (1953) and Dement and Kleitman (1957) studies, human visual-like processing of mental imagery in REM dreaming has been of sustained interest.

During REM dreaming, Aserinsky and Kleitman (1953) first drew attention to the eponymous REMs, but their exact function is still unresolved. There has been an extended debate as to whether REMs are functionally similar to saccades in wake and relate to mental imagery in dreaming, for review, see (Miyauchi et al., 2009). However recent work has made some progress on the function of REMs. In goal-oriented dreams with motor behavior, REMs were directed toward the dream events (Leclair-Visonneau et al., 2010). Sprenger et al. (2010) found that when people imagine vivid scenes during dreaming, their REMs are similar to eye movements with open eyes when imagining remembered scenes in wake. Although, research on REMs has tended to dichotomise their function as either scanning (Leclair-Visonneau et al., 2010) or generating visual (dream) imagery, other work indicates that REMs do both (Hong et al., 2009). In the absence of sensory input (as during REM dreaming), imagination is required to generate a mental image (Conway, 2009; Nir and Tononi, 2010). As discussed earlier, predicting the future relies on the imaginative association of elements of past experiences (Szpunar et al., 2007; Addis et al., 2009; Addis and Schacter, 2011) to identify the patterns which enable predictions.

Friston et al. (2012) argue that saccades are directed visual searches to generate sensory evidence for a hypothesis formed on the basis of previous experience. For example, the hypothesis may be that movement in the undergrowth surrounding the waterhole is caused by a "sit and wait" predator. Similarly, REMs may be directed visual-like searches of memories to generate evidence for a prospective code which can be mobilized in the future wake state as a predictive code or perceptual hypothesis. Such a conclusion is congruent with Hong et al. (2009) who argue that REMs both scan and generate dream imagery. It is also compatible with Andrillon et al. (2015) who demonstrate that saccades and REMs are both "reminiscent of visual-mnemonic responses" and both occur at transitions in visual (or visual-like) processing. Such transitions may, in REMs, trigger a new dream image.

As noted by Friston et al. (2012) active sampling reflects the self-organizing nature of the brain. The idea that REMs both scan and generate dream imagery is also a self-organizing principle. Self-organizing systems, like the brain, are characterized by circular causality which is not tautologous (Kelso, 1997; Freeman, 1999; Hardy, 2001; Keller, 2007). Much of contemporary physiology and psychology still holds to the linear cause and effect assumptions of "inputs and outputs, stimuli and responses," self-organizing poses a fundamental challenge to these suppositions (Kelso, 1997) and speaks to the constructive aspect of perception as exemplified, par excellence, in dreaming.

REM Dream Bizarreness and Prospective Coding

McCarley and Hoffman (1981) reported that 67% of REM dreams exhibit bizarreness, i.e., incongruities, indeterminacy or discontinuities, see below and discussion in Rittenhouse et al. (1994). Bizarreness may be caused by the conflation of memory elements (Cicogna and Bosinelli, 2001). As noted above, prospective coding in REM dreaming may conflate memory elements which have the same meaning for the dreamer. For example, in my illustrative dream below I conflate failing an eye test with a saggy, old, toy, cloth cat because, to me, they both mean visual field restriction. This conflation engenders a bizarre dream image. The term "bizarre" describes a place, person or object which assumes multiple (seemingly inconsistent) elements. However, judgements about bizarreness (or inconsistency) in dreams are made from the wake state. As discussed above, Stickgold et al. (1999) found changes in associative memory systems across wake, NREM and REM where the normal pattern of priming (more response to strong primes) was demonstrated in wake and on awakening from NREM sleep whereas there was more response to non-obvious or "looser" primes on awakening from REM sleep. This research implies that the mind in wake may not easily identify the "looser," non-obvious associations made in REM dreaming, giving rise to judgements that the associations made in dreams are "bizarre." Whereas it may be that REM meaning-based associations are more creative because they are non-obvious but, at least potentially, discernible in the wake state. Edwards et al. (2013) found that dream analysis gave rise to "Aha!" insights in relation to both the associative nature of the dream content and its memory source. Indeed, the very use of the term "prospective *coding*" implies opacity but also the possibility of discerning the code.

Rittenhouse et al. (1994) argue that bizarreness in dreams operates under constraints which limit it to incongruities (inconsistent or fused features of people, objects, or places), indeterminacy (where the identity of a person, object or place remains explicitly vague) and discontinuities (sudden changes in these features of people, objects or places). As argued above, the inconsistency may be apparent, arising from the propensity of the mind in wake to be more attuned to obvious, rather than non-obvious, more creative, associations.

Hobson and Friston (2012) suggest that sleep reduces model complexity and prunes redundancy to optimize predictive coding during wake (in formal statistical terms complexity minimization is known as Occam's principle), see also Hobson et al. (2014). During REM dreaming, a reduction in prospective coding complexity may be achieved, in part, through fusion of memory elements with the same meaning for the dreamer, which elicit similar emotions in the dreamer and may require the same motor responses—if used as a predictive code in wake. Similarly, pruning of redundancy during sleep may be achieved through rendering the identity of people, objects, or places vague—where their explicit details are not required to generate an effective image-based prospective code. Indeed, including such non-relevant details would distract from the essential "message" of the code for new situations. Indeed, eliminating redundant aspects of internal models ensures generalization to new circumstances. A good internal model only captures the essentials of what is important for (my) inferences about the world.

Both of these aspects of pruning redundancy (fusion and vagueness) enable abstraction or generalization-as noted by Hobson et al. (2014). Pruning redundancy can be conceptualized as de-contextualization which, as noted by Horton and Malinowski (2015), also enables generalization through stripping away the original context. For example, although a lion and a hyena are different they both belong to the more abstract category of "predators." They also both inspire fear and require the same motor response of freeze or flight. Fusing a lion and a hyena in a "liena" associative image would generalize a prospective code to more than one predator. Similarly if both a lion and a hyena had been sighted on separate occasions on approach to a waterhole, memories of these associated waterhole events may be rendered vague in a prospective code- excepting for the relevant predator focus.

The scene discontinuities which Rittenhouse et al. (1994) identify as bizarre may, in a similar manner to the inconsistencies, reflect non-obvious associations or themes which link dream scenes. Specifically, a peripheral association in one scene may become dominant in the following scene (Llewellyn, 2013), and the continuity may have an emotional basis (Nielsen, 2013).

In the next section I use a dream to illustrate (a) how pattern identification amongst dream memory elements may enable prospective coding and also, sometimes, fuse associated memory elements (b) how vagueness in dreams may be engendered by pruning redundancy and (c) how apparent scene discontinuities may result from transitions between image-based codes which are connected by an underlying emotional theme.

The illustrative dream was collected in the home and recorded in a dream diary. There are no claims that it is typical in any way. It is self-identified as a REM dream because it conforms more to REM dream characteristics than NREM. Distinctions between REM and NREM dreams are debated and differences may resemble a continuum rather than reflect discrete binary oppositions. Nevertheless, REM dreams have been found to be more story-like, hyperassociative and bizarre, spatially defined, animated, characterized by vivid internal imagery, driven by primary emotions (such as fear, anxiety, and elation) and typified by more threatening interactions than NREM dreams, which are shorter, more literal, and thought-like, perseverative, verbal, and feature more friendly interactions (Lavie et al., 1984; Foulkes et al., 1989; Cavallero et al., 1990; Stickgold et al., 1994; Nielsen, 1999, 2000; Nielsen et al., 2001; Hobson, 2002; Fosse et al., 2004; McNamara et al., 2005; Desseilles et al., 2011).

ILLUSTRATIVE DREAM – "BAGPUSS"

The analysis of this dream encompassed two related processes: memory sources were identified and patterns in remembered past events were isolated.

The memory sources of dreams are, often, non-obvious (Nielsen and Stenstrom, 2005). Dream reports are also open systems, being always potentially open to additional or new interpretations. In consequence, a hermeneutic approach was used to identify memory sources and patterns for "Bagpuss." Hermeneutic inquiry is a textual method (where the "text" can be a remembered event) for open systems which is appropriate when associations are not readily apparent and, therefore, have to be recovered through iterative processes of projection and modification (Ricoeur, 1974, 1981).

For a dream report, it is not possible to "falsify" (Popper, 1959) an identified memory source or pattern. Additionally, the hermeneutics of recovery do not seek to identify the "world behind the text" or the hidden intention, desire or fear of the (dream) author but the "world in front of the text"—which are phenomena (associations, patterns in past events) of which the author could be aware but the construction of the text has obscured (Bauman, 2010). When the text is a dream (or dream report), Bauman's ideas imply that the dreamer has not intentionally disguised the memory sources of the dream (cf. Freud) but the hyperassociative and decontextualizing process of dream construction has masked the memories which constitute the dream.

The hermeneutic process of recovery is essentially reconstructive. Reconstruction characterizes memory recall which shares the same neural networks as imagining the future and navigating, see, for example (Bartlett, 1932; Schachtel, 1947; Conway and Pleydell-Pearce, 2000; Hassabis and Maguire, 2007; Schacter and Addis, 2007). As discussed earlier, dream analysis gives rise to "Aha!" experiences both in relation to memory sources and associative patterns in the content (Edwards et al., 2013). "Aha!" moments occurred during the analysis of "Bagpuss" and were experienced as insights into memory sources or patterns but, as discussed here, insights cannot be taken as definitive.

"Bagpuss"

Date: July, 2009

Scene 1

I am waiting with PB in the Eye Hospital. I'm in the main part of the hospital but I am (kind of) aware that I have to go somewhere else. I tell a nurse that I can't see properly, that my vision isn't right. She says that I have to see someone in the other building. I am anxious about getting there and getting lost.

Scene 2

I am in another building and walking toward some carpeted steps. Someone (a man?) is close behind me, is he helping me or threatening me in some way? I am getting anxious again. He is gray-haired. I think he is East European, maybe he is a Pole? Also he may be the ophthalmologist.

Scene 3

I am sitting at a desk. The ophthalmologist is testing my eyes. He produces a saggy, stripy cat- a kind of large, soft toy. But I can't see properly what it is. I have to identify some black signs (like the letters on an eye chart but they may not be letters) that are under the cat's skin. I can't see them properly. So the ophthalmologist pushes the toy cat closer to show me. I know that I have failed the eye test. I feel very anxious.

The Possible Associated Source Memories for "Bagpuss"

In July 2009 a few evenings previous to the Bagpuss dream I went out to dinner with my partner and D, his brother. D was talking about walking in the countryside with his "pole." I felt confused and had to ask for clarification because, prior to this conversation I had never heard of a walking stick being called a "pole." For some reason, the "pole" discussion which ensued caught my imagination.

About 2 weeks prior to this dream I went to the Eye Hospital to have a test for glaucoma. I was very anxious about this test. Glaucoma results in loss of peripheral vision and is common in the elderly. I usually get my eyes tested at the local optometrist. This was the first time I had been back to the Eye Hospital since I was a child. The visit made me feel old. I went to the building that I used to visit as a child but, on approaching the steps, realized that this old building (although still having the sign "Eye Hospital") was actually closed down. The new Eye Hospital was around the corner but I was uncertain exactly where. Scene 1 reflects this- in the sense that in waking I went to the wrong building. In the dream, however, I am in the original Eye Hospital building and see a nurse. PB did not go with me to the Eye Hospital either as a child or an adult. I worked with PB, however, in the Main Hospital—which adjoins the old Eye Hospital when we were both young women.

The steps I approach in Scene 2 could reflect the ones at the entrance to the old Eye Hospital. The positioning of the gray-haired man and me in Scene 2 resembles the sign used in the UK to indicate that elderly people may be crossing the road (an old man leaning on a walking stick with a bent old woman immediately behind him; **Figure 1**).

FIGURE 1 | Sign used in the UK to indicate that elderly people may be crossing the road.

In the dream, the gray-haired man is behind me. Indeed in wake I had misremembered this aspect of the sign because on seeing it on the internet I surprised that the woman is behind rather than in front of the man. The East European (Pole) reference may be a memory of East European immigration which (at the time) was a political issue in the UK.

In Scene 3 the action resembles memories of many of the eye tests I have undergone in the sense that there is an ocular specialist, a means of eye testing and me.

Pattern Identification Amongst Memories May Enable Prospective Coding and, as a Result, Engender Bizarreness

As discussed above, Scene 1 may portray associations amongst my recent appointment at the Eye Hospital with the ones I had as a child where I did enter, wait and then see a nurse. As discussed above, prospective coding must rely on discerning patterns in the world. The pattern, here, may be "not being able to see" accompanied by anxiety. As a child I had to remove my glasses to have my eyes tested whereas as an adult I take out contact lenses but in both cases because I am so short-sighted it engenders anxiety about moving around. Another possible related pattern is "fear of blindness." As a child, I wore glasses from the age of five. I used to fear that the increasingly strong spectacles I was prescribed indicated I may go blind. As an adult I am being tested for glaucoma which can cause blindness.

In Scene 2 the non-obvious pattern appears to be "pole" or "Pole." Various associations to "pole" may be distinguished in this scene. Blind people, like the elderly, need sticks or "poles" to walk. The gray-haired man behind me who is helping me to walk (or may be threatening in some way) may reflect the elderly man in the road sign using a walking stick or "pole." One of my former colleagues, who specialized in geriatrics, very much disliked this sign. She said that it stigmatized older people as bent and incapable and also looked as if one was a pickpocket- in that it portrayed the couple as though one was taking money from the other, this association may explain why, in the dream, I am uncertain if the man is helping or threatening. At the time of the dream, many UK nationals thought Poles were a threat to "their" jobs and were, therefore, taking money from them. This issue was much discussed on the news.

In Scene 3 the non-obvious pattern may be "loss of peripheral vision." The eye chart is fused with a soft, cat toy creating a bizarre image. "Bagpuss" is a 1970s children's television character: an old, pink striped, saggy cloth cat. Bagpuss is always shown in scenes that fade out into hazy, blankness (see, Bagpuss on youtube, https://www.youtube.com/watch?v=dpwhohWhrEE). Glaucoma involves a loss of peripheral vision. Therefore, in the sense of an image-based code for visual field restriction, Bagpuss is a non-obvious association with glaucoma. To me, Bagpuss and glaucoma both *mean* visual field restriction.

Vagueness in Dreams may be Engendered by Pruning Redundancy

In "Bagpuss" vagueness, or ambiguity, is most apparent in Scene 2. In terms of reducing model complexity and pruning redundancy (Hobson and Friston, 2012; Hobson et al., 2014), prospective coding in sleep may induce fusion (as described above) *and* vagueness because both would reduce the complexity of the visual image, which, in turn, would facilitate rapid deployment in wake. Complexity is reduced through pruning detail from the memories involved- whenever this detail is not required for the associations which are being portrayed in the dream. In this sense, "pruning" is analogous to memory condensation through association, noted by Freud. In Scene 2 there are three ambiguities: the man is behind me and, therefore, not visible and yet I next note his gray hair, implying I have seen him; his intentions are unclear- is he assisting me or menacing in some way: and his identity is ambiguous, is he a "Pole" or the ophthalmologist or is he a Polish ophthalmologist. And yet, from the perspective of associational meaning, the image is, arguably, unambiguous. It portrays my associations to "poles/ Poles."

Scene Discontinuities may Mark Transitions to a New Image-Based Prospective Code but have an Underlying Emotional Theme

Bagpuss has a story-like progression. I am looking for a place in the Eye Hospital in Scene 1, in Scene 2 I may be approaching that place and in Scene 3 my eyes are being tested. Nevertheless, there is discontinuity in the sense of the abrupt transitions between scenes. As discussed earlier, Andrillon et al. (2015) found that REMs, like saccades in wake, signify transitions in image-based or visual processing. Therefore, REMs may generate new dream scenes which may constitute linked, prospective image-based codes. All three scenes may be occurring at the Eye Hospital which, for me, may be an emotionally-charged "landmark" place (see below). The emotive theme of "vision loss or failure" also links the three scenes. This is less apparent in Scene 2 than the other two scenes, albeit there is a reference to an ophthalmologist. However, Scene 2 is concerned with "poles" which are needed by the blind or the elderly to move about. And the "Pole" appears to be linked to "poles" through the associated pickpocket threat (as perceived by my former colleague) in the "elderly people crossing" sign and the perception held by some UK Nationals that "Poles" are taking "their" jobs and, therefore, "their" money.

Summary of Prospective Coding during REM Sleep and Dreaming

Through discerning patterns inherent in prior experiences (and knowledge), REM dreaming may portray the associations between the memory elements which make up the pattern. These associations may constitute new memory content. During REM sleep, Landmann et al. (2015) report that memory "reorganization" results in novel (i.e., new) memory content which was not encoded directly during wake. This new associational memory content may enable predictions though constituting image-based prospective codes which can mobilized as predictive codes during wake.

A self-organizing brain may both engender and identify meaning through making associations. As argued earlier, meaning is often idiosyncratic to the individual, being derived from prior experiences (and knowledge) and the individual's needs, desires, and goals—all of which may be opaque- even to those intimate with them. For this reason, the dreamer should have privileged insight into meaningful dream associations, which is not equivalent to asserting that the dreamer is necessarily correct. Hill et al. (1993) found interpreting one's own dream engendered more insight than interpreting that of another person, see also Edwards et al. (2013) and Edwards et al. (2015) for dream insight studies.

In psychology the term "elaborative encoding" designates the process of discerning meaning in past events and the binding together of meaningfully associated elements of past experience to enable inferences to be drawn (Craik and Tulving, 1975; Tulving, 1983; Craik, 2002). Llewellyn (2013) argues that REM dreaming is elaborative encoding during sleep. This may be another way of contending that REM dreaming constitutes prospective coding because elaborative encoding enables inferences which, in turn, generate predictions. Indeed, to "encode" may imply generating the meaningful associations which constitute a "code." Theta oscillations occur during associative mnemonic processes (Miller, 1989, 1991), concomitantly, theta is essential to encoding (Buzsáki, 2002; Vertes, 2005). A theta-gamma code underlies the associative encoding of multiple items or events and their contexts (Lisman, 2005; Lisman and Buzsáki, 2008; Tort et al., 2009; Lisman and Jensen, 2013). Theta-gamma coordination is present during both wake and REM sleep (Montgomery et al., 2008), indicating that encoding may characterize both states, but encoding during REM sleep may be more elaborate (Hutchison and Rathore, 2015) in the sense of the associations created during REM being non-obvious or "looser."

In evolutionary terms, the creative, non-obvious associations forged in REM dreaming may serve to complement the more obvious, tight associations made in wake (Stickgold et al., 1999). As argued earlier, Wallas (1926) pointed out the evolutionary imperative to recognize "resemblance in difference." Bagpuss and glaucoma are very different but they are both characterized by visual field restriction. Contemporarily, loss of peripheral vision is a frightening prospect but does not jeopardize my survival. In evolutionary terms, however, such vision loss would have been life-threatening. During REM dreaming when prefrontal regions are deactivated, cognitive control is attenuated which may enable the identification of non-obvious associations (see earlier). Hence, this threat of vision loss may have generated an inclusive search for any "resemblance in difference" associations. Any previous experiences with visual field restriction could constitute part of a meaningful pattern which could possibly assist in coping with the threat.

A related way of explaining the identification of loose associations in REM dreaming is that non-obvious or "bizarre," personally meaningful, visual associations are mnemonic i.e., they aid memory retention and retrieval (Luria, 1968; Groninger, 1971; Roediger, 1980; McDaniel and Einstein, 1986; Einstein and McDaniel, 1987; Wilding and Valentine, 1997; Wang and Thomas, 2000; Worthen and Hunt, 2011; Llewellyn, 2013).

OFF-LINE STATES AND PROSPECTIVE CODING

As discussed above, during off-line states, people review the past to predict the future (Bar, 2007, 2011; Schütz-Bosbach and Prinz, 2007). Such reviews of the past may assume somewhat dissimilar forms in different off-line states. As discussed above, the off-line state of REM dreaming may engender a prospective code which results from the identification of an associative, non-obvious probabilistic pattern in events, for example, the associative pattern amongst "waterhole" and "abundance of prey" and "presence of a predator." Off-line states also occur during wake, when, rather than perception of the immediate sensory environment, brain processing turns to cogitation on the past and future. For example, the off-line "default mode" (Binder et al., 1999; Raichle et al., 2001) shows overlap with brain regions activated during the associative processing which may generate predictions (Bar et al., 2007). Brain processing during wake, however, is more attuned to tighter, more logical associations than the looser, non-obvious associations discerned during REM sleep (Stickgold et al., 1999). In turn, this may imply that the patterns identified during wake are more strongly determined by regular co-occurrences or tight *sequences* of events. Therefore, prospective coding during wake may take a different form as compared to prospective coding during REM dreaming- albeit that these different forms may constitute more of a continuum than a dichotomy. Different forms of prospective coding may relate to the ecological context within which prospective coding may have evolved.

Before discussing- in some detail- the possible ecological context for the evolution of different forms of prospective coding, it is worth noting that formal or computational approaches speak to the evolutionary significance of prospective coding. There is a body of work that shows prospective coding is necessary for planning and inference, demonstrated most clearly in the context of Markov decision processes—as a model for planning and choice behavior, see Friston et al. (2015). Crucially, this work indicates that prospective coding enables agents to interrogate affordances (see earlier) to select actions or plans with the greatest epistemic or pragmatic utility. In other words, prospective coding is necessary to both derive knowledge from the environment and obtain pragmatic rewards, which has obvious evolutionary imperatives.

The Ecological Context for Prospective Coding?

We live on a patchwork planet (MacDonald and Johnson, 2015). Natural resources, including food and water, are clumped rather than evenly or randomly dispersed, consuming food from clumped areas requires retained knowledge of their locations ("place memory"), indeed, patchy resource consumption may have driven the evolution of spatial memory (Cunningham and Janson, 2013).

Few animals are nomadic (Powell, 2000). Nearly all occupy confined, fairly stable habitats for a season, a year or even a lifetime, this regularly exploited territory is the 'home range' (Burt, 1943), a concept which originates with Darwin (Börger et al., 2008). Within the home range, animals will tend to return to resource-rich locations (i.e., ones with food, water, refuge or mates) whilst trying to avoid places where they have encountered aggression or danger, for review, see Stamps and Krishnan (1999). Such strategies increase fitness through exploiting resources efficiently and avoiding risk (Spencer, 2012).

In consequence, for any animal (or early human), there would have been key landmark places which were used regularly, for example, dependable food sources and refuges from predators (Kaufmann, 1962; Samuel et al., 1985; Benhamou and Riotte-Lambert, 2012). In natural environments, animals still make tours, sometimes daily, between a series of such resource-rich places, where they spend time, followed by a straight return to the home base, indicating memory for what-where place associations and the use of landmark navigation- at least of a rudimentary kind (Janzen, 1971; Gallistel, 1990; Wallace et al., 2006; Noser and Byrne, 2007, 2010).

In such an ecological context, two forms of prospective coding may have evolved, prospective coding which required probabilistic, non-obvious associations amongst prior events at the landmark places and prospective coding of the sequences which constituted the pathways or journeys between the landmark places, see Llewellyn and Hobson (2015). The visual sequences along regularly used pathways or frequently undertaken journeys would, in all likelihood, be more characterized by a tighter associational status than the discontiguous events (e.g., sightings of predators at different times) at the landmark place.

Prospective Coding of Landmark Places and REM Dreaming

Landmark places are characterized by spatially clumped resource availability which attracts many animals and is associated with increased aggressive behavior, for review, see Robb and Grant (1998). For example, animals which drink water must make regular visits to waterholes, rendering them "landscapes of fear" (Willems and Hill, 2009; Hayward and Hayward, 2012) because both prey and predators congregate there (Burger, 2001) and predators often hunt their prey in the vicinity of water (Meer et al., 2012). As mentioned earlier, male lions are "sit and wait" predators, they take advantage of long vegetation around waterholes to ambush prey (Hopcraft et al., 2005; Valeix et al., 2009, 2010). Similarly, snakes select their ambush sites at oases < 5 m from the water (Tsairi and Bouskila, 2004). At waterholes, elephants intimidate, aggressively chase and passively interfere with others present (Valeix et al., 2007). For an animal (or early human) on approach to a waterhole, predicting the cumulative patterned place-reward-danger associations of this landmark would enable appropriate action with respect to risk. If there is only one waterhole available to the animal, it cannot always avoid visiting for fear of predators or aggressive competitors.

On any tour, the animal's approach to a landmark is the most dangerous time (Valeix et al., 2009; Périquet et al., 2010). Congruent with dreaming associating experiences which, in evolutionary time, occurred on approach to a regularly visited landmark place, in a study (not distinguishing between REM and non-REM) 73% of dreams portrayed approach behaviors (Malcolm-Smith et al., 2012). Perogamvros et al. (2013) stated that dreams prioritize significant phenomena which have a high value for survival. The self (the dreamer) features in 95% of REM dreams (Snyder, 1970), McCarley and Hoffman (1981) found that 79% of REM dreams are characterized by movement of the lower-extremities, as would be required for spatial navigation. Typical themes in dream reports may reflect evolutionary "landmark" origins, for example, two studies (not distinguishing between REM and non-REM) reported "being chased or pursued," "falling," and "a person now alive as dead" occurring in 92.2, 87.1, and 75.0% of one student sample and 94.6, 76.8, and 69.6% of another (Yu, 2008, 2011). Anxious uncertainty about outcomes is common in dreams (Schwartz, 2012). Dream reports encompass more social interactions than wake reports and REM dreams portray more aggressive interactions than non-REM, the difference was threefold (McNamara et al., 2005). As discussed above, landmark places, such as waterholes, would be "social," interactive places because they attract mates and competitors but would also harbor threat causing anxious uncertainty because of the predation risk.

Prospective coding of probabilistic events at a landmark place would have survival value. Anticipation would increase the chances of the animal obtaining rewards (e.g., food, water, and mating), whilst avoiding aggression (Valeix et al., 2009). As noted earlier, the imperative to make tours to consume resources at landmark places may have driven the evolution of spatial memory networks (Cunningham and Janson, 2013). Indeed, the basic spatial network characteristic of pathways which meet at omnidirectional landmark junctions may be conserved in human brain networks (Burgess et al., 2002; Llewellyn, 2013; Llewellyn and Hobson, 2015). At an omnidirectional landmark junction, individual pathways are superimposed and, therefore, associated (O'Keefe and Burgess, 1996) in both world and mental space. An omnidirectional junction is comprised of neurons which collectively express its meaning or significance (Buzsáki, 2005). In evolutionary terms, this associative meaning may have had concrete significance for the needs, desires and goals (Clore and Ortony, 2000) of an animal on approach to a landmark junction. REM dreaming may engender a prospective image-based code of any meaningful, associative, probabilistic, experiential pattern in past events at a landmark. On approach to the landmark in wake, in the context of sensory input which could be indicative of threat, this prospective code could be mobilized rapidly and unconsciously as a predictive code to decide whether to continue to approach or to retreat. Prospective coding may also be undertaken for the pathways which link the landmarks, this will, briefly, be considered next.

Prospective Coding of Sequences during Wake

In contrast to prospective coding during REM dreaming, which may associate and encode "temporally discontiguous events" (Rawlins, 1985; Buzsáki, 1996) to engender an omnidirectional landmark junction, prospective coding during off-line states during wake may encode spatiotemporally ordered sequences which, across evolutionary time, equated to the pathways, journeys or trajectories which linked the landmark places. When traveling along any previously experienced trajectory, sensory data triggers memories of the upcoming places (Jensen and Lisman, 1996) through hippocampal forward "sweeps" (Johnson and Redish, 2007; Lisman and Redish, 2009). This form of prospective coding may rely on tighter, more deterministic, associations than that undertaken in REM dreaming.

Prospective Coding during NREM Sleep and Dreaming

This paper offers a hypothesis: REM dreaming is one form of prospective coding which evolved from identifying a loose or non-obvious associative pattern in personally significant events at a frequently visited landmark place. Dreaming also occurs during NREM sleep, however. Although, as discussed above, NREM dreams are rather different, being, inter alia, shorter, less hyperassociative, more literal, and thought-like.

It is suggested above that prospective coding during wake may encode associative sequences, evolving from the encoding of the pathways which linked the omnidirectional landmark places. However, the theory of cognitive mapping encompasses landmark locations and *their relationships to one another* (O'Keefe and Nadel, 1978; Maguire et al., 1999; Burgess et al., 2002). Associations between the landmark places would be the routes traveled and their relative directions. Prospective coding during NREM dreams may have evolved from encoding these associations.

There would also have been an imperative to encode associations between what could be found at different landmark places. For example, if there were two waterholes within reach of the animal these would be associated because water was afforded at both. Computer simulation produces cognitive maps encompassing both object-scene and scene-scene associations (Sato and Yamaguchi, 2005). Object-scene-scene associations (such as water at two different waterholes) may be encoded during REM dreams but directional scene-scene associations may be encoded during NREM.

Testing the Hypothesis

The overall hypothesis is testable through observing the consequences of brain lesions which obliterate dreaming- if, indeed, such elimination occurs. For example, Solms (1997) undertook a study of patients who reported loss of dreaming after either bilateral lesions of the ventromesial region or lesions of the parieto-temporo-occipital junction. He observed that these patients became "aspontaneous, inert and apathetic…[and] showed a massive depletion in…libido (appetitive interest)" (Solms and Turnbull, 2002). Such depletion in drive and energy would be expected from a loss in the ability to derive those patterns in past events which enable the anticipation of the future. In turn, loss of the ability to anticipate, indeed, to enact the future (Varela et al., 1991; Di Paolo, 2009) would engender loss of meaning and abolish willed action. A critique of such studies, however, is that patients with such lesions may have lost the ability to remember dreams rather ceased dreaming. Replication is required to address this and extend Solm's findings on the loss of appetitive interest.

CONCLUDING COMMENTS

Prime facie, "dream to predict" sounds implausible, not least because the bizarre events in dreams never materialize in the wake state. But if prediction involves prospective codes which fuse phenomena with the same meaning, given a particular context, and render other phenomena vague, if they are not essential to that context, one can entertain a role for REM dreaming in prospective coding. Dream bizarreness may be an aspect of the prospective coding process rather than a concrete signal of things to come. A prospective code, generated in REM dreaming, may identify a personally salient, non-obvious probabilistic pattern in past events and portray that pattern in an unconscious, sensorimotor image which, if mobilized as a predictive code in wake, supports cognition in wake through rapidly co-ordinating sensory input with appropriate action. The form taken by any prospective code may also relate to the ecological context for the predictive brain, where REM dreaming evolved to engender an image-based code which hyperassociates temporally discontiguous events at what was, in evolutionary terms, a frequently visited landmark place.

Dreams are odd but as Dobzhansky (1973) remarked "Nothing in biology makes sense except in the light of evolution."

REFERENCES

Addis, D. R., Pan, L. Vu, M.-A., Laiser, N., and Schacter, D. L. (2009). Constructive episodic simulation of the future and the past: distinct subsystems of a core brain network mediate imagining and remembering. *Neuropsychologia* 47, 2222–2238. doi: 10.1016/j.neuropsychologia.2008.10.026

Addis, D. R., and Schacter, D. L. (2011). The hippocampus and imagining the future: where do we stand? *Front Hum. Neurosci.* 5:173. doi: 10.3389/fnhum.2011.00173

Aminoff, E., Schacter, D. L., and Bar, M. (2008). The cortical underpinnings of context-based memory distortion. *J. Cogn. Neurosci.* 20, 2226–2237. doi: 10.1162/jocn.2008.20156

Anderson, E., Siegel, E. H., and Barrett, L. F. (2011). What you feel influences what you see: the role of affective feelings in resolving binocular rivalry. *J. Exp. Soc. Psychol.* 47, 856–860. doi: 10.1016/j.jesp.2011.02.009

Andrillon, T., Nir, Y., Cirelli, C., Tononi, G., and Fried, I. (2015). Single-neuron activity and eye movements during human REM sleep and awake vision. *Nat. Commun.* 6:7884. doi: 10.1038/ncomms8884

Aserinsky, E., and Kleitman, N. (1953). Regularly occurring periods of eye motility, and concomitant phenomena, during sleep. *Science* 118, 273–274. doi: 10.1126/science.118.3062.273

Bar, M. (2007). The proactive brain: using analogies and associations to generate predictions. *Trends Cogn. Sci.* 11, 280–289. doi: 10.1016/j.tics.2007.05.005

Bar, M. (2011). "The proactive brain," in *Predictions in the Brain: Using Our Past to Generate a Future,* ed M. Bar (Oxford: Oxford University Press), 13–26.

Bar, M., Aminoff, E., Mason, M., and Fenske, M. (2007). The units of thought. *Hippocampus* 17, 420–428. doi: 10.1002/hipo.20287

Bargh, J. A., and Morsella, E. (2008). The unconscious mind. *Perspect. Psychol. Sci.* 3, 73–79. doi: 10.1111/j.1745-6916.2008.00064.x

Barrett, L. F., and Bar, M. (2009). See it with feeling: affective predictions during object perception. *Philos. Trans. R. Soc. B Biol. Sci.* 364, 1325–1334. doi: 10.1098/rstb.2008.0312

Barsky, M. M., Tucker, M. A., and Stickgold, R. (2015). REM sleep enhancement of probabilistic classification learning is sensitive to subsequent interference. *Neurobiol. Learn. Mem*. 122, 63–68. doi: 10.1016/j.nlm.2015.02.015

Bartlett, F. C. (1932). *Remembering: A Study in Experimental and Social Psychology*. Cambridge: Cambridge University Press.

Bauman, Z. (2010). *Hermeneutics and Social Science: Approaches to Understanding*. Abingdon: Routledge Revivals.

Baumeister, R. F., and Masicampo, E. (2010). Conscious thought is for facilitating social and cultural interactions: how mental simulations serve the animal–culture interface. *Psychol. Rev.* 117, 945. doi: 10.1037/a0019393

Benhamou, S., and Riotte-Lambert, L. (2012). Beyond the utilization distribution: identifying home range areas that are intensively exploited or repeatedly visited. *Ecol. Model.* 227, 112–116. doi: 10.1016/j.ecolmodel.2011.12.015

Binder, J. R., Frost, J. A., Hammeke, T. A., Bellgowan, P., Rao, S. M., and Cox, R. W. (1999). Conceptual processing during the conscious resting state: a functional MRI study. *J. Cogn. Neurosci.* 11, 80–93. doi: 10.1162/089892999563265

Börger, L., Dalziel, B. D., and Fryxell, J. M. (2008). Are there general mechanisms of animal home range behaviour? A review and prospects for future research. *Ecol. Lett.* 11, 637–650. doi: 10.1111/j.1461-0248.2008.01182.x

Bowden, E. M., Jung-Beeman, M., Fleck, J., and Kounios, J. (2005). New approaches to demystifying insight. *Trends Cogn. Sci.* 9, 322–328. doi: 10.1016/j.tics.2005.05.012

Braun, A. R., Balkin, T. J., Wesensten, N. J., Carson, R. E., Varga, M., Baldwin, P., et al. (1997). Regional cerebral blood flow throughout the sleep-wake cycle. *Brain* 120, 1173–1197. doi: 10.1093/brain/120.7.1173

Bruner, J. S. (1990). *Acts of Meaning*. Boston, MA: Harvard University Press.

Bubic, A., von Cramon, D. Y., and Schubotz, R. I. (2010). Prediction, cognition and the brain. *Front. Hum. Neurosci.* 4:25. doi: 10.3389/fnhum.2010.00025

Buckner, R. L. (2010). The role of the hippocampus in prediction and imagination. *Annu. Rev. Psychol.* 61, 27–48. doi: 10.1146/annurev.psych.60.110707.163508

Burger, J. (2001). Visibility, group size, vigilance, and drinking behavior in coati (*Nasua narica*) and white-faced capuchins (*Cebus capucinus*): experimental evidence. *Acta Ethol.* 3, 111–119. doi: 10.1007/s102110000035

Burgess, N., Maguire, E. A., and O'Keefe, J. (2002). The human hippocampus and spatial and episodic memory. *Neuron* 35, 625–641. doi: 10.1016/S0896-6273(02)00830-9

Burt, W. H. (1943). Territoriality and home range concepts as applied to mammals. *J. Mammal.* 24, 346–352. doi: 10.2307/1374834

Buzsáki, G. (1996). The hippocampo-neocortical dialogue. *Cereb. Cortex* 6, 81–92. doi: 10.1093/cercor/6.2.81

Buzsáki, G. (2002). Theta oscillations in the hippocampus. *Neuron* 33, 325–340. doi: 10.1016/S0896-6273(02)00586-X

Buzsáki, G. (2005). Theta rhythm of navigation: link between path integration and landmark navigation, episodic and semantic memory. *Hippocampus* 15, 827–840. doi: 10.1002/hipo.20113

Cahill, L., Haier, R. J., Fallon, J., Alkire, M. T., Tang, C., Keator, D., et al. (1996). Amygdala activity at encoding correlated with long-term, free recall of emotional information. *Proc. Natl. Acad. Sci. U.S.A.* 93, 8016–8021.

Cahill, L., and McGaugh, J. L. (1998). Mechanisms of emotional arousal and lasting declarative memory. *Trends Neurosci.* 21, 294–299.

Cai, D. J., Mednick, S. A., Harrison, E. M., Kanady, J. C., and Mednick, S. C. (2009). REM, not incubation, improves creativity by priming associative networks. *Proc. Nat. Acad. Sci. U.S.A.*106, 10130–10134. doi: 10.1073/pnas.0900271106

Carretié, L., Hinojosa, J. A., Mercado, F., and Tapia, M. (2005). Cortical response to subjectively unconscious danger. *Neuroimage* 24, 615–623. doi: 10.1016/j.neuroimage.2004.09.009

Carruthers, M., and Ziolkowski, J. M. (2002). *The Medieval Craft of Memory: An Anthology of Texts and Pictures.* Philadelphia, PA: University of Pennsylvania Press.

Carver, C. S., Sutton, S. K., and Scheier, M. F. (2000). Action, emotion, and personality: Emerging conceptual integration. *Pers. Soc. Psychol. Bull.* 26, 741–751. doi: 10.1177/0146167200268008

Cavallero, C., Foulkes, D., Hollifield, M., and Terry, R. (1990). Memory sources of REM and NREM dreams. *Sleep* 13, 449–455.

Chemero, A. (2003). An outline of a theory of affordances. *Ecol. Psychol.* 15, 181–195. doi: 10.1207/S15326969ECO1502_5

Chen, M., and Bargh, J. A. (1999). Consequences of automatic evaluation: immediate behavioral predispositions to approach or avoid the stimulus. *Pers. Soc. Psychol. Bull.* 25, 215–224. doi: 10.1177/0146167299025002007

Chow, H. M., Horovitz, S. G., Carr, W. S., Picchioni, D., Coddington, N., Fukunaga, M., et al. (2013). Rhythmic alternating patterns of brain activity distinguish rapid eye movement sleep from other states of consciousness. *Proc. Nat. Acad. Sci.* 110, 10300–10305. doi: 10.1073/pnas.1217691110

Cicogna, P. C., and Bosinelli, M. (2001). Consciousness during dreams. *Conscious. Cogn.* 10, 26–41. doi: 10.1006/ccog.2000.0471

Clark, A. (2013). Whatever next? Predictive brains, situated agents, and the future of cognitive science. *Behav. Brain Sci.* 36, 181–204. doi: 10.1017/S0140525X12000477

Clore, G. L., and Ortony, A. (2000). "Cognitive Neuroscience of Emotion," in *Cognition in Emotion: Always, Sometimes, or Never*, eds R. D. Lane and L. Nadel (New York, NY: Oxford University Press), 24–61.

Conway, M. A. (2009). Episodic memories. *Neuropsychologia* 47, 2305–2313. doi: 10.1016/j.neuropsychologia.2009.02.003

Conway, M. A., and Pleydell-Pearce, C. W. (2000). The construction of autobiographical memories in the self-memory system. *Psychol. Rev.* 107, 261. doi: 10.1037/0033-295X.107.2.261

Craik, F. I. (2002). Levels of processing: Past, present. and future? *Memory* 10, 305–318. doi: 10.1080/09658210244000135

Craik, F. I., and Tulving, E. (1975). Depth of processing and the retention of words in episodic memory. *J. Exp. Psychol. Gen.* 104, 268. doi: 10.1037/0096-3445.104.3.268

Cunningham, E. P., and Janson, C. H. (2013). Effect of fruit scarcity on use of spatial memory in a seed predator, white-faced saki (*Pithecia pithecia*). *Int. J. Primatol.* 34, 808–822. doi: 10.1007/s10764-013-9697-5

Cuthbert, B. N., Vrana, S. R., and Bradley, M. M. (1991). "Imagery: Function and physiology," in *Advances in Psychophysiology*, eds J. R. Jennings, P. K. Ackles, and M. G. H. Coles (London, UK, Jessica Kingsley Publishers), 1–42.

Dayan, P., Hinton, G. E., Neal, R. M., and Zemel, R. S. (1995). The helmholtz machine. *Neural Comput.* 7, 889–904. doi: 10.1162/neco.1995.7.5.889

Dement, W., and Kleitman, N. (1957). The relation of eye movements during sleep to dream activity: an objective method for the study of dreaming. *J. Exp. Psychol.* 53, 339. doi: 10.1037/h0048189

Desseilles, M., Dang-Vu, T. T., Sterpenich, V., and Schwartz, S. (2011). Cognitive and emotional processes during dreaming: a neuroimaging view. *Conscious. Cogn.* 20, 998–1008. doi: 10.1016/j.concog.2010.10.005

Di Paolo, E. (2009). Extended life. *Topoi* 28, 9–21. doi: 10.1007/s11245-008-9042-3

Djonlagic, I., Rosenfeld, A., Shohamy, D., Myers, C., Gluck, M., and Stickgold, R. (2009). Sleep enhances category learning. *Learn. Mem.* 16, 751–755. doi: 10.1101/lm.1634509

Dobzhansky, T. (1973). Nothing in biology makes sense except in the light of evolution. *Am. Biol. Teach.* 35, 125–129. doi: 10.2307/4444260

Doricchi, F., Iaria, G., Silvetti, M., Figliozzi, F., and Siegler, I. (2007). The "ways" we look at dreams: evidence from unilateral spatial neglect (with an evolutionary account of dream bizarreness). *Exp. Brain Res.* 178, 450–461. doi: 10.1007/s00221-006-0750-x

Edwards, C. L., Malinowski, J. E., McGee, S. L., Bennett, P. D., Ruby, P. M., and Blagrove, M. T. (2015). Comparing personal insight gains due to consideration of a recent dream and consideration of a recent event using the Ullman and Schredl dream group methods. *Front. Psychol.* 6:831. doi: 10.3389/fpsyg.2015.00831

Edwards, C. L., Ruby, P. M., Malinowski, J. E., Bennett, P. D., and Blagrove, M. T. (2013). Dreaming and insight. *Front. Psychol.* 4:979. doi: 10.3389/fpsyg.2013.00979

Einstein, G. O., and McDaniel, M. A. (1987). "Distinctiveness and the mnemonic benefits of bizarre imagery," in *Imagery and Related Mnemonic Processes,* eds M. A. McDaniel and M. Pressley (New York, NY: Springer), 78–102.

Elliot, A. J. (2006). The hierarchical model of approach-avoidance motivation. *Motiv. Emot.* 30, 111–116. doi: 10.1007/s11031-006-9028-7

Elliot, A. J., and Church, M. A. (1997). A hierarchical model of approach and avoidance achievement motivation. *J. Pers. Soc. Psychol.* 72, 218. doi: 10.1037/0022-3514.72.1.218

Ferbinteanu, J., and Shapiro, M. L. (2003). Prospective and retrospective memory coding in the hippocampus. *Neuron* 40, 1227–1239. doi: 10.1016/S0896-6273(03)00752-9

Fischer, S., and Born, J. (2009). Anticipated reward enhances offline learning during sleep. *J. Exp. Psychol. Learn. Mem. Cogn.* 35, 1586–1593. doi: 10.1037/a0017256

Fischer, S., Diekelmann, S., and Born, J. (2011). Sleep's role in the processing of unwanted memories. *J. Sleep Res.* 20, 267–274. doi: 10.1111/j.1365-2869.2010.00881.x

Fosse, M. J., Fosse, R., Hobson, J. A., and Stickgold, R. J. (2003). Dreaming and episodic memory: a functional dissociation? *J. Cogn. Neurosci.* 15, 1–9. doi: 10.1162/089892903321107774

Fosse, R., Stickgold, R., and Hobson, J. A. (2004). Thinking and hallucinating: reciprocal changes in sleep. *Psychophysiology* 41, 298–305. doi: 10.1111/j.1469-8986.2003.00146.x

Foulkes, D., Bradley, L., Cavallero, C., and Hollifield, M. (1989). Processing of memories and knowledge in REM and NREM dreams. *Percept. Mot. Skills* 68, 365–366. doi: 10.2466/pms.1989.68.2.365

Freeman, W. J. (1999). Consciousness, intentionality and causality. *J. Conscious. Stud.* 6, 143–172.

Friston, K. (2005). A theory of cortical responses. *Philos. Trans. R. Soc. B Biol. Sci.* 360, 815–836. doi: 10.1098/rstb.2005.1622

Friston, K. (2010). The free-energy principle: a unified brain theory? *Nat. Rev. Neurosci.* 11, 127–138. doi: 10.1038/nrn2787

Friston, K. (2012). Prediction, perception and agency. *Int. J. Psychophysiol.* 83, 248–252. doi: 10.1016/j.ijpsycho.2011.11.014

Friston, K., Adams, R. A., Perrinet, L., and Breakspear, M. (2012). Perceptions as hypotheses: saccades as experiments. *Front. Psychol.* 3:151. doi: 10.3389/fpsyg.2012.00151

Friston, K., and Kiebel, S. (2009). Predictive coding under the free-energy principle. *Philos. Trans. R. Soc. B. Biol. Sci.* 364, 1211–1221. doi: 10.1098/rstb.2008.0300

Friston, K., Rigoli, F., Ognibene, D., Mathys, C., Fitzgerald, T., and Pezzulo, G. (2015). Active inference and epistemic value. *Cogn. Neurosci.* 6, 187–214. doi: 10.1080/17588928.2015.1020053

Fuster, J. M. (1997). Network memory. *Trends Neurosci.* 20, 451–459. doi: 10.1016/S0166-2236(97)01128-4

Fuster, J. M. (1999). *Memory in the Cerebral Cortex: An Empirical Approach to Neural Networks in the Human and Nonhuman Primate*. Cambridge, MA: MIT Press.

Gallistel, C. R. (1990). *The Organization of Learning*. Cambridge, MA: The MIT Press.

Gilbert, D. T., and Wilson, T. D. (2011). "Previews, premotions, and predictions," in *Predictions in the Brain: Using our Past to Generate a Future*, ed M. Bar (Oxford: Oxford University Press), 159–169.

Goel, V., and Dolan, R. J. (2004). Differential involvement of left prefrontal cortexin inductive and deductive reasoning. *Cognition* 93, B109–B121. doi: 10.1016/j.cognition.2004.03.001

Goodale, M. A., and Milner, A. D. (1992). Separate visual pathways for perception and action. *Trends Neurosci.* 15, 20–25. doi: 10.1016/0166-2236(92)90344-8

Goodale, M., and Milner, D. (2013). *Sight Unseen: An Exploration of Conscious and Unconscious Vision*. Oxford: Oxford University Press.

Gregory, R. L. (1980). Perceptions as hypotheses. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* 290, 181–197. doi: 10.1098/rstb.1980.0090

Groninger, L. D. (1971). Mnemonic imagery and forgetting. *Psychon. Sci.* 23, 161–163. doi: 10.3758/BF03336056

Hamann, S. B., Ely, T. D., Grafton, S. T., and Kilts, C. D. (1999). Amygdala activity related to enhanced memory for pleasant and aversive stimuli. *Nat. Neurosci.* 2, 289–293.

Hampson, R. E., Pons, T. P., Stanford, T. R., and Deadwyler, S. A. (2004). Categorization in the monkey hippocampus: a possible mechanism for encoding information into memory. *Proc. Natl. Acad. Sci. U.S.A.* 101, 3184–3189. doi: 10.1073/pnas.0400162101

Hardy, C. (2001). Self-organization, self-reference and inter-influences in Multilevel Webs: beyond causality and determinism. *Cybern. Hum. Knowing* 8, 35–59.

Hartmann, E. (1996). Outline for a theory on the nature and functions of dreaming. *Dreaming* 6, 147. doi: 10.1037/h0094452

Hassabis, D., and Maguire, E. A. (2007). Deconstructing episodic memory with construction. *Trends Cogn. Sci.* 11, 299–306. doi: 10.1016/j.tics.2007.05.001

Hayward, M. W., and Hayward, M. D. (2012). Waterhole use by African Fauna. *South Afr. J. Wildl. Res.* 42, 117–127. doi: 10.3957/056.042.0209

Helmholtz, H., V. (1909). *Physiological Optics. English translation 1962 by JPC Southall from the 3rd German edition of Handbuch der Physiologischen Optik*. New York, NY: Vos, Hamburg; Dover.

Hill, C. E., Diemer, R., Hess, S., Hillyer, A., and Seeman, R. (1993). Are the effects of dream interpretation on session quality, insight, and emotions due to the dream itself, to projection, or to the interpretation process? *Dreaming* 3, 269. doi: 10.1037/h0094385

Hobson, J. A. (1988). *The Dreaming Brain*. New York, NY: Basic Books.

Hobson, J. A. (2002). *Dreaming: An Introduction to the Science of Sleep*. Oxford: Oxford University Press.

Hobson, J. A., C.,Hong, C.-C., and Friston, K. J. (2014). Virtual reality and consciousness inference in dreaming. *Front. Psychol.* 5:1133. doi: 10.3389/fpsyg.2014.01133

Hobson, J. A., Pace-Schott, E. F., and Stickgold, R. (2000). Dreaming and the brain: toward a cognitive neuroscience of conscious states. *Behav. Brain Sci.* 23, 793–842. doi: 10.1017/S0140525X00003976

Hobson, J. A., Stickgold, R., and Pace-Schott, E. F. (1998). The neuropsychology of REM sleep dreaming. *Neuroreport* 9, R1–R14. doi: 10.1097/00001756-199802160-00033

Hobson, J. A., and Friston, K. J. (2012). Waking and dreaming consciousness: neurobiological and functional considerations. *Prog. Neurobiol.* 98, 82–98. doi: 10.1016/j.pneurobio.2012.05.003

Honey, R. C., Iordanova, M. D., and Good, M. (2014). Associative structures in animal learning: dissociating elemental and configural processes. *Neurobiol. Learn. Mem.* 108, 96–103. doi: 10.1016/j.nlm.2013.06.002

Hong, C. C. H., Harris, J. C., Pearlson, G. D., Kim, J. S., Calhoun, V. D., Fallon, J. H., et al. (2009). fMRI evidence for multisensory recruitment associated with rapid eye movements during sleep. *Hum. Brain Mapp.* 30, 1705–1722. doi: 10.1002/hbm.20635

Hopcraft, J. G. C., Sinclair, A., and Packer, C. (2005). Planning for success: serengeti lions seek prey accessibility rather than abundance. *J. Anim. Ecol.* 74, 559–566. doi: 10.1111/j.1365-2656.2005.00955.x

Horne, J. (2013). Why REM sleep? Clues beyond the laboratory in a more challenging world. *Biol. Psychol.* 92, 152–168. doi: 10.1016/j.biopsycho.2012.10.010

Horne, J. (2015). Human REM sleep: influence on feeding behaviour with clinical implications. *Sleep Med.* 16: 910–916. doi: 10.1016/j.sleep.2015.04.002

Horton, C. L., and Malinowski, J. E. (2015). Autobiographical memory and hyperassociativity in the dreaming brain: implications for memory consolidation in sleep. *Front. Psychol.* 6:874. doi: 10.3389/fpsyg.2015.00874

Hutchison, I. C., and Rathore, S. (2015). The role of REM sleep theta activity in emotional memory. *Front. Psychol.* 6:1439. doi: 10.3389/fpsyg.2015.01439

James, W. (1890). *The Principles of Psychology*, Vol. 1. New York, NY: Dover Publications.

Janzen, D. (1971). Euglossine bees as long-distance pollinators of tropical plants. *Science* 171, 203–205. doi: 10.1126/science.171.3967.203

Jensen, O., and Lisman, J. E. (1996). Hippocampal CA3 region predicts memory sequences: accounting for the phase precession of place cells. *Learn. Mem.* 3, 279–287. doi: 10.1101/lm.3.2-3.279

Johnson, A., and Redish, A. D. (2007). Neural ensembles in CA3 transiently encode paths forward of the animal at a decision point. *J. Neurosci.* 27, 12176–12189. doi: 10.1523/JNEUROSCI.3761-07.2007

Jouvet, M. (1999). *The Paradox of Sleep: The Story of Dreaming*. Cambridge, MA: MIT Press.

Kaufmann, J. H. (1962). *The ecology and social behavior of the coati, Nasua narica, of Barro Colorado Island, Panama.* University of California, Berkeley.

Keller, E. F. (2007). "The disappearance of function from 'Self-Organizing Systems,'" in *Systems Biology,* eds F. Boogerd, F. J. Bruggeman, J. S. Hofmeyr, and H. V. Westerhoff (Amsterdam: Elsevier), 303–317.

Kelso, J. S. (1997). *Dynamic Patterns: The Self-Organization of Brain and Behavior.* Cambridge, MA: MIT Press.

Kersten, D., Mamassian, P., and Yuille, A. (2004). Object perception as Bayesian inference. *Annu. Rev. Psychol.* 55, 271–304. doi: 10.1146/annurev.psych.55.090902.142005

Knill, D. C., and Pouget, A. (2004). The Bayesian brain: the role of uncertainty in neural coding and computation. *Trends Neurosci.* 27, 712–719. doi: 10.1016/j.tins.2004.10.007

Landmann, N., Kuhn, M., Maier, J.-G., Spiegelhalder, K., Baglioni, C., Frase, L., et al. (2015). REM sleep and memory reorganization: potential relevance for psychiatry and psychotherapy. *Neurobiol. Learn. Mem.* 122, 28–40. doi: 10.1016/j.nlm.2015.01.004

Lang, P. J. (1995). The emotion probe: studies of motivation and attention. *Am. Psychol.* 50, 372. doi: 10.1037/0003-066X.50.5.372

Lang, P. J., Bradley, M. M., and Cuthbert, B. N. (1990). Emotion, attention, and the startle reflex. *Psychol. Rev.* 97, 377. doi: 10.1037/0033-295X.97.3.377

Laureys, S., Peigneux, P., Phillips, C., Fuchs, S., Degueldre, C., Aerts, J., et al. (2001). Experience-dependent changes in cerebral functional connectivity during human rapid eye movement sleep. *Neuroscience* 105, 521–525. doi: 10.1016/S0306-4522(01)00269-X

Lavie, P., Matanya, Y., and Yehuda, S. (1984). Cognitive asymmetries after wakings from REM and NONREM sleep in right-handed females. *Int. J. Neurosci.* 23, 111–115. doi: 10.3109/00207458408985352

Leclair-Visonneau, L., Oudiette, D., Gaymard, B., Leu-Semenescu, S., and Arnulf, I. (2010). Do the eyes scan dream images during rapid eye movement sleep? Evidence from the rapid eye movement sleep behaviour disorder model. *Brain* 133, 1737–1746. doi: 10.1093/brain/awq110

Limb, C. J., and Braun, A. R. (2008). Neural substrates of spontaneous musical performance: An fMRI study of jazz improvisation. *PLoS ONE* 3:e1679. doi: 10.1371/journal.pone.0001679

Lisman, J. (2005). The theta/gamma discrete phase code occurring during the hippocampal phase precession may be a more general brain coding scheme. *Hippocampus* 15, 913–922. doi: 10.1002/hipo.20121

Lisman, J., and Buzsáki, G. (2008). A neural coding scheme formed by the combined function of gamma and theta oscillations. *Schizophr. Bull.* 34, 974–980. doi: 10.1093/schbul/sbn060

Lisman, J. E., and Jensen, O. (2013). The theta-gamma neural code. *Neuron* 77, 1002–1016. doi: 10.1016/j.neuron.2013.03.007

Lisman, J., and Redish, A. D. (2009). Prediction, sequences and the hippocampus. *Philos. Trans. R. Soc. B Biol. Sci.* 364, 1193–1201. doi: 10.1098/rstb.2008.0316

Liu, S., Chow, H. M., Xu, Y., Erkkinen, M. G., Swett, K. E., Eagle, M. W., et al. (2012). Neural correlates of lyrical improvisation: an fMRI study of freestyle rap. *Sci. Rep.* 2:834. doi: 10.1038/srep00834

Llewellyn, S. (2013). Such stuff as dreams are made on? Elaborative encoding, the ancient art of memory, and the hippocampus. *Behav. Brain Sci.* 36, 589–607. doi: 10.1017/S0140525X12003135

Llewellyn, S., and Hobson, J. A. (2015). Not only but also: REM sleep creates and NREM Stage 2 instantiates landmark junctions in cortical memory networks. *Neurobiol. Learn. Mem.* 122, 69–87. doi: 10.1016/j.nlm.2015.04.005

Llinás, R. R. (2002). *I of the Vortex: From Neurons to Self*. Cambridge, MA: MIT Press.

Luria, A. R. (1968). *The Mind of a Mnemonist: A Little Book about a Vast Memory*. Boston, MA: Harvard University Press.

MacDonald, D., and Johnson, D. (2015). Patchwork planet: the resource dispersion hypothesis, society, and the ecology of life. *J. Zool.* 295, 75–107. doi: 10.1111/jzo.12202

Maguire, E. A., Burgess, N., and O'Keefe, J. (1999). Human spatial navigation: cognitive maps, sexual dimorphism, and neural substrates. *Curr. Opin. Neurobiol.* 9, 171–177. doi: 10.1016/S0959-4388(99)80023-3

Malcolm-Smith, S., Koopowitz, S., Pantelis, E., and Solms, M. (2012). Approach/avoidance in dreams. *Conscious. Cogn.* 21, 408–412. doi: 10.1016/j.concog.2011.11.004

Malinowski, J. E., and Horton, C. L. (2014). Memory sources of dreams: the incorporation of autobiographical rather than episodic experiences. *J. Sleep Res.* 23, 441–447. doi: 10.1111/jsr.12134

Malinowski, J. E., and Horton, C. L. (2015). Metaphor and hyperassociativity: the imagination mechanisms behind emotion assimilation in sleep and dreaming. *Front. Psychol.* 6:1132. doi: 10.3389/fpsyg.2015.01132

Maquet, P. (2000). Functional neuroimaging of normal human sleep by positron emission tomography. *J. Sleep Res.* 9, 207–232. doi: 10.1046/j.1365-2869.2000.00214.x

Maquet, P., Péters, J.-M., Aerts, J., Delfiore, G., Degueldre, C., Franck, G., et al. (1996). Functional neuroanatomy of human rapid-eye-movement sleep and dreaming. *Nature* 383, 163–166. doi: 10.1038/383163a0

McCarley, R. W., and Hoffman, E. (1981). REM sleep dreams and the activation-synthesis hypothesis. *Am. J. Psychiatry* 138, 904–912.

McDaniel, M. A., and Einstein, G. O. (1986). Bizarre imagery as an effective memory aid: the importance of distinctiveness. *J. Exp. Psychol. Learn. Mem. Cogn.* 12, 54. doi: 10.1037/0278-7393.12.1.54

McNamara, P., McLaren, D., Smith, D., Brown, A., and Stickgold, R. (2005). A "Jekyll and Hyde" within aggressive versus friendly interactions in REM and non-REM dreams. *Psychol. Sci.* 16, 130–136. doi: 10.1111/j.0956-7976.2005.00793.x

Meer, E., Pays, O., and Fritz, H. (2012). The effect of simulated African wild dog presence on anti−predator behaviour of Kudu and Impala. *Ethology* 118, 1018–1027. doi: 10.1111/eth.12003

Metzinger, T. (2009). *The Ego Tunnel: The Science of the Mind and the Myth of the Self.* New York, NY: Basic Books.

Miller, R. (1989). Cortico-hippocampal interplay: self-organizing phase-locked loops for indexing memory. *Psychobiology* 17, 115–128.

Miller, R. (1991). *Cortico-Hippocampal Interplay and the Representation of Contexts in the Brain*. Berlin: Springer.

Milner, A. D., and Goodale, M. A. (2008). Two visual systems re-viewed. *Neuropsychologia* 46, 774–785. doi: 10.1016/j.neuropsychologia.2007.10.005

Miyauchi, S., Misaki, M., Kan, S., Fukunaga, T., and Koike, T. (2009). Human brain activity time-locked to rapid eye movements during REM sleep. *Exp. Brain Res.* 192, 657–667. doi: 10.1007/s00221-008-1579-2

Montgomery, S. M., Sirota, A., and Buzsáki, G. (2008). Theta and gamma coordination of hippocampal networks during waking and rapid eye movement sleep. *J. Neurosci.* 28, 6731–6741. doi: 10.1523/JNEUROSCI.1227-08.2008

Moulton, S. T., and Kosslyn, S. M. (2009). Imagining predictions: mental imagery as mental emulation. *Philos. Trans. R. Soc. B Biol. Sci.* 364, 1273–1280. doi: 10.1098/rstb.2008.0314

Nathaniel-James, D. A., and Frith, C. D. (2002). The role of the dorsolateral prefrontal cortex: evidence from the effects of contextual constraint in a sentence completion task. *Neuroimage* 16, 1094–1102. doi: 10.1006/nimg.2002.1167

Neumann, R., Förster, J., and Strack, F. (2003). "Motor compatibility: the bidirectional link between behavior and evaluation," *The Psychology of Evaluation: Affective Processes in Cognition and Emotion*, eds J. Musch and K. C. Klauer (Mahwah, NJ: Erlbaum), 371–391.

Nielsen, T. (2013). The method of loci (MoL) and memory consolidation: dreaming is not MoL-like. *Behav. Brain Sci.* 36, 624–625. doi: 10.1017/S0140525X13001398

Nielsen, T. A. (1999). "Mentation during sleep: the NREM/REM distinction," in *Handbook of Behavioral State Control: Cellular and Molecular Mechanisms,* eds R. Lydic and H. A. Baghdoyan (Boca Raton; London; New York, NY; Washington, DC: CRC Press), 101–129.

Nielsen, T. A. (2000). A review of mentation in REM and NREM sleep:"covert" REM sleep as a possible reconciliation of two opposing models. *Behav. Brain Sci.* 23, 851–866. doi: 10.1017/S0140525X0000399X

Nielsen, T. A., and Stenstrom, P. (2005). What are the memory sources of dreaming? *Nature* 437, 1286–1289. doi: 10.1038/nature04288

Nielsen, T., Kuiken, D., Hoffmann, R., and Moffitt, A. (2001). REM and NREM sleep mentation differences: a question of story structure? *Sleep Hypnosis* 3, 9–17.

Nir, Y., and Tononi, G. (2010). Dreaming and the brain: from phenomenology to neurophysiology. *Trends Cogn. Sci.* 14, 88–100. doi: 10.1016/j.tics.2009.12.001

Nishida, M., Pearsall, J., Buckner, R. L., and Walker, M. P. (2009). REM sleep, prefrontal theta, and the consolidation of human emotional memory. *Cereb. Cortex* 19, 1158–1166. doi: 10.1093/cercor/bhn155

Noser, R., and Byrne, R. W. (2007). Travel routes and planning of visits to out-of-sight resources in wild chacma baboons,< i> *Papio ursinus*</i>. *Anim. Behav.* 73, 257–266. doi: 10.1016/j.anbehav.2006.04.012

Noser, R., and Byrne, R. W. (2010). How do wild baboons (*Papio ursinus*) plan their routes? Travel among multiple high-quality food sources with inter-group competition. *Anim. Cogn.* 13, 145–155. doi: 10.1007/s10071-009-0254-8

Öhman, A., Flykt, A., and Lundqvist, D. (2000). "Unconscious emotion, evolutionary perspectives, psychophysiological data, and neuropsychological mechanisms," in *Cognitive Neuroscience of Emotion*, eds R. D. Lane and L. Nadel (New York, NY: Oxford University Press), 296–327

O'Keefe, J., and Burgess, N. (1996). Geometric determinants of the place fields of hippocampal neurons. *Nature* 381, 425–428. doi: 10.1038/381425a0

O'Keefe, J., and Nadel, L. (1978). *The Hippocampus as a Cognitive Map*. Oxford: Clarendon Press.

Paivio, A. (1990). *Mental Representations: A Dual Coding Approach*. Oxford: Oxford University Press.

Paivio, A. (2013). *Imagery and Verbal Processes*. New York, NY: Psychology Press.

Panichello, M. F., Cheung, O. S., and Bar, M. (2012). Predictive feedback and conscious visual experience. *Front. Psychol.* 3:620. doi: 10.3389/fpsyg.2012.00620

Peigneux, P., Laureys, S., Fuchs, S., Destrebecqz, A., Collette, F., Delbeuck, X., et al. (2003). Learned material content and acquisition level modulate cerebral reactivation during posttraining rapid-eye-movements sleep. *Neuroimage* 20, 125–134. doi: 10.1016/S1053-8119(03)00278-7

Périquet, S., Valeix, M., Loveridge, A. J., Madzikanda, H., Macdonald, D. W., and Fritz, H. (2010). Individual vigilance of African herbivores while drinking: the role of immediate predation risk and context. *Anim. Behav.* 79, 665–671. doi: 10.1016/j.anbehav.2009.12.016

Perogamvros, L., Dang-Vu, T. T., Desseilles, M., and Schwartz, S. (2013). Sleep and dreaming are for important matters. *Front. Psychol.* 4:474. doi: 10.3389/fpsyg.2013.00474

Pfeiffer, B. E., and Foster, D. J. (2013). Hippocampal place-cell sequences depict future paths to remembered goals. *Nature* 497, 74–79. doi: 10.1038/nature12112

Plihal, W., and Born, J. (1997). Effects of early and late nocturnal sleep on declarative and procedural memory. *J. Cogn. Neurosci.* 9, 534–547. doi: 10.1162/jocn.1997.9.4.534

Popper, K. R. (1959). *The Logic of Scientific Discovery*. London: Hutchinson.

Powell, R. A. (2000). "Animal home ranges and territories and home range estimators." in *Research Techniques in Animal Ecology: Controversies and Consequences,* ed L. Boitani and T. Fuller (New York, NY: Columbia University Press), 65–103.

Raichle, M. E., MacLeod, A. M., Snyder, A. Z., Powers, W. J., Gusnard, D. A., and Shulman, G. L. (2001). A default mode of brain function. *Proc. Nat. Acad. Sci. U.S.A.* 98, 676–682. doi: 10.1073/pnas.98.2.676

Rainer, G., Rao, S. C., and Miller, E. K. (1999). Prospective coding for objects in primate prefrontal cortex. *J. Neurosci.* 19, 5493–5505.

Rao, R. P., and Ballard, D. H. (1999). Predictive coding in the visual cortex: a functional interpretation of some extra-classical receptive-field effects. *Nat. Neurosci.* 2, 79–87. doi: 10.1038/4580

Rawlins, J. (1985). Associations across time: the hippocampus as a temporary memory store. *Behav. Brain Sci.* 8, 479–497. doi: 10.1017/S0140525X00001291

Reverberi, C., Lavaroni, A., Gigli, G. L., Skrap, M., and Shallice, T. (2005a). Specific impairments of rule induction in different frontal lobe subgroups. *Neuropsychologia* 43, 460–472. doi: 10.1016/j.neuropsychologia.2004.06.008

Reverberi, C., Toraldo, A., D'Agostini, S., and Skrap, M. (2005b). Better without (lateral) frontal cortex? Insight problems solved by frontal patients. *Brain* 128, 2882–2890. doi: 10.1093/brain/awh577

Revonsuo, A. (2000). The reinterpretation of dreams: an evolutionary hypothesis of the function of dreaming. *Behav. Brain Sci.* 23, 877–901. doi: 10.1017/S0140525X00004015

Ricoeur, P. (1974). "The conflict of interpretations: essays in hermeneutics," in *Northwestern University Studies in Phenomenology and Existential Philosophy*, ed D. Ihde (Evanston, IL: Northwestern University Press).

Ricoeur, P. (1981). *Hermeneutics and the Human Sciences: Essays on Language, Action and Interpretation*. Cambridge, UK: Cambridge University Press.

Ridderinkhof, K. R., van den Wildenberg, W. P., Segalowitz, S. J., and Carter, C. S. (2004). Neurocognitive mechanisms of cognitive control: the role of prefrontal cortex in action selection, response inhibition, performance monitoring, and reward-based learning. *Brain Cogn.* 56, 129–140. doi: 10.1016/j.bandc.2004.09.016

Rittenhouse, C. D., Stickgold, R., and Hobson, J., A. (1994). Constraint on the transformation of characters, objects, and settings in dream reports. *Conscious. Cogn.* 3, 100–113. doi: 10.1006/ccog.1994.1007

Robb, S. E., and Grant, J. W. (1998). Interactions between the spatial and temporal clumping of food affect the intensity of aggression in Japanese medaka. *Anim. Behav.* 56, 29–34. doi: 10.1006/anbe.1998.0735

Roediger, H. L. (1980). The effectiveness of four mnemonics in ordering recall. *J. Exp. Psychol. Hum. Learn. Mem.* 6, 558. doi: 10.1037/0278-7393.6.5.558

Samuel, M. D., Pierce, D., and Garton, E. O. (1985). Identifying areas of concentrated use within the home range. *J. Anim. Ecol.* 54, 711–719. doi: 10.2307/4373

Sato, N., and Yamaguchi, Y. (2005). Online formation of a hierarchical cognitive map for object–place association by theta phase coding. *Hippocampus* 15, 963–978. doi: 10.1002/hipo.20110

Schachtel, E. G. (1947). On memory and childhood amnesia. *Psychiatry* 10, 1–26.

Schacter, D. L., and Addis, D. R. (2007). The cognitive neuroscience of constructive memory: remembering the past and imagining the future. *Philos. Trans. R. Soc. B. Biol. Sci.* 362, 773–786. doi: 10.1098/rstb.2007.2087

Schooler, J. W., and Melcher, J. (1995). "The Creative Cognitive Approach," in *The Ineffability of Insight*, eds S. M, Smith, T. B. Ward, and R. A. Finke (Cambridge: MIT Press), 97–133.

Schultz, W., Dayan, P., and Montague, P. R. (1997). A neural substrate of prediction and reward. *Science* 275, 1593–1599. doi: 10.1126/science.275.5306.1593

Schütz-Bosbach, S., and Prinz, W. (2007). Prospective coding in event representation. *Cogn. Process.* 8, 93–102. doi: 10.1007/s10339-007-0167-x

Schwartz, S. (2012). "Dreams, emotions and brain plasticity," in *Behind and Beyond the Brain* (Lisboa: Foundation Bial), 51–63.

Smith, C. (1995). Sleep states and memory processes. *Behav. Brain Res.* 69, 137–145. doi: 10.1016/0166-4328(95)00024-N

Smith, M. R., Antrobus, J. S., Gordon, E., Tucker, M. A., Hirota, Y., Wamsley, E. J., et al. (2004). Motivation and affect in REM sleep and the mentation reporting process. *Conscious. Cogn.* 13, 501–511. doi: 10.1016/j.concog.2004.03.002

Snyder, F. (1970). "The phenomenology of dreaming," in *The Psychodynamic Implications of the Physiological Studies on Dreams*, eds L. Madow and L. D. Snow (Charles C. Thomas), 124–151.

Solms, M. (1997). *The Neuropsychology of Dreams: A Clinico-Anatomical Study*. Mahwah, NJ: L. Erlbaum.

Solms, M., and Turnbull, O. (2002). *The Brain and the Inner World: An Introduction to the Neuroscience of Subjective Experience*. New York, NY: Other Press.

Spencer, W. D. (2012). Home ranges and the value of spatial information. *J. Mammal.* 93, 929–947. doi: 10.1644/12-MAMM-S-061.1

Sprenger, A., Lappe-Osthege, M., Talamo, S., Gais, S., Kimmig, H., and Helmchen, C. (2010). Eye movements during REM sleep and imagination of visual scenes. *Neuroreport* 21, 45–49. doi: 10.1097/WNR.0b013e32833370b2

Stamps, J. A., and Krishnan, V. (1999). A learning-based model of territory establishment. *Q. Rev. Biol.* 74, 291–318. doi: 10.1086/393163

Sterpenich, V., Albouy, G., Boly, M., Vandewalle, G., Darsaud, A., Balteau, E., et al. (2007). Sleep-related hippocampo-cortical interplay during emotional memory recollection. *PLoS Biol.* 5:e282. doi: 10.1371/journal.pbio.0050282

Sterpenich, V., Albouy, G., Darsaud, A., Schmidt, C., Vandewalle, G., Dang Vu, T. T., et al. (2009). Sleep promotes the neural reorganization of remote emotional memory. *J. Neurosci.* 29, 5143–5152. doi: 10.1523/JNEUROSCI.0561-09.2009

Sterpenich, V., Schmidt, C., Albouy, G., Matarazzo, L., Vanhaudenhuyse, A., Boveroux, P., et al. (2014). Memory reactivation during rapid eye movement sleep promotes its generalization and integration in cortical stores. *Sleep* 37, 1061. doi: 10.5665/sleep.3762

Stickgold, R. (2002). EMDR: A putative neurobiological mechanism of action. *J. Clin. Psychol.* 58, 61–75. doi: 10.1002/jclp.1129

Stickgold, R., Pace-Schott, E., and Hobson, J. A. (1994). A new paradigm for dream research: mentation reports following spontaneous arousal from REM and NREM sleep recorded in a home setting. *Conscious. Cogn.* 3, 16–29. doi: 10.1006/ccog.1994.1002

Stickgold, R., Scott, L., Rittenhouse, C., and Hobson, J. A. (1999). Sleep-induced changes in associative memory. *J. Cogn. Neurosci.* 11, 182–193. doi: 10.1162/089892999563319

Szpunar, K. K., Watson, J. M., and McDermott, K. B. (2007). Neural substrates of envisioning the future. *Proc. Nat. Acad. Sci. U.S.A.* 104, 642–647. doi: 10.1073/pnas.0610082104

Tolman, E. C. (1948). Cognitive maps in rats and men. *Psychol. Rev.* 55, 189. doi: 10.1037/h0061626

Tort, A. B., Komorowski, R. W., Manns, J. R., Kopell, N. J., and Eichenbaum, H. (2009). Theta–gamma coupling increases during the learning of item–context associations. *Proc. Nat. Acad. Sci.* 106, 20942–20947. doi: 10.1073/pnas.0911331106

Tsairi, H., and Bouskila, A. (2004). Ambush site selection of a desert snake (*Echis coloratus*) at an oasis. *Herpetologica* 60, 13–23. doi: 10.1655/20-47

Tulving, E. (1983). *Elements of Episodic Memory*. Oxford: Oxford University Press.

Turvey, M. T. (1992). Affordances and prospective control: an outline of the ontology. *Ecol. Psychol.* 4, 173–187. doi: 10.1207/s15326969eco0403_3

Valeix, M., Chamaillé-Jammes, S., and Fritz, H. (2007). Interference competition and temporal niche shifts: elephants and herbivore communities at waterholes. *Oecologia* 153, 739–748. doi: 10.1007/s00442-007-0764-5

Valeix, M., Fritz, H., Loveridge, A. J., Davidson, Z., Hunt, J. E., Murindagomo, F., et al. (2009). Does the risk of encountering lions influence African herbivore behaviour at waterholes? *Behav. Ecol. Sociobiol.* 63, 1483–1494. doi: 10.1007/s00265-009-0760-3

Valeix, M., Loveridge, A. J., Davidson, Z., Madzikanda, H., Fritz, H., and Macdonald, D. W. (2010). How key habitat features influence large terrestrial carnivore movements: waterholes and African lions in a semi-arid savanna of north-western Zimbabwe. *Landsc. Ecol.* 25, 337–351. doi: 10.1007/s10980-009-9425-x

van Rijn, E., Eichenlaub, J. B., Lewis, P. A., Walker, M. P., Gaskell, M. G., et al. (2015). The dream-lag effect: Selective processing of personally significant events during Rapid Eye Movement sleep, but not during Slow Wave Sleep. *Neurobiol. Learn. Mem.* 122, 98–109. doi: 10.1016/j.nlm.2015.01.009

Varela, F. J., Thompson, E., and Rosch, E. (1991). *The Embodied Mind: Cognitive Science and Human Experience*. Cambridge, MA: MIT Press.

Vertes, R. P. (2005). Hippocampal theta rhythm: a tag for short-term memory. *Hippocampus* 15, 923–935. doi: 10.1002/hipo.20118

Wagner, U., Gais, S., and Born, J. (2001). Emotional memory formation is enhanced across sleep intervals with high amounts of rapid eye movement sleep. *Learn. Mem.* 8, 112–119. doi: 10.1101/lm.36801

Wagner, U., Hallschmid, M., Verleger, R., and Born, J. (2003). Signs of REM sleep dependent enhancement of implicit face memory: a repetition priming study. *Biol. Psychol.* 62, 197–210. doi: 10.1016/S0301-0511(02)00125-4

Walker, M. P. (2008). Cognitive consequences of sleep and sleep loss. *Sleep Med.* 9, S29–S34. doi: 10.1016/S1389-9457(08)70014-5

Walker, M. P., Liston, C., Hobson, J. A., and Stickgold, R. (2002). Cognitive flexibility across the sleep–wake cycle: REM-sleep enhancement of anagram problem solving. *Cogn. Brain Res.* 14, 317–324. doi: 10.1016/S0926-6410(02)00134-9

Walker, M. P., and Stickgold, R. (2006). Sleep, memory, and plasticity. *Annu. Rev. Psychol.* 57, 139–166. doi: 10.1146/annurev.psych.56.091103.070307

Walker, M. P., and Stickgold, R. (2010). Overnight alchemy: sleep-dependent memory evolution. *Nat. Rev. Neurosci.* 11, 218–218. doi: 10.1038/nrn2762-c1

Wallace, D. G., Hamilton, D. A., and Whishaw, I. Q. (2006). Movement characteristics support a role for dead reckoning in organizing exploratory behavior. *Anim. Cogn.* 9, 219–228. doi: 10.1007/s10071-006-0023-x

Wallas, G. (1926). *The Art of Thought*. Kent: Solis Press.

Wang, A. Y., and Thomas, M. H. (2000). Looking for long-term mnemonic effects on serial recall: The legacy of Simonides. *Am. J. Psychol.* 113, 331. doi: 10.2307/1423362

Wilding, J., and Valentine, E. (1997). *Superior Memory: Essays in Cognitive Psychology*. Hove: Psychology Press/Erlbaum.

Wilhelm, I., Diekelmann, S., Molzow, I., Ayoub, A., Mölle, M., and Born, J. (2011). Sleep selectively enhances memory expected to be of future relevance. *J. Neurosci.* 31, 1563–1569. doi: 10.1523/JNEUROSCI.3575-10.2011

Willems, E. P., and Hill, R. A. (2009). Predator-specific landscapes of fear and resource distribution: effects on spatial range use. *Ecology* 90, 546–555. doi: 10.1890/08-0765.1

Wood, E. R., Dudchenko, P. A., and Eichenbaum, H. (1999). The global record of memory in hippocampal neuronal activity. *Nature* 397, 613–616. doi: 10.1038/17605

Worthen, J. B., and Hunt, R. R. (2011). *Mnemonology: Mnemonics for the 21st Century*. New York, NY: Psychology Press.

Yoo, S.-S., Gujar, N., Hu, P., Jolesz, F. A., and Walker, M. P. (2007). The human emotional brain without sleep–a prefrontal amygdala disconnect. *Curr. Biol.* 17, R877–R878. doi: 10.1016/j.cub.2007.08.007

Yordanova, J., Kolev, V., and Kirov, R. (2012). Brain oscillations and predictive processing. *Front. Psychol.* 3:416. doi: 10.3389/fpsyg.2012.00416

Yordanova, J., Kolev, V., Verleger, R., Bataghva, Z., Born, J., and Wagner, U. (2008). Shifting from implicit to explicit knowledge: different roles of early-and late-night sleep. *Learn. Mem.* 15, 508–515. doi: 10.1101/lm.897908

Yu, C. K.-C. (2008). Typical dreams experienced by Chinese people. *Dreaming* 18:1. doi: 10.1037/1053-0797.18.1.1

Yu, C. K.-C. (2011). The constancy of typical dreams. *Asia Pac. J. Couns. Psychother.* 2, 51–70. doi: 10.1080/21507686.2010.519037

Yuille, A., and Kersten, D. (2006). Vision as Bayesian inference: analysis by synthesis? *Trends Cogn. Sci.* 10, 301–308. doi: 10.1016/j.tics.2006.05.002

Zeithamova, D., Dominick, A. L., and Preston, A. R. (2012). Hippocampal and ventral medial prefrontal activation during retrieval-mediated learning supports novel inference. *Neuron* 75, 168–179. doi: 10.1016/j.neuron.2012.05.010

Zeithamova, D., and Preston, A. R. (2010). Flexible memories: differential roles for medial temporal lobe and prefrontal cortex in cross-episode binding. *J. Neurosci.* 30, 14676–14684. doi: 10.1523/JNEUROSCI.3250-10.2010

Conflict of Interest Statement: The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

PERSPECTIVE
published: 06 July 2015
doi: 10.3389/fpsyg.2015.00928

State- or trait-like individual differences in dream recall: preliminary findings from a within-subjects study of multiple nap REM sleep awakenings

Serena Scarpelli*[1]*, Cristina Marzano*[1]*, Aurora D'Atri*[1]*, Maurizio Gorgoni*[1]*,
Michele Ferrara*[2] *and Luigi De Gennaro*[1]*

[1] Department of Psychology, University of Rome "Sapienza", Rome, Italy, [2] Department of Life, Health and Environmental Sciences, University of L'Aquila, L'Aquila, Italy

OPEN ACCESS

Edited by:
Roumen Kirov,
Institute of Neurobiology – Bulgarian Academy of Sciences, Bulgaria

Reviewed by:
Armando D'Agostino,
Università degli Studi di Milano, Italy
Ursula Voss,
Rheinische Friedrich-Wilhelms Universität Bonn, Germany

****Correspondence:***
Luigi De Gennaro,
Department of Psychology, University of Rome "Sapienza", Via dei Marsi, 78, 00185 Roma, Italy
luigi.degennaro@uniroma1.it

Specialty section:
This article was submitted to Cognitive Science, a section of the journal Frontiers in Psychology

Received: *04 May 2015*
Accepted: *22 June 2015*
Published: *06 July 2015*

Citation:
Scarpelli S, Marzano C, D'Atri A, Gorgoni M, Ferrara M and De Gennaro L (2015) State- or trait-like individual differences in dream recall: preliminary findings from a within-subjects study of multiple nap REM sleep awakenings.
Front. Psychol. 6:928.
doi: 10.3389/fpsyg.2015.00928

We examined the question whether the role of EEG oscillations in predicting presence/absence of dream recall (DR) is explained by "state-" or "trait-like" factors. Six healthy subjects were awakened from REM sleep in a within-subjects design with multiple naps, until a recall and a non-recall condition were obtained. Naps were scheduled in the early afternoon and were separated by 1 week. Topographical EEG data of the 5-min of REM sleep preceding each awakening were analyzed by power spectral analysis [Fast Fourier Transform (FFT)] and by a method to detect oscillatory activity [Better OSCillations (BOSC)]. Both analyses show that REC is associated to higher frontal theta activity (5–7 Hz) and theta oscillations (6.06 Hz) compared to NREC condition, but only the second comparison reached significance. Our pilot study provides support to the notion that sleep and wakefulness share similar EEG correlates of encoding in episodic memories, and supports the "state-like hypothesis": DR may depend on the physiological state related to the sleep stage from which the subject is awakened rather than on a stable individual EEG pattern.

Keywords: dreaming, theta oscillations, REM sleep, frontal cortex, episodic memory

Introduction

Recent neuroimaging studies on dreaming underlined the continuity between mechanisms involved in mental activity across sleep and wakefulness (De Gennaro et al., 2011; Eichenlaub et al., 2014a,b). Some support to this general notion comes from a recent EEG study (Marzano et al., 2011). Although the results of EEG studies are heterogeneous (Nir and Tononi, 2010), they show a link between the alpha band (8–12 Hz) and the retrieval of sleep mentation from non-rapid eye movement (NREM) sleep (Takeuchi et al., 2003; Esposito et al., 2004; Chellappa et al., 2009, 2011; Marzano et al., 2011; Ruby et al., 2013; Eichenlaub et al., 2014a).

Moreover, Marzano et al. (2011) found an increase of frontal theta activity (5–7 Hz) prior to dream recall (DR) from REM sleep. The theta activity over the frontal areas seems particularly involved in the retrieval of episodic mnestic traces also in wakefulness (Hsieh and Ranganath, 2014; Scarpelli et al., 2015). For instance, Klimesch (1999) reported that the increase in theta power anticipates a subsequent successful performance in episodic memory encoding.

Theta enhancement was also observed during retrieval of previously learnt information (Klimesch et al., 2000, 2006). Furthermore, some studies revealed that high pre-stimulus theta activity is associated to subsequent successful recall (REC; Addante et al., 2011; Gruber et al., 2013), supporting the view that memory performance depends on state-related physiological factors *before* the beginning of the task (Addante et al., 2011).

Hence, specific EEG topography and frequencies during sleep have been associated to presence/absence of DR, and they are also predictive of DR frequency. These EEG patterns are also related to episodic memory during wakefulness (Marzano et al., 2011). However, these findings did not respond to the question whether the EEG activity associated to DR was interpretable in terms of "state-like" or "trait-like" differences. In other terms, they fail to address the issue whether the EEG patterns predictive of DR depend on peculiar EEG oscillations of the specific physiological *scenario* from which subject is awakened (i.e., state-like) or whether these patterns represent a stable individual feature of the subjects (i.e., trait-like). Excluding a specific protocol (i.e., a 40-h multiple nap protocol), which introduces a chronobiological confound (Chellappa et al., 2009, 2011), *intraindividual* EEG differences in DR have been investigated only by *between-subjects* designs (Takeuchi et al., 2003; Esposito et al., 2004; Marzano et al., 2011; for a review see Scarpelli et al., 2015).

Another issue is that the standard method adopted to analyze EEG activity related to human cognition is the Fast Fourier Transform (FFT) analysis (van Vugt et al., 2007). This technique is mainly designed for stationary and regular signals (Mallat, 1998; Zhan et al., 2006; van Vugt et al., 2007). In other words, FFT analysis has a limited time-frequency resolution (Bruns, 2004). However, brain signals are seldom stationary (Whitten et al., 2011) and the EEG patterns correlated to dream contents retrieval are more likely characterized by oscillatory (non-stationary) activity. In this respect, Caplan et al. (2001) implemented an oscillatory detection method [Better OSCillation (BOSC)]. This well-established method, which takes into account the functional form of a "background" signal, is able to discriminate the segments of the recording that deviate significantly from the spectral characteristics of the background (Marzano et al., 2011; Whitten et al., 2011). The BOSC has been successfully applied to identify theta oscillations in the human neocortex during both sleep and wakefulness (Caplan et al., 2001, 2003; Caplan and Glaholt, 2007; Marzano et al., 2011, 2013), and delta oscillations in the hippocampal formation by stereo-EEG recordings (Moroni et al., 2012), associated with encoding and consolidation of declarative memory.

In this perspective article, we present a pilot study aimed to disentangle the "state-/trait-like" issue by investigating the role of EEG *oscillations* during REM sleep in DR by a *within-subjects* design.

Methods

Subjects

Six healthy right-handed subjects [5 females (F), 1 male (M); mean age = 21.25 ± 2.75] participated as paid volunteers. They were university students who were selected from the database of our laboratory. Participants were required to maintain regular sleep habits during the week preceding the experimental session: compliance was verified by sleep diaries, which each subjects had to fill out every morning within, 15-min after the awakening. The study was approved by the Institutional Ethics Committee of the Department of Psychology of University of Rome Sapienza and was conducted in accordance with the Declaration of Helsinki.

Procedure

Each subject participated at least in two naps during the early afternoon, until we collected both a DR (REC) and a Non-Recall (NREC) condition. Actually, the mean number of naps was 3.5 (SD = 1.0; min = 2, max = 5). Each experimental session was separated by 1 week.

The polysomnographic (PSG) recordings (28 EEG channels, EMG, and EOG channels) were acquired in a sound-proof, temperature-controlled room. A Brain Amp system was used for PSG recordings. EEG signals were analogically high-pass filtered with a time constant of 0.3 s and low-pass filtered at 30 Hz. The 28 unipolar EEG derivations of the international 10–20 system (C3, C4, Cp1, Cp2, Cp5, Cp6, Cz, F3, F4, F7, F8, Fc1, Fc2, Fc5, Fc6, Fp1, Fp2, Fz, O1, O2, Oz, P3, P4, P7, P8, Pz, T7, T8) were recorded from scalp electrodes with averaged mastoid reference. The submental EMG was recorded with a time constant of 0.03 s. Bipolar horizontal eye movements were recorded with a time constant of 1 s. The bipolar horizontal electrooculogram (EOG) was recorded from electrodes placed about 1 cm from the medial and lateral canthi of the dominant eye. Impedance of these electrodes was kept below 5 kΩ.

Subjects were awakened from first REM sleep episode without stage shifts during the last 5-min of sleep. Hence, analyses have been carried out on 5-min intervals of uninterrupted and artifact-free REM sleep. Assignment to the condition and stage scoring was confirmed off-line.

After awakening, subjects filled out a sleep and dream diary. Preliminarily, each subject was instructed to consider any distinct mental activity occurring during sleep as a dream.

Analyses

We have processed only the data obtained from subjects who have reported both REC and NREC conditions upon awakening from REM sleep.

Data Processing and Statistics

The polygraphic signals of the 5-min of REM sleep preceding the awakening were analog-to-digital converted on-line with sampling rate of 250 Hz. Artifacts were rejected off-line on an 8 s basis by visual inspection. Only tonic REM sleep periods were included in the analysis, to avoid artifacts from rapid eye movements on EEG power.

Power EEG, based on FFT data, were divided in the canonical bands: delta (0.50–4.75 Hz), theta (5.00–7.75 Hz), alpha (8.00–11.75 Hz), sigma (12.00–15.75 Hz), and beta (16.00–24.75 Hz).

Statistical comparisons (paired *t*-tests) were computed on log-transformed values between REC and NREC conditions. The analyses were performed separately for each frequency band and each cortical electrode. EEG power maps were computed for statistical comparisons between REC and NREC conditions from REM sleep. To adjust the α-value for multiple comparisons, a Bonferroni correction was applied (Sankoh et al., 1997; Perneger, 1998). Considering the mean correlation between the dependent variables in REM sleep ($r = 0.66$) and the number of statistical comparisons (140 tests), α level was adjusted to 0.009 ($t \geq 4.12$).

According to the specific aims of our study, we applied the BOSC analysis to the EEG signals in order to identify oscillatory activity (Caplan et al., 2001; Whitten et al., 2011). The analysis was performed separately for each frequency of interest (within the 0.50–24 Hz range) and each electrode. For a given episode, we defined an epoch longer than a duration threshold, DT (set to three cycles in our analysis) during which wavelet power at each frequency exceeded a power threshold (PT). This PT was chosen as follows in the 5 min segments: (1) The EEG was wavelet transformed (Morlet wavelet, window of six cycles) at 47 logarithmically spaced frequencies in the range 0.50–25 Hz. The average of the log-transform of these wavelet values yielded the wavelet power spectrum. (2) The background noise spectrum assumed the form Power(f) = Af–a. The estimate of this background has been obtained by fitting the observed spectrum (at each electrode) with a linear regression in log–log units. The background at f* has been estimated on the mean of its corresponding $\chi^2(2)$ probability distribution function. The PT was set to the 95th percentile of the theoretical probability distribution. The proportion of time in which significant oscillations were detected within a 5 min sleep period was termed P_{episode} (Caplan et al., 2001, 2003; Caplan and Glaholt, 2007; van Vugt et al., 2007).

The BOSC analysis was performed on the EEG signals recorded from each scalp location during the last 5-min of REM sleep before awakening and was averaged across subjects. Then, P_{episode} values in correspondence of the theta peak frequency were compared between REC and NREC conditions by paired *t*-tests. Bonferroni correction (Sankoh et al., 1997; Perneger, 1998) was applied ($r = 0.69$; 28 tests) and α level was adjusted to 0.018 ($t \geq 3.46$).

Results

EEG Power Spectra

The statistical maps (**Figure 1**) show a predominance of theta activity over the right-frontal regions (Fc2) in the REC compared to NREC condition ($t = 2.47$, $p = 0.065$). Furthermore, maps show a lower theta power in centro-occipital regions (Oz, $t = -2.69$, $p = 0.043$; O2, $t = -2.82$, $p = 0.037$) and a lower temporal sigma activity in REC vs. NREC condition (T8, $t = -2.64$, $p = 0.046$). However, these comparisons are not statistically significant after the Bonferroni correction.

Detection of Oscillatory Activity

As depicted by **Figure 2A**, which details EEG oscillations averaged across all the derivations, the EEG recordings of the pre-awakening segment shows three peaks: alpha band peaking at 9.85 Hz, theta band peaking at 6.06 Hz and delta band peaking at 2.83 Hz.

Given the association between frontal theta increase and DR obtained by FFT (Marzano et al., 2011), we calculated the topographic distribution of the peak frequency of the oscillatory theta activity (6.06 Hz; **Figure 2B**). In other words, we detail the topographic distribution of the mean proportion of time in which oscillations were detected (P_{episode}) in correspondence of the peak frequency of interest (6.06 Hz) in the 5-min intervals preceding awakening, associated to REC and NREC conditions. The statistical map (**Figure 2B**) points to a robust difference between REC and NREC conditions, significant in correspondence of Fc1 ($t = 3.60$, $p = 0.015$). Although not significant after the correction, the differences in theta oscillations are also remarkable at Fz ($t = 2.81$, $p = 0.037$) and F3 ($t = 2.78$, $p = 0.039$), suggesting that the increase of theta oscillations in the REC condition spreads to most of the frontal area.

Discussion

Our preliminary data are substantially coherent with previous findings, supporting the idea that higher frontal theta oscillations (and theta activity) are associated to a successful DR (Marzano et al., 2011).

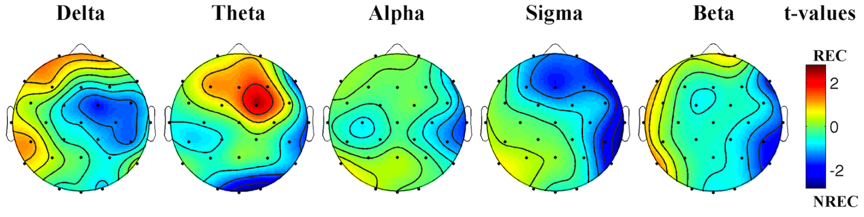


FIGURE 1 | Statistical maps reporting topographic EEG power differences, assessed by paired *t*-tests, between the REC and NREC conditions. Values are expressed in terms of *t*-values: positive t values (warmer colors) indicate a prevalence of the REC over the NREC conditions and vice versa. The maps are based on 28 derivations (electrode positions indicated by black dots). Values are color coded and plotted at the corresponding position on the planar projection of the hemispheric scalp model. Values between electrodes were interpolated (biharmonic spline interpolation).

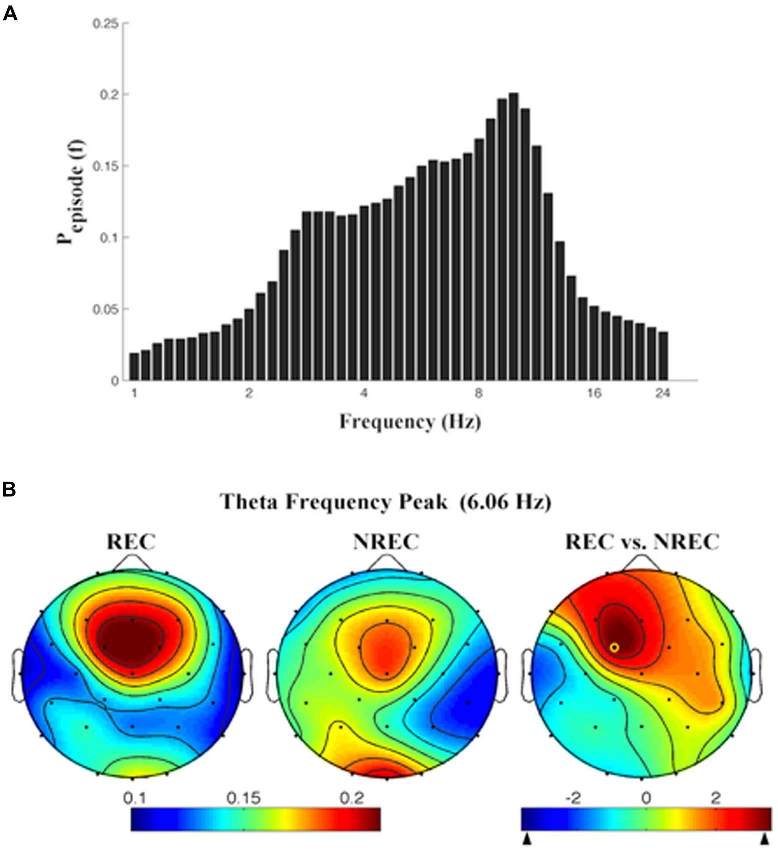


FIGURE 2 | (A) Mean proportion of time [$P_{episode}$ (*f*)] of EEG activity during last segment (5 min) of REM sleep during which oscillations were detected by the BOSC method at each frequency in the 0.25–25.00 Hz Individual oscillations detected across all frequencies by the BOSC method have been averaged across all subjects, and error bars denote SEM $P_{episodesEsp}$ (*f*). **(B)** Topographic distribution of the frequency peak of theta oscillatory activity. From the left, the first two maps show the topographic distribution of the mean proportion of time in which oscillations were detected ($P_{episode}$) in correspondence of the selected frequency of interest (6.06 Hz) in the 5-min intervals preceding awakening, in REC and NREC conditions respectively. The first map on the right side shows topographic statistical $P_{episode}$ differences (assessed by paired *t*-tests) between REC and NREC conditions. The yellow circle indicates the electrode (Fc1, $t = 3.60$; $p = 0.015$), where the comparison between REC and NREC conditions is significant. The maps are based on 28 derivations (electrode positions indicated by black dots). Values are color-coded and plotted at the corresponding position on the planar projection of the hemispheric scalp model. Values between electrodes were interpolated (biharmonic spline interpolation).

Keeping in mind the relationship between frontal theta activity and memory processes (Hsieh and Ranganath, 2014; Scarpelli et al., 2015), if confirmed on a larger sample, these results may provide further support to the hypothesis that the mechanisms of encoding and retrieval of episodic memories remain the same across wakefulness and sleep (De Gennaro et al., 2011; Marzano et al., 2011). Moreover, our results provide arguments in favor of the "state-like hypothesis," according to which the EEG correlates of DR depend on the physiological background of the sleep state in the segment closer to the time of dream report collection, rather than on stable interindividual EEG pattern characterizing each subject.

Notably, the difference between REC vs. NREC conditions is significant only for the BOSC analysis. In other words, although the topographical differences are substantially coherent across the FFT and BOSC analyses, nevertheless differences are larger when comparing theta oscillations. It is possible that this specific difference may be explained by the relatively small sample size. On the other hand, this finding may also suggest that the predictive relation between EEG and presence/absence of DR mostly depends on the oscillatory theta activity, more than on tonic (background) theta activity. This would strengthen the coherence of the present results with those obtained during wakefulness on the relation between theta oscillations and encoding/consolidation of episodic memory. It is worth noting that theta activity (as calculated by FFT routines) is also an expression of homeostatic processes during sleep (even during REM sleep: Marzano et al., 2010). Accordingly, changes in theta activity may index *both* homeostatic processes during sleep and functional relations with mechanisms of dreaming, and this could explain statistical differences between our different analyses. Clearly, at this stage of the study any other consideration would be (further) speculative. Only a larger sample size and the analysis of NREM awakenings (REC and NREC conditions for each subject) will allow drawing definitive conclusions.

Conclusion and Future Directions

To the best of our knowledge, this is the first investigation carried out with the specific purpose to address the "state- or trait-like" issue in order to reveal the EEG correlates of DR. The nap protocol allowed us to collect several sleep recordings in the same time window aimed to obtain REC and NREC conditions in a within-subjects design, allowing a control for trait-like factors and circadian factors (Nielsen, 2004).

Hence, we have found an EEG pattern that appears different for the two conditions. Namely, our data provide information about the specific EEG activity which predicts *whether* subjects will REC a dream when they wake up from REM sleep. On the one hand, our preliminary results give some further support to the "continuity hypothesis" (Domhoff, 2003; Schredl, 2003, 2009) between neurophysiological mechanisms for the encoding and retrieval of episodic memory in sleep and wakefulness (Marzano et al., 2011). On the other hand, for the specific purpose of the study, our preliminary results suggest that DR is associated to a frontal theta oscillatory activity during the last segment of REM sleep before the awakening, supporting a "state-like hypothesis."

As a further approach to this issue, future investigations should consider protocols with multiple awakenings during the night for each subject, and collect DR/NREC for each REM or NREM sleep cycle, also assessing possible homeostatic and circadian influences on DR.

Future studies should also extend the range of the considered EEG oscillations beyond the beta oscillations, since some studies found a functional coupling between fronto-temporal theta and gamma (25–40 Hz) activity in sleep and in wakefulness related to memory processes (Sederberg et al., 2003; Sauseng et al., 2009; Marshall et al., 2011). A significant increase of theta and gamma oscillations during wake encoding predicts the subsequent REC of episodic memory (Sederberg et al., 2003; Nyhus and Curran, 2010). Furthermore, it was reported that the transcranial direct current stimulation (tDCS) at 5 Hz increases the gamma oscillations during REM sleep (Marshall et al., 2011) and –more directly– that the stimulation on the fronto-temporal area in the gamma band during REM sleep elicits lucid dreams, defined as particular state of consciousness in which the sleeper is aware of his dreaming (Hobson et al., 2014; Voss et al., 2014).

Author Contributions

Substantial contributions to the conception and design of the work: LDG, MF.
Acquisition, analysis of data: SS, ADA, MG, CM.
Interpretation of data: LDG, MF, SS, CM.
Drafting the work and revising it critically for important intellectual content: LDG, MF, SS, ADA, MG, CM.
Final approval of the version to be published: LDG, MF, SS, ADA, MG, CM.
Agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved: LDG, MF, SS, ADA, MG, CM.

Acknowledgment

This work was supported by a grant to LDG from "Ministero della Salute" (Ministry of Health) RF-2009-1528677.

References

Addante, R. J., Watrous, A. J., Yonelinas, A. P., Ekstrom, A. D., and Ranganath, C. (2011). Prestimulus theta activity predicts correct source memory retrieval. *Proc. Natl. Acad. Sci. U.S.A.* 108, 10702–10707. doi: 10.1073/pnas.1014528108

Bruns, A. (2004). Fourier-, Hilbert- and wavelet-based signal analysis: are they really different approaches? *J. Neurosci. Methods* 137, 321–332. doi: 10.1016/j.jneumeth.2004.03.002

Caplan, J. B., and Glaholt, M. G. (2007). The roles of EEG oscillations in learning relational information. *Neuroimage* 38, 604–616. doi: 10.1016/j.neuroimage.2007.07.054

Caplan, J. B., Madsen, J. R., Raghavachari, S., and Kahana, M. J. (2001). Distinct patterns of brain oscillations underlie two basic parameters of human maze learning. *J. Neurophysiol.* 86, 368–380.

Caplan, J. B., Madsen, J. R., Schulze-Bonhage, A., Aschenbrenner-Scheibe, R., Newman, E. L., and Kahana, M. J. (2003). Human theta oscillations related to sensorimotor integration and spatial learning. *J. Neurosci.* 23, 4726–4736.

Chellappa, S. L., Frey, S., Knoblauch, V., and Cajochen, C. (2011). Cortical activation patterns herald successful dream recall after NREM and REM sleep. *Biol. Psychol.* 87, 251–256. doi: 10.1016/j.biopsycho.2011.03.004

Chellappa, S. L., Münch, M., Blatter, K., Knoblauch, V., and Cajochen, C. (2009). Does the circadian modulation modify with age? *Sleep* 32, 1201–1209.

De Gennaro, L., Cipolli, C., Cherubini, A., Assogna, F., Cacciari, C., Marzano, C., et al. (2011). Amygdala and hippocampus volumetry and diffusivity in relation to dreaming. *Hum. Brain Mapp.* 32, 1458–1470. doi: 10.1002/hbm.21120

Domhoff, G. W. (2003). *The Scientific Study of Dreams: Neural Networks, Cognitive, Development, and Content Analysis*. Washington, DC: America Psychological Association Press.

Eichenlaub, J. B., Bertrand, O., Morlet, D., and Ruby, P. (2014a). Brain reactivity differentiates subjects with high and low dream recall frequencies during both sleep and wakefulness. *Cereb. Cortex* 24, 1206–1215. doi: 10.1093/cercor/bhs388

Eichenlaub, J. B., Nicolas, A., Daltrozzo, J., Redouté, J., Costes, N., and Ruby, P. (2014b). Resting brain activity varies with dream recall frequency between subjects. *Neuropsychopharmacology* 39, 1594–1602. doi: 10.1038/npp.2014.6

Esposito, M. J., Nielsen, T. A., and Paquette, T. (2004). Reduced alpha power associated with the recall of mentation from Stage 2 and Stage REM sleep. *Psychophysiology* 41, 288–297. doi: 10.1111/j.1469-8986.00143.x

Gruber, M., Watrous, A., Ekstrom, A., and Ranganath, C. (2013). Expected reward modulates encoding-related theta activity before an event. *Neuroimage* 64, 68–74. doi: 10.1002/hipo.10114

Hobson, J. A., Hong, C. C.-H., and Friston, K. J. (2014). Virtual reality and consciousness inference in dreaming. *Front. Psychol.* 5:1133. doi: 10.3389/fpsyg.2014.01133

Hsieh, L.-T., and Ranganath, C. (2014). Frontal midline theta oscillations during working memory maintenance and episodic encoding and retrieval. *Neuroimage* 85, 721–729. doi: 10.1016/j.neuroimage.2013.08.003

Klimesch, W. (1999). EEG alpha and theta oscillations reflect cognitive and memory performance: a review and analysis. *Brain Res. Rev.* 29, 169–195. doi: 10.1016/S0165-0173(98)00056-3

Klimesch, W., Doppelmayr, M., Schwaiger, J., Winkler, T., and Gruber, W. (2000). Theta oscillations and the ERP old/new effect: independent phenomena? *Clin. Neurophysiol.* 111, 781–793. doi: 10.1016/S1388-2457(00)00254-6

Klimesch, W., Hanslmayr, S., Sauseng, P., Gruber, W., Brozinsky, C. J., Kroll, N. E. A., et al. (2006). Oscillatory EEG correlates of episodic trace decay. *Cereb. Cortex* 16, 280–290. doi: 10.1093/cercor/bhi107

Mallat, S. (1998). *A Wavelet tour of Signal Processing.* San Diego, CA: Academic Press.

Marshall, L., Kirov, R., Brade, J., Mölle, M., and Born, J. (2011). Transcranial electrical currents to probe EEG brain rhythms and memory consolidation during sleep in humans. *PLoS ONE* 6:e16905. doi: 10.1371/journal.pone.0016905

Marzano, C., Ferrara, M., Curcio, G., and De Gennaro, L. (2010). The effects of sleep deprivation in humans: topographical electroencephalogram changes in non-rapid eye movement (NREM) sleep versus REM sleep. *J. Sleep Res.* 19, 260–268. doi: 10.1111/j.1365-2869.2009.00776.x

Marzano, C., Ferrara, M., Mauro, F., Moroni, F., Gorgoni, M., Tempesta, D., et al. (2011). Recalling and forgetting dreams: theta and alpha oscillations during sleep predict subsequent dream recall. *J. Neurosci.* 31, 6674–6683. doi: 10.1523/JNEUROSCI.0412-11.2011

Marzano, C., Moroni, F., Gorgoni, M., Nobili, L., Ferrara, M., and De Gennaro, L. (2013). How we fall asleep: regional and temporal differences in electroencephalographic synchronization at sleep onset. *Sleep Med.* 14, 1112–1122. doi: 10.1016/j.sleep.2013.05.021

Moroni, F., Nobili, L., De Carli, F., Massimini, M., Francione, S., Marzano, C., et al. (2012). Slow EEG rhythms and inter-hemispheric synchronization across sleep and wakefulness in the human hippocampus. *Neuroimage* 60, 497–504. doi: 10.1016/j.neuroimage.2011.11.093

Nielsen, T. A. (2004). Chronobiological features of dream production. *Sleep Med. Rev.* 8, 403–424. doi: 10.1016/j.smrv.2004.06.005

Nir, Y., and Tononi, G. (2010). Dreaming and the brain: from phenomenology to neurophysiology. *Trends Cogn. Sci.* 14, 88–100. doi: 10.1016/j.tics.2009.12.001

Nyhus, E., and Curran, T. (2010). Functional role of gamma and theta oscillations in episodic memory. *Neurosci. Biobehav. Rev.* 34, 1023–1035. doi: 10.1016/j.neubiorev.2009.12.014

Perneger, T. V. (1998). What is wrong with Bonferroni adjustments. *Br. Med. J.* 136, 1236–1238. doi: 10.1136/bmj.316.7139.1236

Ruby, P., Blochet, C., Eichenlaub, J. B., Bertrand, O., Morlet, D., and Bidet-Caulet, A. (2013). Alpha reactivity to first names differs in subjects with high and low dream recall frequency. *Front. Psychol.* 4:419. doi: 10.3389/fpsyg.2013.00419

Sankoh, A. J., Huque, M. F., and Dubey, S. D. (1997). Some comments on frequently used multiple endpoint adjustments methods in clinical trials. *Stat. Med.* 16, 2529–2542. doi: 10.1002/(SICI)1097-0258(19971130)16:22<2529::AID-SIM692>3.0.CO;2-J

Sauseng, P., Klimesch, W., Heise, K. F., Gruber, W. R., Holz, E., Karim, A. A., et al. (2009). Brain oscillatory substrates of visual short-term memory capacity. *Curr. Biol.* 19, 1846–1852. doi: 10.1016/j.cub.2009.08.062

Scarpelli, S., D' Atri, A., Gorgoni, M., Ferrara, M., and De Gennaro, L. (2015). EEG oscillations during sleep and dream recall: state- or trait-like individual differences? *Front. Psychol.* 6:605. doi: 10.3389/fpsyg.2015.00605

Schredl, M. (2003). Continuity between waking and dreaming: a proposal for a mathematical model. *Sleep Hypnosis* 5, 26–40.

Schredl, M. (2009). Dreams in patients with sleep disorders. *Sleep Med. Rev.* 13, 215–221. doi: 10.1016/j.smrv.2008.06.002

Sederberg, P. B., Kahana, M. J., Howard, M. W., Donner, E. J., and Madsen, J. R. (2003). Theta and gamma oscillations during encoding predict subsequent recall. *J. Neurosci.* 23, 10809–10814.

Takeuchi, T., Ogilvie, R. D., Murphy, T. I., and Ferrelli, A. V. (2003). EEG activities during elicited sleep onset REM and NREM periods reflect different mechanisms of dream generation. *Clin. Neurophysiol.* 114, 210–220. doi: 10.1016/S1388-2457(02)00385-1

van Vugt, M. K., Sederberg, P. B., and Kahana, M. J. (2007). Comparison of spectral analysis methods for characterizing brain oscillations. *J. Neurosci. Methods* 162, 49–63. doi: 10.1016/j.jneumeth.2006.12.004

Voss, U., Holzmann, R., Hobson, A., Paulus, W., Koppehele-Gossel, J., Klimke, A., et al. (2014). Induction of self awareness in dreams through frontal low current stimulation of gamma activity. *Nat. Neurosci.* 17, 810–812. doi: 10.1038/nn.3719

Whitten, T. A., Hughes, A. M., Dickson, C. T., and Caplan, J. B. (2011). A better oscillation detection method robustly extracts EEG rhythms across brain state changes: the human alpha rhythm as a test case. *Neuroimage* 54, 860–874. doi: 10.1016/j.neuroimage.2010.08.064

Zhan, Y., Halliday, D., Jiang, P., Liu, X., and Feng, J. (2006). Detecting time-dependent coherence between non-stationary electrophysiological signals–a combined statistical and time–frequency approach. *J. Neurosci. Methods* 156, 322–332. doi: 10.1016/j.jneumeth.2006.02.013

Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers
in Psychology

REVIEW
published: 07 May 2015
doi: 10.3389/fpsyg.2015.00605

EEG oscillations during sleep and dream recall: state- or trait-like individual differences?

Serena Scarpelli [1], Aurora D'Atri [1], Maurizio Gorgoni [1], Michele Ferrara [2] and Luigi De Gennaro [1]*

[1] Department of Psychology, Sapienza University of Rome, Rome, Italy, [2] Department of Life, Health and Environmental Sciences, University of L'Aquila, L'Aquila, Italy

Dreaming represents a peculiar form of cognitive activity during sleep. On the basis of the well-known relationship between sleep and memory, there has been a growing interest in the predictive role of human brain activity during sleep on dream recall. Neuroimaging studies indicate that rapid eye movement (REM) sleep is characterized by limbic activation and prefrontal cortex deactivation. This pattern could explain the presence of emotional contents in dream reports. Furthermore, the morphoanatomical measures of amygdala and hippocampus predict some features of dream contents (bizarreness, vividness, and emotional load). More relevant for a general view of dreaming mechanisms, empirical data from neuropsychological and electroencephalographic (EEG) studies support the hypothesis that there is a sort of continuity between the neurophysiological mechanisms of encoding and retrieval of episodic memories across sleep and wakefulness. A notable overlap between the electrophysiological mechanisms underlying emotional memory formation and some peculiar EEG features of REM sleep has been suggested. In particular, theta (5–8 Hz) EEG oscillations on frontal regions in the pre-awakening sleep are predictive of dream recall, which parallels the predictive relation during wakefulness between theta activity and successful retrieval of episodic memory. Although some observations support an interpretation more in terms of an intraindividual than interindividual mechanism, the existing empirical evidence still precludes from definitely disentangling if this relation is explained by state- or trait-like differences.

Keywords: dream, frontal cortex, theta activity, EEG topography, episodic memory, continuity hypothesis

OPEN ACCESS

Edited by:
Roumen Kirov,
Bulgarian Academy of Sciences,
Bulgaria

Reviewed by:
Armando D'Agostino,
Università degli Studi di Milano, Italy
Vincenzo Muto,
Cyclotron Research Centre Université
de Liège, Belgium

***Correspondence:**
Luigi De Gennaro,
Department of Psychology, Sapienza
University of Rome, Via dei Marsi 78,
00185 Roma, Italy
luigi.degennaro@uniroma1.it

Specialty section:
This article was submitted to
Cognitive Science,
a section of the journal
Frontiers in Psychology

Received: *04 March 2015*
Accepted: *23 April 2015*
Published: *07 May 2015*

Citation:
Scarpelli S, D'Atri A, Gorgoni M,
Ferrara M and De Gennaro L (2015)
EEG oscillations during sleep and
dream recall: state- or trait-like
individual differences?
Front. Psychol. 6:605.
doi: 10.3389/fpsyg.2015.00605

Introduction

Over the centuries, dreaming has been studied from multiple points of view, but only recently it has become a neuroscientific object of study. A crucial step for the development of the scientific study of dreams is represented by the discovery of rapid eye movement (REM) sleep stage (Aserinsky and Kleitman, 1953; Dement and Kleitman, 1957a,b). Early results showed that in 80% of the awakenings from REM sleep the subjects reported at least one dream (Dement and Kleitman, 1957a,b). This finding gave rise to the well-known REM = dreaming equation, which dictated empirical dream research for years. The assumption that dreaming is just an epiphenomenon of REM sleep was refuted by Foulkes (1962). He showed that people report dream mentation also when awakened from non-REM (NREM) sleep. Furthermore, subjects were awakened just before the first REM period, pointing to a dream recall also during a sleep period without REM (Foulkes, 1962).

Neuropsychological evidence confirmed that REM sleep and dream recall are modulated by two different brain mechanisms. Patients affected by brainstem lesions in the regions related to REM sleep generation still preserved their dream recall (Solms, 1997, 2000). Conversely, dream recall totally disappeared in patients with focal forebrain lesions and no impairment of REM sleep (Solms, 2000). This double dissociation between REM and dreaming allows us to state that dream recall is possible both after REM and NREM sleep.

Although the dichotomy REM = dreaming/NREM = non-dreaming is outdated, the differentiation between the two types of dream reports generated a "new dichotomy" between REM and NREM dream contents, that still influences the dream research. Mental activity from REM sleep is commonly defined "dream-like," and it is characterized by emotional load, bizarreness, and vividness (Foulkes and Rechtschaffen, 1964; Foulkes, 1967; Antrobus, 1983; Foulkes and Schmidt, 1983; Waterman et al., 1993; Stickgold et al., 1994; Casagrande et al., 1996). Differently, dream report from NREM sleep is typically "thought-like" (Foulkes, 1967); in this case, the mental activity is less emotionally intense and the contents are closer to reality and more fragmented than dream-like reports (Rechtschaffen et al., 1963; Foulkes, 1967). It should be noted that also this "new dichotomy" has been questioned. Indeed, a significant portion of dreams reported from NREM stages shows several features peculiar of "dream-like" mentation (Monroe et al., 1965; Zimmerman, 1970; Solms, 2000). Furthermore, it has been observed that the control for word count makes relatively similar REM and NREM reports (Antrobus, 1983; Foulkes and Schmidt, 1983; Cavallero et al., 1992).

As a result, dream research was focused on the physiological state underlying dreaming, both in REM and NREM sleep. Many studies have been performed by awakenings from specific sleep stages, to explore the differences among the neurobiological (electroencephalographic, EEG) correlates of dreaming. This line of research has stimulated three different models in a bid to explain the mechanisms that generate dreaming. The first model assumed that there is "one-generator" to produce sleep mentation in all sleep stages (Foulkes, 1985). This model posits that the different qualitative features between REM and NREM sleep mentation depend on memory activation, organization of mnestic material in a congruent narrative structure and conscious interpretation. The cortical synchronization during NREM sleep (less cerebral activation) does not allow a complex processing and consolidation of dream contents (Nielsen, 2000). This view is consistent with some studies showing that the differences between REM and NREM dreams only concern quantitative features (Antrobus, 1983; Foulkes and Schmidt, 1983; Cavallero et al., 1992). Furthermore, some studies reported that "dream-like" sleep mentation is detected also closer to sleep onset and to awakening, in correspondence of higher cortical activity (Foulkes, 1962; Foulkes and Vogel, 1965).

Conversely, Hobson and McCarley (1977) supported a "two-generator" model for REM and NREM sleep mentation. According to this perspective, dream contents should be reflected by the peculiar physiological features of the sleep *scenario*. Hence, this could explain the different features of REM and NREM dream reports (Hobson et al., 2000). In an attempt to integrate these two models, Nielsen (2000) proposed a "covert-REM" model. He defined "covert-REM" any NREM sleep episode including some distinctive REM sleep processes (i.e., muscle atonia, rapid eyes movements), which cannot be scored as REM sleep according to the standard criteria. For instance, these episodes may occur during wake-sleep transitions (i.e., sleep onset) or when REM sleep episode skips the first sleep cycle; moreover, "covert-REM" could appear in NREM sleep in proximity (within 15 min) of the subsequent REM sleep episode (Nielsen, 2000). This view could be considered as an extension of the two-generator model, because it supports the hypothesis that dreaming is possible just during a particular NREM sleep stage that embodies some characteristics peculiar of REM sleep (Nielsen, 2000).

It should be emphasized that the empirical studies in support of these models are characterized by a basic limitation, that is the assumption that the dream content is generated in the same stage upon which subject has been awakened. The issue of dream *generation* has affected the physiological approach to dream study for a long time. For instance, neuroimaging investigations (Nofzinger et al., 1997; Maquet et al., 2005) are based on this methodological bias, still considering dreaming intrinsically related to REM sleep and not providing a systematic evaluation of the relations between sleep mentation and cerebral activation patterns before awakenings from different sleep stages (De Gennaro et al., 2012).

More recently, some empirical findings have revitalized the neurobiological approach to dream recall by investigating the association between the electrophysiological pattern in the segment of sleep closer to final awakenings and presence/absence of dream reports, rather than focusing on an hypothetical time of dream generation (Corsi-Cabrera et al., 2003; Takeuchi et al., 2003; Esposito et al., 2004; Chellappa et al., 2009, 2011; Marzano et al., 2011). Quantitative EEG analysis aims to establish correlations between some dream-cognitive features and the brain states prior to awakening. Within some contrasting results, the most consistent finding points to a continuity between the electrophysiological brain mechanisms involved in the encoding of episodic memory across wakefulness and sleep state (Takeuchi et al., 2003; Esposito et al., 2004; Chellappa et al., 2011; Marzano et al., 2011). In particular, the EEG oscillations predictive of subsequent successful memory performance in wakefulness resemble the EEG frequencies and topography detected before successful dream recall, both from REM and NREM sleep (Takeuchi et al., 2003; Esposito et al., 2004; Chellappa et al., 2011; Marzano et al., 2011).

This review focuses on the EEG patterns related to dream recall, with specific reference to recent empirical evidence about the relationship between theta oscillations and episodic memory. The ultimate purpose is to discuss the issue of whether the predictive relationship between EEG oscillations and dream recall can be interpreted in terms of "state- or trait-like" differences. Namely, the neurobiological correlates of a successful recall may depend on the physiological *scenario* related to the specific sleep stage of awakening ("state-like" factors), or they could be linked to interindividual differences that steadily characterize recallers and non-recallers ("trait-like" factors).

Theta Brain Oscillations Involved in Episodic Memory During Wakefulness

Several studies have reported that memory processing is modulated by specific brain oscillations (Klimesch et al., 1996; Başar et al., 1999; Klimesch, 1999). Recent evidence indicates that EEG activity could predict the subsequent cognitive performance (Paller and Wagner, 2002; Nyhus and Curran, 2010; Addante et al., 2011). In particular, theta rhythm, traditionally defined in the 4–8 Hz range (Niedermeyer and Lopes da Silva, 1993), seems to correlate consistently with episodic memory (Klimesch et al., 1996; Klimesch, 1999), described as the ability to remember past experiences and autobiographical events (Tulving, 2002).

Theta rhythm may be considered as the local field potential (LFP) that represents an electrophysiological marker of hippocampal activity (Rutishauser et al., 2010), both during awake behavior and REM sleep (Klimesch, 1996; Cantero et al., 2003). Theta activity modulates neuronal changes in hippocampal formation and in neocortical structures (Mitchell et al., 2008). In this regard, many researchers have tried to explain the relationship between hippocampal and cortical theta, although the exact mechanisms involved in this interaction are still uncertain (Klimesch, 1996; Lega et al., 2012). Moreover, field theta oscillations are not always coherent with hippocampal theta (Kahana et al., 1999; Raghavachari et al., 2001). Some authors have suggested that cortical theta may be induced via the extensive projections from the hippocampus to the neocortex, described as hippocampo-cortical feedback loops (Miller, 1991; Klimesch, 1996).

In humans, studies on hippocampal theta have been performed by intracranial electrodes (intracranial-EEG, iEEG) in neurosurgical patients while engaged in cognitive tasks, or were focused on cortical theta by scalp recordings [EEG or magnetoencephalography (MEG); Nyhus and Curran, 2010]. Scalp EEG recordings in humans have shown that theta power increases during memory tasks (Hsieh and Ranganath, 2014). Specifically, the role of theta activity both in encoding and retrieval of episodic information has recently received considerable attention (Klimesch et al., 1997, 2001; Klimesch, 1999; Molle et al., 2002; Guderian and Düzel, 2005; White et al., 2013). Klimesch et al. (1996), using an event related synchronization/desynchronization (ERS/ERD) approach, investigated differences in EEG power between the encoding phase of information that should be correctly remembered and not remembered later. During the encoding, subjects did not know that they would be subsequently retested. The authors found that theta activity increases especially during encoding of items subsequently recalled. Further results from the same group confirmed that changes in theta power were indicative of good or bad performance in retrieval memory (Klimesch et al., 1997; Doppelmayr et al., 1998; Klimesch, 1999). Later studies have demonstrated that theta activity increases also during retrieval of previously studied information (Klimesch et al., 2000, 2006). These works have emphasized that theta enhancement is larger during recognition than encoding phase.

Similarly, Molle et al. (2002) found that an efficient recognition of words and faces was correlated with theta synchronization (and alpha desynchronization) as compared to bad performance.

More interestingly, some studies have observed that also theta oscillations prior to the effective stimulus presentation are related to an efficient episodic encoding or retrieval (Guderian et al., 2009; Addante et al., 2011; Gruber et al., 2013). Guderian et al. (2009) reported that high pre-stimulus theta oscillations were related to a successful recall. Similarly, Addante et al. (2011) found a frontal theta enhancement during pre-stimulus phase associated to a subsequent successful retrieval. In other words, these results support the view that memory performance depends on state-related physiological factors *before* the beginning of the task (Addante et al., 2011).

Evidences from MEG recordings are coherent with these findings. Results point to differential patterns between recall and non-recall conditions associated to memory tasks (Jensen and Tesche, 2002; Osipova et al., 2006). In particular it was found that encoding and recall of picture stimuli are linked to theta oscillations in the right hemisphere (Osipova et al., 2006).

Intracranial EEG studies have confirmed that theta oscillations have a role in memory formation (Sederberg et al., 2003; Rutishauser et al., 2010; Lega et al., 2012). An increase of theta activity in temporal and right frontal lobes correlated with successful recall of lists of words (Sederberg et al., 2003). Hippocampal/parahippocampal-cortical theta phase-coupling has also been investigated by iEEG recording in neurosurgical patients (Fell et al., 2003; Anderson et al., 2010; Rutishauser et al., 2010; Lega et al., 2012). Rutishauser et al. (2010) showed that an optimal memory performance was predicted by a tight coordination of spike timing in correspondence of the local theta oscillations. In addition, higher theta hippocampal-cortical phase-coupling was related to successful retrieval in a memory task (Lega et al., 2012).

The above-mentioned increase of theta activity has been typically reported over the frontal areas (Klimesch et al., 1996, 1997, 2006; Jensen and Tesche, 2002; Molle et al., 2002). Specifically, this phenomenon occurs over Fz, F3, F4 channels, and it is known as "frontal midline theta" (FMT; Ishihara and Yoshi, 1972; Klimesch et al., 2006; Mitchell et al., 2008; Hsieh and Ranganath, 2014).

It is well known that the prefrontal cortex (PFC) is involved in memory processes (Grady et al., 2003; Gazzaley et al., 2004; Nee and Jonides, 2008). In line with this finding, an innovative neuroimaging study, by using diffusion tensor imaging (DTI), demonstrated that the relationship between theta and memory depends on hippocampus-prefrontal cortex connectivity by showing that participants with a remarkable connectivity had better long-term memory (Cohen, 2011). These subjects exhibited EEG patterns characterized by theta and delta oscillations over the frontal regions. In addition, iEEG recordings also showed that theta activity modulates the interaction between PFC and the medial temporal lobe (MTL), suggesting that both these areas may be part of the same network engaged in recall operations (Anderson et al., 2010). In particular, MEG studies have shown that the frontal theta rhythm could be generated by the medial prefrontal cortex (mPFC) and the anterior cingulate cortex (ACC; Asada et al., 1999; Ishii et al., 1999; Nishida et al., 2004). These regions seem to play a central role in selective and continuous attention during working memory and recall tasks (Cohen et al., 1997; Petit et al., 1998; Smith and Jonides, 1999; Rowe et al., 2000).

However, it should be underlined that some studies found increased theta coherence between intracranial electrodes during the encoding of subsequently recognized items, without observing any variation in theta power (Fell et al., 2003). In some cases, the frontal theta correlated negatively with retrieval and positively with forgetting (Hanslmayr et al., 2010; Staudigl et al., 2010; Khader and Rösler, 2011; Lega et al., 2012; Pastötter and Bäuml, 2014). For instance, Staudigl et al. (2010) reported an increased FMT related to the increased interference during episodic retrieval task. Recent works suggested that it might be useful to consider two sub-ranges of theta activity, i.e., slow theta (∼3 Hz) and fast theta (∼7 Hz) oscillations (Lega et al., 2012; Pastötter and Bäuml, 2014). These bands differently affected memory performance since slow cortical and hippocampal theta oscillations were positively related to an optimal retrieval, while fast cortical and hippocampal theta oscillations were negatively related to it (Lega et al., 2012; Pastötter and Bäuml, 2014).

Frontal theta oscillations have been observed also during meditation and state of drowsiness (Takahashi et al., 1997; Kubota et al., 2001). In this respect, Norman et al. (2007) proposed an "Oscillating Inhibition Model," which posits that theta rhythm may represent a mechanism for inhibition of useless items in memory system. In other words, theta activity could help to suppress the external interference with selective retrieval of target memory during cognitive tasks or in meditative state, while subjects are focused on inner experiences.

Finally, it should be considered that EEG power in the theta band is strictly associated to subjective sleepiness and sleep propensity (Finelli et al., 2000; Tinguely et al., 2006; De Gennaro et al., 2007; Marzano et al., 2007; Gorgoni et al., 2015). Indeed, an increase of theta power during extended wakefulness has been demonstrated (Cajochen et al., 1996; Aeschbach et al., 1997; Finelli et al., 2000). In this respect, the cognitive performance, especially memory function, may be affected by the time of data collection. Therefore, it is necessary underline that circadian and homeostatic modulation on theta activity should be taken into account -at least, by maintaining them constant across conditions- as possible confounding variables.

Summing up, the most studies seem to confirm that theta oscillations could be predictive of memory performance. It should be noted that a relatively high theta activity is commonly detected in REM sleep (Marzano et al., 2010). In particular, the theta band shows a fronto-central gradient with highest values over the midline regions (Marzano et al., 2010). Furthermore, several studies suggest a link between REM sleep and memory consolidation (Siegel, 2001; Nishida et al., 2009). For instance, a relationship between prefrontal theta rhythm during REM sleep and emotional memory consolidation has been reported (Nishida et al., 2009).

Keeping in mind these considerations, we hypothesize that the analysis of the changes in spectral power during sleep, in association with the specific mental activity of sleep (i.e., dreaming), might give a significant contribution in understanding the role of theta band in cognitive processes.

Neurobiological Approach to Dream Recall

In the last decades, there has been a growing interest in the neurobiological correlates of dreaming. Considerable strides in dream research have been made mostly thanks to the investigations in brain damage patients, as well as to the employment of brain imaging techniques and quantitative analysis of polysomnographic (PSG) measures.

However, it should be emphasized that dreaming is a peculiar object of study, especially because it is impossible to access directly to sleep mental contents. We can access dream content only by awakening the subject: therefore, the real object of study is the dream recall, rather than dreaming in itself. It follows that dream report is inevitably influenced by two states of consciousness, wakefulness and sleep. We may consider dream recall as a particular type of mental activity, which shares some features with encoding and retrieval of episodic memories during daytime activity (Marzano et al., 2011).

Neuropsychological Findings

The first neuropsychological studies on dreaming aimed at evaluating the correlations between dream features in brain damaged patients and anatomical lesion sites.

Some studies have explored the different role played by the brain hemispheres in sleep mentation. Originally, it was hypothesized that dreaming depends on the right hemisphere. However, a pionieristic meta-analysis refuted this view (Doricchi and Violani, 1992). It was highlighted that also subjects who have undergone a right hemispherectomy reported dream contents relatively similar to healthy people (Doricchi and Violani, 1992). Furthermore, it was evidenced that frontal lobe damage was not systematically associated to dream loss; instead, parietal lesions caused complete dream cessation. This phenomenon was observed both as a consequence of unilateral and bilateral lesions. With respect to the specific issue of laterality, the authors hypothesized that right hemisphere is linked to dream materials and left hemisphere to dream encoding and interpretation (Doricchi and Violani, 1992).

Further investigations have demonstrated that total dream loss is also observed in patients affected by ventromesial frontal white matter damages (Solms, 1997). It should be noted that this area corresponds to the region affected by prefrontal lobotomy. The 80% of lobotomized subjects did not report mental activity during sleep (Frank, 1946; Partridge, 1950; Solms, 1997). Consistently, empirical evidences have underlined that the chemical stimulation of this area by L-dopa elicits psychotic symptoms, nightmares and more vivid dream contents (Scharf et al., 1978; Nausieda et al., 1982).

Starting from brain damage studies, a nosology of dream activity alterations was implemented (Solms, 1997). Solms defined "*visual anoneria*" the condition characterized by mental sleep activity without visual components. This deficit was associated with temporo-occipital lesions (Brodmann 40 area). In this case, the patients showed visual impairment also in wakefulness, in particular on visuo-spatial tasks (Epstein and Simmons, 1983; Murri et al., 1985; Solms, 2000). The "*global anoneria*" consists of complete cessation of dreaming. Typically, this syndrome was associated with posterior cortical lesions, near the temporo-occipital-parietal junction or deep and bilateral frontal damage, in correspondence of the ventromesial region (Solms, 1997; Domhoff, 2011). Commonly, these patients show reiterations and disinhibition (Bischof and Bassetti, 2004). Again, these anomalies can be observed during spatial memory tasks in wakefulness. The third syndrome, "*anoneirognosis*," concerns the impossibility to distinguish internal experiences (i.e., dream) from reality. This alteration may be observed in patients with limbic-frontal lesions, over mPFC, ACC, and basal forebrain. This syndrome is always associated to a general state of confusion during wakefulness. For instance, patients reported an intrusion of dream contents into waking thought (Solms, 1997; Domhoff, 2011). Furthermore, the "*recurring nightmares*" syndrome was typically found in correspondence of temporal-limbic seizures that sometimes are associated to paroxysms (Solms, 1997).

Brain damage studies are not free from limitations. Firstly, the mental sleep activity in these patients is never compared to dreaming during *premorbid* condition. This means that mental sleep activity before the brain damage have been investigated only by retrospective self-report (Schwartz and Maquet, 2002). Furthermore, it is quite common that patients take medications that may influence some cognitive mechanisms involved in dreaming (Gottesmann, 2002).

More recently, the use of neuroimaging techniques [i.e., positron emission tomography (PET) and functional magnetic resonance imaging (fMRI)] has allowed to substantially replicate the data obtained from anatomical studies. The early neuroimaging studies on dreaming were based on the assumption that dream contents reflect the activation level of neural structures that typically regulate cognitive processes. These studies, still bounded to the implicit assumption that sleep mentation strictly depends on REM sleep physiology, tried to find for each "dream-like" feature a relationship with specific activation/deactivation of brain areas.

Imaging studies mostly show that REM sleep is characterized by a general high cerebral activation (Maquet et al., 1996; Braun et al., 1997, 1998; Nofzinger et al., 1997; Maquet, 2000; Wehrle et al., 2007; Hong et al., 2009; Nir and Tononi, 2010). It was observed an increase of activity in the thalamus (Peigneux et al., 2001; Wehrle et al., 2005), hippocampal formation (Wehrle et al., 2007), visual cortex (Lövblad et al., 1999; Wehrle et al., 2007; Hong et al., 2009), orbitofrontal cortex (Maquet et al., 1996; Braun et al., 1997, 1998; Hong et al., 2009), amygdala and ACC (Maquet et al., 1996; Braun et al., 1997, 1998; Nofzinger et al., 1997).

It is well known that the amygdala and the hippocampal formation are involved in memory processes (Nofzinger et al., 1997; Braun et al., 1998). The activation of amygdala and hippocampus seems to play a putative role in the processing of emotional contents during REM sleep. In this regard, it should be noted that an important feature of dreaming is the alteration of mnestic processes: indeed, except for particular emotional contents, subjects have difficulties in retrieving their dream activity (Nir and Tononi, 2010). Some alterations in memory system are probably associated to the relative deactivation of the prefrontal cortex (Maquet et al., 1996, 2005). Typically, this area controls working memory, rational thought and executive functions (Nir and Tononi, 2010).

Furthermore, some results have demonstrated that the attenuation in the voluntary control on thoughts and actions during dreaming depends on the right inferior parietal cortex during REM sleep (Maquet et al., 1996; Braun et al., 1997). Such findings fit quite well with the "traditional" viewpoint that dream-like activity is strictly related to the REM sleep brain activation pattern. However, as previously mentioned, it should be underlined that these neuroimaging studies, with one notable exception (Maquet et al., 1996), have overlooked the actual presence of a successful dream recall, inferring relationships between neural structures and dream material.

EEG Brain Oscillations Involved in Mental Activity During Sleep

Polysomnographic technique and laboratory awakenings are considered the *gold standard* method to investigate sleep mentation. After awakenings from NREM sleep, some studies have found a relationship between alpha activity and dream recall (Takeuchi et al., 2003; Esposito et al., 2004; Marzano et al., 2011), although the results are not always consistent. For instance, one study reported that dream recall correlated with a decrease of alpha activity in correspondence of central areas (Takeuchi et al., 2003). On the other hand, two more recent studies showed an increase of alpha oscillations in temporo-parietal regions (Esposito et al., 2004; Marzano et al., 2011). Differently, Chellappa et al. (2011) observed that dream report from NREM sleep is associated with a decline of delta and sigma EEG power over the centro-parietal regions.

Also dream recall after REM sleep is associated to alpha activity. In particular, a correlation between dream report and a decrease of alpha band on the frontal region has been reported (Esposito et al., 2004; Chellappa et al., 2011). However, these data are incoherent with the evidence that dream recall is predicted by an enhancement of theta activity in frontal area prior to awakening (Marzano et al., 2011). Keeping in mind the role played by the theta and alpha rhythms in the episodic memory formation and retrieval (Klimesch, 1996), it may be hypothesized a sort of continuity between the mechanisms that modulate episodic memory processes across sleep and wakefulness (Marzano et al., 2011). This is also in line with a psychological point of view which underlines that qualitative and quantitative aspects of sleep mentation are determined by waking-life experiences and feelings (Domhoff, 2003; Schredl, 2003, 2009).

To sum up, the neuroscientific literature on the EEG correlates of dream recall still depict an heterogeneous picture. We must bear in mind that the data have been obtained by partly different methodologies (such as time of awakening and procedures to collect dream content). Indeed, dream reports were collected after the first sleep cycle (Esposito et al., 2004), the entire night (Marzano et al., 2011), multiple nap (Chellappa et al., 2011), or REM sleep onset (SOREMP) and NREM sleep onset (NREMP) periods (Takeuchi et al., 2003). Consequently, they take in account partially different phenomena.

State- or Trait-Like Differences?

It should be highlighted that the most of the empirical data on neural correlates of dreaming are based on *between-subjects* designs, making impossible to disentangle whether the patterns observed are state-like or trait-like. In order to reach a more complete knowledge about dreaming, it is necessary to clarify if dream recall is influenced by specific stable differences characterizing each subject (i.e., the trait-like hypothesis) or, alternatively if dream contents can only be retrieved in correspondence with specific brain activity strictly related to the physiological sleep *scenario* (i.e., the state-like hypothesis). Specifically, the first hypothesis implies that some individuals could show steady topographical EEG pattern, independently from dream recall or non-recall conditions. Hence, the trait-like relationship may be interpreted in terms of specific EEG features which allow subjects to stably recall or not recall dreams. On the other hand, the second hypothesis suggests that it is a recognizable EEG pattern during a specific sleep stage to determine or at least predict the subsequent dream recall at awakening.

Very few studies have tried to disentangle this issue. For instance, Marzano et al. (2011) evaluated if the EEG pattern observed in the last sleep segment prior to awakening was also evidenced during the previous nocturnal sleep cycles (i.e., if it was a stable pattern in entire night). They examined EEG power in correspondence of the midpoint of each sleep cycle (second, third and fourth episodes of REM and stage 2), and reported that significant differences in the EEG pattern between recallers (REC) and non-recallers (NREC) groups were detected only in proximity to the awakening time. Hence, those differences were not a stable pattern of EEG activity during the night (Marzano et al., 2011). However, the lack of systematic differences across all sleep episodes do not provide a definitive evidence on the state- or trait-like question.

A recent neuroimaging study investigated, by DTI technique, the association between qualitative and quantitative features of dream recall and morphoanatomical measures of the amygdala and hippocampus. In this approach, dream recall has been investigated according to a trait-like view, and correlated to interindividual differences of the subcortical structures. A correlation between the bizarreness of dreams and some microstructural features of the amygdala (smaller volume and lower structural integrity) was found (De Gennaro et al., 2011). Furthermore, emotional load was associated to a smaller volume of the left hippocampus and to a larger volume of the right hippocampus. Moreover, a relationship between emotional load and structural integrity of the left amygdala was reported (De Gennaro et al., 2011). These data support the hypothesis that the amygdala is related to the emotional encoding of dream contents, suggesting a continuity between the formation of emotional memory across wakefulness and sleep. The central role of the amygdala in the emotional regulation in wakefulness as in sleep is particularly clear in post-traumatic stress disorder (PTSD) patients. Chronic post-traumatic nightmares could be considered "the hallmark of PTSD" (Ross et al., 1989; Germain, 2013). Dream reports in PTSD patients are characterized by themes, vivid images and emotions associated to the traumatic events. It should be noted that many studies have found a hyperactivity of the amygdala in this disorder (Shin et al., 2006; Germain et al., 2008). Specifically, REM sleep could amplify the altered function of the amygdala in these patients, increasing dysphoric dreams (Germain et al., 2008).

"Trait-like" differences have also been considered in terms of "*dream recall frequency*" (DRF). A PET study demonstrated that High Recallers (higher DRF) show a greater regional cerebral blood flow (rCBF) in temporo-parietal junction (TPJ) during REM sleep, stage 3 and wakefulness than Low Recallers (lower DRF). It was also observed a higher rCBF in High Recallers in mPFC only during REM sleep and wakefulness (Eichenlaub et al., 2014a). These evidences are consistent with Solms's (1997) observations about the role played by TPJ and mPFC in the sleep mentation production.

It should be underlined that these regions are involved in the "default mode network" (DMN), a neural system activated during resting state, daydreaming and mental imagery processes (Desseilles et al., 2011; Domhoff, 2011; Eichenlaub et al., 2014a). Mind wandering represents a state of attention toward interior feelings and personal thoughts, rather than processing items from the external environment (Smallwood and Schooler, 2006). This definition could be applied also to dreaming (Domhoff, 2011). A lot of studies evidenced that the mPFC, the anterior and posterior cingulate cortex, the precuneus and the temporo-parietal area are the regional substrate of mind wandering (Mason et al., 2007; Christoff et al., 2009). Specifically, Andrews-Hanna et al. (2010) observed that the DMN is organized in two subsystems: the dorsal mPFC system and the MTL system. In other words, mind wandering and dreaming both refers to a peculiar internal cognition, so it is plausible that the neural substrate for sleep mentation shares some brain regions with the network for mind wandering (i.e., DMN; Fosse and Domhoff, 2007; Ioannides et al., 2009; Nir and Tononi, 2010). Hence, it could be hypothesized that High Recallers are more interested in their inner word (Eichenlaub et al., 2014a). This aspect may represent a trait variable that can contribute to the episodic memory recall. Once again, the data appear consistent with the continuity hypothesis between mechanisms involved in cognitive processes across sleep and wakefulness. The same group demonstrated that High Recallers show a greater intrasleep wakefulness than Low Recallers (Ruby et al., 2013; Eichenlaub et al., 2014b). This result also provides some support to the arousal-retrieval model (Koulack and Goodenough, 1976). The model assumes that the information processing of dream mentation and the subsequent retrieval are facilitated if awakenings occur during sleep. The nocturnal awakenings could promote the transition of mnestic traces (i.e., dream contents) from short-term memory store to a long-memory storage (Koulack and Goodenough, 1976).

These studies have mainly investigated *interindividual* factors (structural features of amygdala and hippocampus). On the other hand, the *intraindividual* issue should be also considered, addressing the question of measuring DRF across different conditions. Some information on intraindividual differences comes from a recent study that performed a 40-h nap protocol under constant routine, awakening subjects every 75 min (Chellappa et al., 2009, 2011). This protocol ensures more possibilities to obtain recall or non-recall conditions in different sleep stages (NREM or REM sleep). However, this procedure raises other problems, concerning the influence of circadian and ultradian variables on dream activity. As matter of fact, it has been remarked that some components of dreaming vary as a function of chronobiological features (Nielsen, 2004, 2010). For instance, the length of dream reports shows a sinusoidal profile: NREM reports are longer when the awakening is closer to a prior REM sleep episode (Goodenough et al., 1965; Arkin et al., 1978). Furthermore, some features change in a circadian-dependent manner. Notable differences between dream reports from the first third and later parts of the night have been reported (Nielsen, 2004, 2010). In particular, sleep mentation increased in dream-like quality from the first REM to all later REM episodes (Kramer et al., 1980).

As mentioned above, despite some progresses in the dream research, the "state- or trait-like" question still remains unsolved. An alternative way to clarify this issue is represented by protocols with multiple sleep recordings in the same subject, carefully avoiding the influence of circadian factors. Our recent pilot study, applying a within-subject nap protocol, represents a first step toward this direction (Scarpelli et al., 2014). We have replicated the finding that dream recall subsequent the awakening from REM sleep is related to prior increasing of frontal theta oscillations (Marzano et al., 2011), providing further support to the "continuity hypothesis" between neurophysiological mechanisms for the encoding and retrieval of episodic memory in sleep and wakefulness (Marzano et al., 2011). More interestingly, these preliminary results suggest that dream recall, compared to absence of dream recall, is associated to a specific EEG pattern (frontal theta) during a specific sleep stage (REM sleep), supporting a "state-like hypothesis" (Scarpelli et al., 2014).

Concluding Remarks

From the viewpoint of the neurosciences, dream research could be considered as the study of cognitive processes during sleep. However, neurobiological evidence is intrinsically limited by the impossibility to directly access to dreaming, and by the necessity to focus on recall of dream experience collected during post-awakening wakefulness (i.e., dream recall). A consistent number of studies underlined the continuity between mechanisms that regulate cognitive functions in wakefulness and sleep. In particular, here, it has been stressed that EEG studies have provided empirical data to sustain the predictive role played by theta oscillations in the retrieval of episodic information both in wakefulness (Klimesch et al., 1997, 2001; Klimesch, 1999; Kahana et al., 2001; Molle et al., 2002; Guderian and Düzel, 2005; Nyhus and Curran, 2010; White et al., 2013; Hsieh and Ranganath, 2014) and sleep, considering dream recall as an episodic mnestic trace (Marzano et al., 2011). Also neuropsychological studies reported a continuity across different states of consciousness. For instance, different types of dream activity alterations seem to have an equivalent in wakefulness (Solms, 1997). Neuroimaging investigations evidenced that amygdala and hippocampus are fundamental to consolidate and retrieve emotional memories in sleep as in wakefulness (De Gennaro et al., 2011). Furthermore, some structures of the DMN (i.e., mPFC and MTL) activated during internal cognition in wakefulness, are particularly activated also during sleep in subjects that recall more frequently dream contents (Domhoff, 2011; Eichenlaub et al., 2014a).

Taking into account the intrinsic difficulties in studying dream mentation, we have emphasized that PSG with laboratory awakenings should be still considered as a gold standard to investigate dreaming. The heterogeneous literature here discussed highlights that dream recall is associated to a particular EEG topography and frequency. We have also underlined that the existing literature does not provide compelling evidence to clarify the "state- or trait-like" factors influencing the neurobiological mechanisms of dream recall. Although some observations support the "state-like hypothesis," only future studies could disentangle this issue by using designs with multiple within-subjects awakenings.

Author Contributions

Substantial contributions to the conception and design of the work: LDG, MF, SS, ADA, MG; Drafting the work and revising it critically for important intellectual content: LDG, MF, SS, ADA, MG; Final approval of the version to be published: LDG, MF, SS, ADA, MG; Agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved: LDG, MF, SS, ADA, MG.

Acknowledgment

This work was partly supported by a grant to LDG from "Ministero della Salute" (Ministry of Health) RF-2009-1528677.

References

Addante, R. J., Watrous, A. J., Yonelinas, A. P., Ekstrom, A. D., and Ranganath, C. (2011). Prestimulus theta activity predicts correct source memory retrieval. *Proc. Natl. Acad. Sci. U.S.A.* 108, 10702–10707. doi: 10.1073/pnas.1014528108

Aeschbach, D., Matthews, J. R., Postolache, T. T., Jackson, M. A., Giesen, H. A., and Wehr, T. A. (1997). Dynamics of the human EEG during prolonged wakefulness: evidence for frequency-specific circadian and homeostatic influences. *Neurosci. Lett.* 239, 121–124. doi: 10.1016/S0304-3940(97)00904-X

Anderson, K. L., Rajagovindan, R., Ghacibeh, G. A., Meador, K. J., and Ding, M. (2010). Theta oscillations mediate interaction between prefrontal cortex and medial temporal lobe in human memory. *Cereb. Cortex* 20, 1604–1612. doi: 10.1093/cercor/bhp223

Andrews-Hanna, J., Reidler, J., Huang, C., and Buckner, R. (2010). Evidence for the default network's role in spontaneous cognition. *J. Neurophysiol.* 104, 322–335. doi: 10.1152/jn.00830.2009

Antrobus, J. (1983). REM and NREM sleep reports: comparison of word frequencies by cognitive classes. *Psychophysiology* 20, 562–568. doi: 10.1111/j.1469-8986.1983.tb03015.x

Arkin, A. M., Antrobus, J. S., Ellman, S. J., and Farber, J. (1978). "Sleep mentation as affected by REM deprivation," in *The Mind in Sleep: Psychology and Psychophysiology*, eds A. M. Arkin, J. S. Antrobus, and S. J. Ellman (Hillsdale, NJ: Lawrence Erlbaum), 459–484.

Asada, H., Fukuda, Y., Tsunoda, S., Yamaguchi, M., and Tonoike, M. (1999). Frontal midline theta rhythms reflect alternative activation of prefrontal cortex and anterior cingulate cortex in humans. *Neurosci. Lett.* 274, 29–32. doi: 10.1016/S0304-3940(99)00679-5

Aserinsky, E., and Kleitman, N. (1953). Regularly occurring periods of eye motility, and concomitant phenomena, during sleep. *Science* 118, 273–274. doi: 10.1126/science.118.3062.273

Başar, E., Başar-Eroglu, C., Karakas, S., and Schurmann, M. (1999). Are cognitive processes manifested in event-related gamma, alpha, theta and delta oscillations in the EEG? *Neurosci. Lett.* 259, 165–168. doi: 10.1016/S0304-3940(98)00934-3

Bischof, M., and Bassetti, C. L. (2004). Total dream loss: a distinct neuropsychological dysfunction after bilateral PCA stroke. *Ann. Neurol.* 56, 583–586. doi: 10.1002/ana.20246

Braun, A. R., Balkin, T. J., Wesensten, N. J., Carson, R. E., Varga, M., Baldwin, P., et al. (1997). Regional cerebral blood flow throughout the sleep-wake cycle: an H2O-15 positron emission tomography study. *Brain* 120, 1173–1197. doi: 10.1093/brain/120.7.1173

Braun, A. R., Balkin, T. J., Wesensten, N. J., Gwadry, F., Carson, R. E., Varga, M., et al. (1998). Dissociated pattern of activity in visual cortices and their projections during human rapid eye movement sleep. *Science* 279, 91–95. doi: 10.1126/science.279.5347.91

Cajochen, C., Kräuchi, K., von Arx, M. A., Möri, D., Graw, P., and Wirz-Justice, A. (1996). Daytime melatonin administration enhances sleepiness and theta/alpha activity in the waking EEG. *Neurosci. Lett.* 207, 209–213. doi: 10.1016/0304-3940(96)12517-9

Cantero, J. L., Atienza, M., Stickgold, R., Kahana, M. J., Madsen, J. R., and Kocsis, B. (2003). Sleep-dependent θ oscillations in the human hippocampus and neocortex. *J. Neurosci.* 23, 10897–10903.

Casagrande, M., Violani, C., and Bertini, M. (1996). A psycholinguistic method for analyzing two modalities of thought in dream reports. *Dreaming* 6, 43–55. doi: 10.1037/h0094445

Cavallero, C., Cicogna, P., Natale, V., Occhionero, M., and Zito, A. (1992). Slow wave sleep dreaming: dream research. *Sleep* 15, 562–566.

Chellappa, S. L., Frey, S., Knoblauch, V., and Cajochen, C. (2011). Cortical activation patterns herald successful dream recall after NREM and REM sleep. *Biol. Psychol.* 87, 251–256. doi: 10.1016/j.biopsycho.2011.03.004

Chellappa, S. L., Münch, M., Blatter, K., Knoblauch, V., and Cajochen, C. (2009). Does the circadian modulation modify with age? *Sleep* 32, 1201–1209.

Christoff, K., Gordon, A., Smallwood, J., Smith, R., and Schooler, J. (2009). Experience sampling during fMRI reveals default network and executive system contributions to mind wandering. *Proc. Natl. Acad. Sci. U.S.A.* 106, 8719–8724. doi: 10.1073/pnas.0900234106

Cohen, J. D., Perlstein, W. M., Braver, T. S., Nystrom, L. E., Noll, D. C., Jonides, J., et al. (1997). Temporal dynamics of brain activation during a working memory task. *Nature* 386, 604–608. doi: 10.1038/386604a0

Cohen, M. X. (2011). Hippocampal–prefrontal connectivity predicts midfrontal oscillations and long-term memory performance. *Curr. Biol.* 21, 1900–1905. doi: 10.1016/j.cub.2011.09.036

Corsi-Cabrera, M., Miro, E., del-Río-Portilla, Y., Perez-Garci, E., Villanueva, Y., and Guevara, M. A. (2003). Rapid eye movement sleep dreaming is characterized by uncoupled EEG activity between frontal and perceptual cortical regions. *Brain Cogn.* 51, 337–345. doi: 10.1016/S0278-2626(03)00037-X

De Gennaro, L., Cipolli, C., Cherubini, A., Assogna, F., Cacciari, C., Marzano, C., et al. (2011). Amygdala and hippocampus volumetry and diffusivity in relation to dreaming. *Hum. Brain Mapp.* 32, 1458–1470. doi: 10.1002/hbm.21120

De Gennaro, L., Marzano, C., Cipolli, C., and Ferrara, M. (2012). How we remember the stuff that dreams are made of: neurobiological approaches to the brain mechanisms of dream recall. *Behav. Brain Res.* 226, 592–596. doi: 10.1016/j.bbr.2011.10.017

De Gennaro, L., Marzano, C., Veniero, D., Moroni, F., Fratello, F., Curcio, G., et al. (2007). Neurophysiological correlates of sleepiness: a combined TMS and EEG study. *Neuroimage* 36, 1277–1287. doi: 10.1016/j.neuroimage.2007.04.013

Dement, W., and Kleitman, N. (1957a). Cyclic variations in EEG during sleep and their relation to eye movements, body motility, and dreaming. *Electroencephalogr. Clin. Neurophysiol.* 9, 673–690. doi: 10.1016/0013-4694(57)90088-3

Dement, W., and Kleitman, N. (1957b). The relation of eye movements during sleep to dream activity: an objective method for the study of dreaming. *J. Exp. Psychol.* 53, 339–346. doi: 10.1037/h0048189

Desseilles, M., Dang-Vu, T. T., Sterpenich, V., and Schwartz, S. (2011). Cognitive and emotional processes during dreaming: a neuroimaging view. *Conscious. Cogn.* 20, 998–1008. doi:10.1016/j.concog.2010.10.005

Domhoff, G. W. (2003). *The Scientific Study of Dreams: Neural Networks, Cognitive, Development, and Content Analysis*. Washington: America Psychological Association Press.

Domhoff, G. W. (2011). The neural substrate for dreaming: is it a subsystem of the default network? *Conscious. Cogn.* 20, 1163–1174. doi: 10.1016/j.concog.2011.03.001

Doppelmayr, M., Klimesch, W., Schwaiger, J., Auinger, P., and Winkler, T. (1998). Theta synchronization in the human EEG and episodic retrieval. *Neurosci. Lett.* 257, 41–44. doi: 10.1016/S0304-3940(98)00805-2

Doricchi, F., and Violani, C. (1992). "Dream recall in brain-damaged patients: a contribution to the neuropsychology of dreaming through a review of the literature," in *The Neuropsychology of Sleep and Dreaming*, eds J. S. Antrobus and M. Bertini (Hillsdale, NJ: Erlbaum), 99–129.

Eichenlaub, J. B., Nicolas, A., Daltrozzo, J., Redouté, J., Costes, N., and Ruby, P. (2014a). Resting brain activity varies with dream recall frequency between subjects. *Neuropsychopharmacology* 39, 1594–1602. doi: 10.1038/npp.2014.6

Eichenlaub, J. B., Bertrand, O., Morlet, D., and Ruby, P. (2014b). Brain reactivity differentiates subjects with high and low dream recall frequencies during both sleep and wakefulness. *Cereb. Cortex* 24, 1206–1215. doi: 10.1093/cercor/bhs388

Epstein, E., and Simmons, N. (1983). Aphasia with reported loss of dreaming. *Am. J. Psychiatry* 140, 108–109. doi: 10.1176/ajp.140.1.108

Esposito, M. J., Nielsen, T. A., and Paquette, T. (2004). Reduced alpha power associated with the recall of mentation from Stage 2 and Stage REM sleep. *Psychophysiology* 41, 288–297. doi: 10.1111/j.1469-8986.00143.x

Fell, J., Staedtgen, M., Burr, W., Kockelmann, E., Helmstaedter, C., Schaller, C., et al. (2003). Rhinal–hippocampal EEG coherence is reduced during human sleep. *Eur. J. Neurosci.* 18, 1711–1716. doi: 10.1046/j.1460-9568.2003.02934.x

Finelli, L. A., Baumann, H., Borbély, A. A., and Achermann, P. (2000). Dual electroencephalogram markers of human sleep homeostasis: correlation between theta activity in waking and slow-wave activity in sleep. *Neuroscience* 101, 523–529. doi: 10.1016/S0306-4522(00)00409-7

Fosse, R., and Domhoff, G. W. (2007). "Dreaming as non-executive orienting: a conceptual framework for consciousness during sleep," in *The New Science of Dreaming: Content, Recall and Personality Correlates*, Vol. 2, eds D. Barrett and P. McNamara (Westport, CT: Praeger), 49–78.

Foulkes, D. (1962). Dream reports from different stages of sleep. *J. Abnorm. Soc. Psychol.* 65, 14–25. doi: 10.1037/h0040431

Foulkes, D. (1967). Nonrapid eye movement mentation. *Exp. Neurol.* 19, 28–38. doi: 10.1016/0014-4886(67)90154-9

Foulkes, D. (1985). *Dreaming: a Cognitive-Psychological Analysis*. Hillsdale: Lawrence Erlbaum Associates.

Foulkes, D., and Rechtschaffen, A. (1964). Presleep determinants of dream content: effects of two films. *Percept. Mot. Skills* 19, 983–1005. doi: 10.2466/pms.1964.19.3.983

Foulkes, D., and Schmidt, M. (1983). Temporal sequence and unit composition in dream reports from different stages of sleep. *Sleep* 6, 265–280.

Foulkes, D., and Vogel, G. (1965). Mental activity at sleep onset. *J. Abnorm. Psychol.* 70, 231–243. doi: 10.1037/h0022217

Frank, J. (1946). Clinical survey and results of 200 cases of prefrontal leucotomy. *J. Ment. Sci.* 92, 497–508. doi: 10.1192/bjp.92.388.497

Gazzaley, A., Rissman, J., and D'Esposito, M. (2004). Functional connectivity during working memory maintenance. *Cogn. Affect. Behav. Neurosci.* 4, 580–599. doi: 10.3758/CABN.4.4.580

Germain, A. (2013). Sleep disturbances as the hallmark of PTSD: where are we now? *Am. J. Psychiatry* 170, 372–382. doi: 10.1176/appi.ajp.2012.12040432

Germain, A., Buysse, D. J., and Nofzinger, E. (2008). Sleep-specific mechanisms underlying posttraumatic stress disorder: integrative review and neurobiological hypotheses. *Sleep Med. Rev.* 12, 185–195. doi: 10.1016/j.smrv.2007.09.003

Goodenough, D. R., Lewis, H. B., Shapiro, A., Jaret, L., and Sleser, I. (1965). Dream reporting following abrupt and gradual awakenings from different types of sleep. *J. Pers. Soc. Psychol.* 2, 170. doi: 10.1037/h0022424

Gorgoni, M., Ferrara, M., D'Atri, A., Lauri, G., Scarpelli, S., Truglia, I., et al. (2015). EEG topography during sleep inertia upon awakening after a period of increased homeostatic sleep pressure. *Sleep Med.* doi: 10.1016/j.sleep.2015.03.009 [Epub ahead of print].

Gottesmann, C. (2002). The neurochemistry of waking and sleeping mental activity: the disinhibition-dopamine hypothesis. *Psychiatry Clin. Neurosci.* 56, 345–354. doi: 10.1046/j.1440-1819.2002.01022.x

Grady, C. L., McIntosh, A. R., and Craik, F. I. M. (2003). Age-related differences in the functional connectivity of the hippocampus during memory encoding. *Hippocampus* 13, 572–586. doi: 10.1002/hipo.10114

Gruber, M., Watrous, A., Ekstrom, A., and Ranganath, C. (2013). Expected reward modulates encoding-related theta activity before an event. *Neuroimage* 64, 68–74. doi: 10.1016/j.neuroimage.2012.07.064

Guderian, S., and Düzel, E. (2005). Induced theta oscillations mediate large-scale synchrony with mediotemporal areas during recollection in humans. *Hippocampus* 15, 901–912. doi: 10.1002/hipo.20125

Guderian, S., Schott, B. H., Richardson-Klavehn, A., and Düzel, E. (2009). Medial temporal theta state before an event predicts episodic encoding success in humans. *Proc. Natl. Acad. Sci. U.S.A.* 106, 5365–5370. doi: 10.1073/pnas.0900289106

Hanslmayr, S., Staudigl, T., Aslan, A., and Bäuml, K.-H. (2010). Theta oscillations predict the detrimental effects of memory retrieval. *Cogn. Affect. Behav. Neurosci.* 10, 329–338. doi: 10.3758/CABN.10.3.329

Hobson, J. A., and McCarley, R. W. (1977). The brain as a dream state generator: an activation-synthesis hypothesis of the dream process. *Am. J. Psychiatry* 134, 1335–1348. doi: 10.1176/ajp.134.12.1335

Hobson, J. A., Pace-Schott, E. F., and Stickgold, R. (2000). Dreaming and the brain: toward a cognitive neuroscience of conscious states. *Behav. Brain Sci.* 23, 793–842. doi: 10.1017/S0140525X00003976

Hong, C. C. H., Harris, J. C., Pearlson, G. D., Kim, J. S., Calhoun, V. D., Fallon, J. H., et al. (2009). fMRI evidence for multisensory recruitment associated with rapid eye movements during sleep. *Hum. Brain Mapp.* 30, 1705–1722. doi: 10.1002/hbm.20635

Hsieh, L.-T., and Ranganath, C. (2014). Frontal midline theta oscillations during working memory maintenance and episodic encoding and retrieval. *Neuroimage* 85, 721–729. doi: 10.1016/j.neuroimage.2013.08.003

Ioannides, A., Kostopoulos, K., Liu, L., and Fenwick, P. (2009). MEG identifies dorsal medial brain activations during sleep. *Neuroimage* 44, 455–468. doi: 10.1016/j.neuroimage.2008.09.030

Ishihara, T., and Yoshi, N. (1972). Multivariate analytic study of EEG and mental activity in juvenile delinquents. *Electroencephalogr. Clin. Neurophysiol.* 33, 71–80. doi: 10.1016/0013-4694(72)90026-0

Ishii, R., Shinosaki, K., Ukai, S., Inouye, T., Ishihara, T., Yoshimine, T., et al. (1999). Medial prefrontal cortex generates frontal midline theta rhythm. *Neuroimage* 10, 675–679. doi: 10.1097/00001756-199903170-00003

Jensen, O., and Tesche, C. D. (2002). Frontal theta activity in humans increases with memory load in a working memory task. *Eur. J. Neurosci.* 15, 1395–1399. doi: 10.1046/j.1460-9568.2002.01975.x

Kahana, M. J., Seelig, D., and Madsen, J. R. (2001). Theta returns. *Curr. Opin. Neurobiol.* 11, 739–744. doi: 10.1016/S0959-4388(01)00278-1

Kahana, M. J., Sekuler, R., Caplan, J. B., Kirschen, M., and Madsen, J. R. (1999). Human theta oscillations exhibit task dependence during virtual maze navigation. *Nature* 399, 781–784. doi: 10.1038/21645

Khader, P. H., and Rösler, F. (2011). EEG power changes reflect distinct mechanisms during long-term memory retrieval. *Psychophysiology* 48, 362–369. doi: 10.1111/j.1469-8986.2010.01063.x

Klimesch, W. (1996). Memory processes, brain oscillations and EEG synchronization. *Int. J. Psychophysiol.* 24, 61–100. doi: 10.1016/S0167-8760(96)00057-8

Klimesch, W. (1999). EEG alpha and theta oscillations reflect cognitive and memory performance: a review and analysis. *Brain Res. Rev.* 29, 169–195. doi: 10.1016/S0165-0173(98)00056-3

Klimesch, W., Doppelmayr, M., Russegger, H., and Pachinger, T. (1996). Theta band power in the human scalp EEG and the encoding of new information. *Neuroimage* 7, 1235–1240. doi: 10.1097/00001756-199605170-00002

Klimesch, W., Doppelmayr, M., Schimke, H., and Ripper, B. (1997). Theta synchronization and alpha desynchronization in a memory task. *Psychophysiology* 34, 169–176. doi: 10.1111/j.1469-8986.1997.tb02128.x

Klimesch, W., Doppelmayr, M., Schwaiger, J., Winkler, T., and Gruber, W. (2000). Theta oscillations and the ERP old/new effect: independent phenomena? *Clin. Neurophysiol.* 111, 781–793. doi: 10.1016/S1388-2457(00)00254-6

Klimesch, W., Doppelmayr, M., Stadler, W., Pöllhuber, D., Sauseng, P., and Roehm, D. (2001). Episodic retrieval is reflected by a process specific increase in human electroencephalographic theta activity. *Neurosci. Lett.* 302, 49–52. doi: 10.1016/S0304-3940(01)01656-1

Klimesch, W., Hanslmayr, S., Sauseng, P., Gruber, W., Brozinsky, C. J., Kroll, N. E. A., et al. (2006). Oscillatory EEG correlates of episodic trace decay. *Cereb. Cortex* 16, 280–290. doi: 10.1093/cercor/bhi107

Koulack, D., and Goodenough, D. R. (1976). Dream recall and dream recall failure: an arousal-retrieval model. *Psychol. Bull.* 83, 975. doi: 10.1037/0033-2909.83.5.975

Kramer, M., McQuarrie, E., and Bonnet, M. (1980). Dream differences as a function of REM period position. *Sleep Res.* 9, 155.

Kubota, Y., Sato, W., Toichi, M., Murai, T., Okada, T., Hayashi, A., et al. (2001). Frontal midline theta rhythm is correlated with cardiac autonomic activities during the performance of an attention demanding meditation procedure. *Cogn. Brain Res.* 11, 281–287. doi: 10.1016/S0926-6410(00)00086-0

Lega, B. C., Jacobs, J., and Kahana, M. (2012). Human hippocampal theta oscillations and the formation of episodic memories. *Hippocampus* 22, 748–761. doi: 10.1002/hipo.20937

Lövblad, K. O., Thomas, R., Jakob, P. M., Scammell, T., Bassetti, C., Griswold, M., et al. (1999). Silent functional magnetic resonance imaging demonstrates focal activation in rapid eye movement sleep. *Neurology* 53, 2193–2193. doi: 10.1212/WNL.53.9.2193

Maquet, P. (2000). Functional neuroimaging of normal human sleep by positron emission tomography. *J. Sleep Res.* 9, 207–231. doi: 10.1046/j.1365-2869.2000.00214.x

Maquet, P., Péters, J. M., Aerts, J., Delfiore, G., Degueldre, C., Luxen, A., et al. (1996). Functional neuroanatomy of human rapid eye movement sleep and dreaming. *Nature* 383, 163–166. doi: 10.1038/383163a0

Maquet, P., Ruby, P., Maudoux, A., Albouy, G., Sterpenich, V., Dang Vu, T., et al. (2005). Human cognition during REM sleep and the activity profile within frontal and parietal cortices: a reappraisal of functional neuroimaging data. *Prog. Brain Res.* 150, 219–227. doi: 10.1016/S0079-6123(05)50016-5

Marzano, C., Ferrara, M., Curcio, G., and De Gennaro, L. (2010). The effects of sleep deprivation in humans: topographical EEG changes in NREM vs. REM sleep. *J. Sleep Res.* 19, 260–268. doi: 10.1111/j.1365-2869.2009.00776.x

Marzano, C., Ferrara, M., Mauro, F., Moroni, F., Gorgoni, M., Tempesta, D., et al. (2011). Recalling and forgetting dreams: theta and alpha oscillations during sleep predict subsequent dream recall. *J. Neurosci.* 31, 6674–6683. doi: 10.1523/JNEUROSCI.0412-11.2011

Marzano, C., Fratello, F., Moroni, F., Pellicciari, M. C., Curcio, G., Ferrara, M., et al. (2007). Slow eye movements and subjective estimates of sleepiness predict EEG power changes during sleep deprivation. *Sleep* 30, 610–616.

Mason, M., Norton, M., Van Horn, J., Wenger, D., Grafton, S., and Macrae, N. (2007). Wandering minds: the default network and stimulus-independent thought. *Science* 315, 393–395. doi: 10.1126/science.1131295

Miller, R. (1991). *Cortico-Hippocampal Interplay and the Representation of Contexts in the Brain*. Berlin: Springer.

Mitchell, D. J., McNaughton, N., Flanagan, D., and Kirk, I. J. (2008). Frontal–midline theta from the perspective of hippocampal "theta". *Prog. Neurobiol.* 86, 156–185. doi: 10.1016/j.pneurobio.2008.09.005

Molle, M., Marshall, L., Fehm, H. L., and Born, J. (2002). EEG theta synchronization conjoined with alpha desynchronization indicate intentional encoding. *Eur. J. Neurosci.* 15, 923–928. doi: 10.1046/j.1460-9568.2002.01921.x

Monroe, L. J., Rechtschaffen, A., Foulkes, D., and Jensen, J. (1965). Discriminability of REM and NREM reports. *J. Pers. Soc. Psychol.* 2, 456–460. doi: 10.1037/h0022218

Murri, L., Massetani, R., Siciliano, G., and Arena, R. (1985). Dream recall after sleep interruption in brain-injured patients. *Sleep* 8, 356–362.

Nausieda, P. A., Weiner, W. J., Kaplan, L. R., Weber, S., and Klawans, H. L. (1982). Sleep disruption in the course of chronic levodopa therapy: an early feature of the levodopa psychosis. *Clin. Neuropharmacol.* 5, 183–194. doi: 10.1097/00002826-198205020-00003

Nee, D. E., and Jonides, J. (2008). Neural correlates of access to short-term memory. *Proc. Natl. Acad. Sci. U.S.A.* 105, 14228–14233. doi: 10.1073/pnas.0802081105

Niedermeyer, E., and Lopes da Silva, F. H. (1993). *Electroencephalography: Basic Principles, Clinical Applications, and Related Fields*. Baltimore: Williams and Wilkins.

Nielsen, T. (2000). A review of mentation in REM and NREM sleep: covert REM sleep as a possible reconciliation of two opposing models. *Behav. Brain Sci.* 23, 851–866. doi: 10.1017/S0140525X0000399X

Nielsen, T. (2004). Chronobiological features of dream production. *Sleep Med. Rev.* 8, 403–424. doi: 10.1016/j.smrv.2004.06.005

Nielsen, T. (2010). Nightmares associated with the eveningness chronotype. *J. Biol. Rhythms* 25, 53–62. doi: 10.1177/0748730409351677

Nir, Y., and Tononi, G. (2010). Dreaming and the brain: from phenomenology to neurophysiology. *Trends Cogn. Sci.* 14, 88–100. doi: 10.1016/j.tics.2009.12.001

Nishida, M., Hirai, N., Miwakeichi, F., Maehara, T., Kawai, K., Shimizu, H., et al. (2004). Theta oscillation in the human anterior cingulate cortex during all-night sleep: an electrocorticographic study. *Neurosci. Res.* 50, 331–341. doi: 10.1016/j.neures.2004.08.004

Nishida, M., Pearsall, J., Buckner, R. L., and Walker, M. P. (2009). REM sleep, prefrontal theta, and the consolidation of human emotional memory. *Cereb. Cortex* 19, 1158–1166. doi: 10.1093/cercor/bhn155

Nofzinger, E. A., Mintun, M. A., Wiseman, M., Kupfer, D. J., and Moore, R. Y. (1997). Forebrain activation in REM sleep: an FDG PET study. *Brain Res.* 770, 192–201. doi: 10.1016/S0006-8993(97)00807-X

Norman, K. A., Newman, E. L., and Detre, G. (2007). A neural network model of retrieval-induced forgetting. *Psychol. Rev.* 114, 887–953. doi: 10.1037/0033-295X.114.4.887

Nyhus, E., and Curran, T. (2010). Functional role of gamma and theta oscillations in episodic memory. *Neurosci. Biobehav. Rev.* 34, 1023–1035. doi: 10.1016/j.neubiorev.2009.12.014

Osipova, D., Takashima, A., Oostenveld, R., Fernández, G., Maris, E., and Jensen, O. (2006). Theta and gamma oscillations predict encoding and retrieval of declarative memory. *J. Neurosci.* 26, 7523–7531. doi: 10.1523/JNEUROSCI.1948-06.2006

Paller, K. A., and Wagner, A. D. (2002). Observing the transformation of experience into memory. *Trends Cogn. Sci.* 6, 93–102. doi: 10.1016/S1364-6613(00)01845-3

Partridge, M. (1950). *Pre-Frontal Leucotomy: A Survey of 300 Cases Personally Followed for 1–3 Years*. Oxford: Blackwell.

Pastötter, B., and Bäuml, K. H. T. (2014). Distinct slow and fast cortical theta dynamics in episodic memory retrieval. *Neuroimage* 94, 155–161. doi: 10.1016/j.neuroimage.2014.03.002

Peigneux, P., Laureys, S., Fuchs, S., Delbeuck, X., Degueldre, C., Aerts, J., et al. (2001). Generation of rapid eye movements during paradoxical sleep in humans. *Neuroimage* 14, 701–708. doi: 10.1006/nimg.2001.0874

Petit, L., Courtney, S. M., Ungerleider, L. G., and Haxby, J. V. (1998). Sustained activity in the medial wall during working memory delays. *J. Neurosci.* 18, 9429–9437.

Raghavachari, S., Kahana, M. J., Rizzuto, D., Caplan, J., Kirschen, M., Bourgeois, B., et al. (2001). Gating of human theta oscillations by a working memory task. *J. Neurosci.* 21, 3175–3183.

Rechtschaffen, A., Verdone, P., and Wheaton, J. (1963). Reports of mental activity during sleep. *Can. Psychiatr. Assoc. J.* 257, 409–414.

Ross, R. J., Ball, W. A., Sullivan, K. A., and Caroff, S. N. (1989). Sleep disturbance as the hallmark of posttraumatic stress disorder. *Am. J. Psychiatry* 146, 697–707. doi: 10.1176/ajp.146.1.128-a

Rowe, J. B., Toni, I., Josephs, O., Frackowiak, R. S., and Passingham, R. E. (2000). The prefrontal cortex: response selection or maintenance within working memory? *Science* 288, 1656–1660. doi: 10.1126/science.288.5471.1656

Ruby, P., Blochet, C., Eichenlaub, J. B., Bertrand, O., Morlet, D., and Bidet-Caulet, A. (2013). Alpha reactivity to first names differs in subjects with high and low dream recall frequency. *Front. Psychol.* 4:419. doi: 10.3389/fpsyg.2013.00419

Rutishauser, U., Ross, I. B., Mamelak, A. N., and Schuman, E. M. (2010). Human memory strength is predicted by theta-frequency phase-locking of single neurons. *Nature* 464, 903–907. doi: 10.1038/nature08860

Scarpelli, S., Marzano, C., D'Atri, A., Gorgoni, M., Ferrara, M., and De Gennaro, L. (2014). *Correlati EEG del ricordo onirico: relazione di stato o di tratto?* [EEG correlates of dream recall: a state- or trait-like relation?], XXIV Congresso Nazionale Associazione Italiana di Medicina del Sonno (A.I.M.S.) Pisa, 5–7 November, p. 20.

Scharf, B., Moskowitz, C., Lupton, M., and Klawans, H. (1978). Dream phenomena induced by chronic Levodopa therapy. *J. Neural. Transm.* 43, 143–151. doi: 10.1007/BF01579073

Schredl, M. (2003). Continuity between waking and dreaming: a proposal for a mathematical model. *Sleep Hypn.* 5, 26–40.

Schredl, M. (2009). Dreams in patients with sleep disorders. *Sleep Med. Rev.* 13, 215–221. doi: 10.1016/j.smrv.2008.06.002

Schwartz, S., and Maquet, P. (2002). Sleep imaging and the neuropsychological assessment of dreams. *Trends Cogn.* 6, 23–30. doi: 10.1016/S1364-6613(00)01818-0

Sederberg, P. B., Kahana, M. J., Howard, M. W., Donner, E. J., and Madsen, J. R. (2003). Theta and gamma oscillations during encoding predict subsequent recall. *J. Neurosci.* 23, 10809–10814.

Shin, L. M., Rauch, S. L., and Pitman, R. K. (2006). Amygdala, medial prefrontal cortex, and hippocampal function in PTSD. *Ann. N. Y. Acad. Sci.* 1071, 67–79. doi: 10.1196/annals.1364.007

Siegel, J. M. (2001). The REM sleep-memory consolidation hypothesis. *Science* 294, 1058–1063. doi: 10.1126/science.1063049

Smallwood, J., and Schooler, J. (2006). The restless mind. *Psychol. Bull.* 132, 946–958. doi: 10.1037/0033-2909.132.6.946

Smith, E. E., and Jonides, J. (1999). Storage and executive processes in the frontal lobes. *Science* 283, 1657–1661. doi: 10.1126/science.283.5408.1657

Solms, M. (1997). *The Neuropsychology of Dreams: A Clinico-Anatomical Study*. Hillsdale: Erlbaum.

Solms, M. (2000). Dreaming and REM sleep are controlled by different brain mechanisms. *Behav. Brain Sci.* 2, 843–850. doi: 10.1017/S0140525X00003988

Staudigl, T., Hanslmayr, S., and Bäuml, K. H. T. (2010). Theta oscillations reflect the dynamics of interference in episodic memory retrieval. *J. Neurosci.* 30, 11356–11362. doi: 10.1523/JNEUROSCI.0637-10.2010

Stickgold, R., Pace-Schott, E. F., and Hobson, J. A. (1994). A new paradigm for dream research: mentation reports following spontaneous arousal from REM and NREM sleep recorded in a home setting. *Conscious. Cogn.* 3, 16–29. doi: 10.1006/ccog.1994.1002

Takahashi, N., Shinomiya, S., Mori, D., and Tachibana, S. (1997). Frontal midline theta rhythm in young healthy adults. *Clin. Electroencephalogr.* 28, 49–54. doi: 10.1177/155005949702800109

Takeuchi, T., Ogilvie, R. D., Murphy, T. I., and Ferrelli, A. V. (2003). EEG activities during elicited sleep onset REM and NREM periods reflect different mechanisms of dream generation. *Clin. Neurophysiol.* 114, 210–220. doi: 10.1016/S1388-2457(02)00385-1

Tinguely, G., Finelli, L. A., Landolt, H. P., Borbély, A. A., and Achermann, P. (2006). Functional EEG topography in sleep and waking: state-dependent and state-independent features. *Neuroimage* 32, 283–292. doi: 10.1016/j.neuroimage.2006.03.017

Tulving, E. (2002). Episodic memory: from mind to brain. *Annu. Rev. Psychol.* 53, 1–25. doi: 10.1146/annurev.psych.53.100901.135114

Waterman, D., Elton, M., and Kenemans, J. L. (1993). Methodological issues affecting the collection of dreams. *J. Sleep Res.* 2, 8–12. doi: 10.1111/j.1365-2869.1993.tb00053.x

Wehrle, R., Czisch, M., Kaufmann, C., Wetter, T. C., Holsboer, F., Auer, D. P., et al. (2005). Rapid eye movement related brain activation in human sleep: a functional magnetic resonance imaging study. *Neuroreport* 16, 853–857. doi: 10.1097/00001756-200505310-00015

Wehrle, R., Kaufmann, C., Wetter, T. C., Holsboer, F., Auer, D. P., Pollmächer, T., et al. (2007). Functional microstates within human REM sleep: first evidence from fMRI of a thalamocortical network specific for phasic REM periods. *Eur. J. Neurosci.* 25, 863–871. doi: 10.1111/j.1460-9568.2007.05314.x

White, T., Jansen, M., Doege, K., Mullinger, K. J., Park, S. B., Liddle, E. B., et al. (2013). Theta power during encoding predicts subsequent memory performance and default mode network deactivation. *Hum. Brain Mapp.* 34, 2929–2943. doi: 10.1002/hbm.22114

Zimmerman, W. B. (1970). Sleep mentation and auditory awakening thresholds. *Psychophysiology* 6, 540–549. doi: 10.1111/j.1469-8986.1970.tb02243.x

Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers
in Psychology

OPINION
published: 20 April 2015
doi: 10.3389/fpsyg.2015.00478

Schizophrenia: from neurophysiological abnormalities to clinical symptoms

Anna Castelnovo [1, 2], *Fabio Ferrarelli* [2] *and Armando D'Agostino* [1]*

[1] Department of Health Sciences, Università degli Studi di Milano, Milan, Italy, [2] Department of Psychiatry, University of Wisconsin-Madison, Madison, WI, USA

Keywords: psychotic disorders, sleep spindles, parvalbumin-positive interneuron, basket cells, reward system, gamma frequency oscillations, prediction error, predictive coding

OPEN ACCESS

Edited by:
Roumen Kirov,
Bulgarian Academy of Sciences,
Bulgaria

Reviewed by:
Timo Partonen,
National Institute for Health and
Welfare, Finland
Karl Friston,
University College London, UK

Correspondence:
Armando D'Agostino,
armando.dagostino@unimi.it

Specialty section:
This article was submitted to
Cognitive Science,
a section of the journal
Frontiers in Psychology

Received: *13 March 2015*
Paper pending published:
23 March 2015
Accepted: *02 April 2015*
Published: *20 April 2015*

Citation:
Castelnovo A, Ferrarelli F and
D'Agostino A (2015) Schizophrenia:
from neurophysiological abnormalities
to clinical symptoms.
Front. Psychol. 6:478.
doi: 10.3389/fpsyg.2015.00478

Introduction

Schizophrenia (SCZ) has long been associated with multifaceted dysfunctions and multiple genetic as well as environmental etiological factors (Réthelyi et al., 2013). Therefore, after a century of inconsistent results, the search for a unifying pathogenetic mechanism has become one of the most challenging issues in SCZ research.

During the last decade, a growing literature has pointed to the so-called disconnection hypothesis (Friston, 1998; Tononi and Edelman, 2000; Stephan et al., 2009), i.e., to a defective integration among distributed brain areas, which may lead to a systematic impairment of information processing. EEG is a suitable tool to probe this hypothesis in the time domain, since the EEG oscillatory activity can capture subtle functional changes of underlying neuronal systems with exquisite temporal resolution. Consistent with this prediction, several recent EEG findings have shown abnormalities in SCZ neural oscillations during both wakefulness (Uhlhaas and Singer, 2014) and sleep (Gardner et al., 2014).

Cognitive and theoretical approaches of brain functioning have been used to explain phenomenological features and neural disruptions in SCZ. Since its earliest conceptualizations, abnormalities of self-experience have been identified as a critical feature of the illness (Schneider, 1950). Positive and passivity symptoms in SCZ have been hypothesized to involve a misattribution of self-generated actions, thoughts and percepts to an external agency (Frith, 2005). One possible neurophysiological explanation for this peculiar subjective experience is an aberrant generation of corollary discharge (CD) by efference copy mechanisms (Feinberg, 2011). More recently, predictive coding theories began to add an integrated and structured framework to previous observations (Van de Cruys et al., 2014; Moran et al., 2015).

We herein attempt to reconcile recent major neurophysiological findings with currently established approaches to SCZ psychopathology.

Predictive Coding in Schizophrenia

Predictive coding theory considers the brain as learning the statistical regularities in the world and performing inferences using the evidence reported by precision-weighted prediction errors. According to this model, the comparison between bottom-up inputs and top-down predictions yields a prediction error that is weighted in proportion to its expected precision, thus reducing redundancy by removing the predictable components of the input signal. This early theory of sensory processing (Attneave, 1954) was recently implemented by perceptual learning (Friston, 2003) and its application to all brain circuits and cortical microcircuits (Bastos et al., 2012).

Above and beyond the generalization of the model, its use in the context of the reward system seems of particular biological relevance. Indeed, it has been shown that ventral striatum (VS) neurons fire in anticipation of outcomes, and only subsets may also respond during reward consumption (Pennartz et al., 2004, 2011). In particular, dopamine is thought to selectively modulate the strength or gain of associative control over motivated behavior in a regionally specific manner (Pennartz et al., 2011). Crucially, the neuromodulatory effect of dopamine on the gain of postsynaptic responses appears to fit with its putative role in mediating the precision or gain of reward-related prediction errors (Oyama et al., 2010; Schwartenbeck et al., 2014).

A disruption of the delicate balance of precision between beliefs and sensory evidence (Fletcher and Frith, 2009) and the aberrant assignment of salience to elements from one's own experience (Kapur, 2003) have been proposed to underlie the positive symptoms observed in SCZ. Under predictive coding theory SCZ pathology could be described as a failure of neural modulatory gain control that leads to an aberrant weighting of prediction errors and a failure to afford them the precision of salience necessary for perceptual inference and action selection.

In what follows, we will consider the neuromodulatory and synchronous gain mechanisms that may underlie this aberrant processing and subsequent false inference.

Sleep EEG Major Findings in Schizophrenia

The study of spontaneous neural activity during sleep provides a unique window to investigate the function of the normal and disordered brain. Sleep minimizes possible confounding factors related to waking activities, including changes in the level of attention, decreased motivation or cognitive capacity, and the presence of a variety of symptoms that prevent a reliable task performance (Ferrarelli et al., 2007).

Disruptions in sleep homeostasis, in the sleep/circadian rhythm, as well as in sleep architecture have long been recognized as a symptom in SCZ, and often precede the first clinical breakdown (reviewed in Zanini et al., 2013). More subtle, microarchitectural changes in sleep were recently reported by several different laboratories (reviewed by Gardner et al., 2014).

Whole night deficits in sleep spindles, waxing-and-waning EEG oscillations in the 11–16 Hz frequency range, have been recently reported by several studies. Specifically, spindle density and Integrated Spindle Activity (ISA) were found to be reduced in prefrontal, centro-parietal, and temporal regions (Ferrarelli et al., 2007, 2010). A marked reduction of sleep spindles has been also demonstrated in first-degree relatives and in early course, drug-naïve subjects (Manoach et al., 2014). Conversely, conflicting reports exist regarding slow wave activity (SWA), and no direct data are available to date on sharp-wave/ripple complexes since they cannot be detected with non-invasive scalp EEG recordings.

The Search for the Missing Link: PV Interneurons

Sleep spindles are generated in the thalamic reticular nucleus (TRN), a thin sheet of cells surrounding the anterolateral part of the thalamus (Halassa et al., 2011). The TRN is entirely composed of a rather heterogeneous population of parvalbumin immunoreactive GABAergic neurons (PV+) (Celio, 1990). Several line of evidence currently converge on the implication of PV+ neurons in SCZ. Post-mortem studies revealed GABAergic alterations, in particular in PV+ and calretin neurons (e.g., Beasley et al., 2002) in schizophrenia patients. Moreover, abnormal amplitude and synchrony of oscillatory activity, mainly frontal and at high (gamma) frequencies, have been found in SCZ, during task-related, spontaneous neuronal activity (Uhlhaas and Singer, 2013), as well as after transcranial magnetic stimulation (Ferrarelli et al., 2012; Rogasch et al., 2014). Gamma frequency (30–80 Hz) oscillations require the synchronized inhibition of neighboring populations of pyramidal neurons by the subclass of cortical PV+GABA interneurons (Sohal et al., 2009).

Finally, some animal models have given preliminary support to the hypothesis of a deregulation of PV+ neurons in SCZ (e.g., Carlson et al., 2011; Phillips et al., 2012; Kaalund et al., 2013). PV+ neurons can be found throughout the CNS (Celio, 1990), including the TRN, the hippocampus and the neocortex. They selectively express high levels of the PV Ca^{2+}-binding protein acting as a "slow Ca^{2+} buffer" to modulate Ca^{2+} cytosolic homeostasis, short action potential duration and a fast-spiking action potential phenotype. The buffering capacity of PV may protect from Ca^{2+}-mediated excitotoxic insult (Figueredo-Cardenas et al., 1998).

Optogenetic and pharmacogenetic approaches have begun to provide insight into the function of PV+ interneurons not only at the cellular, but at both the network and behavioural levels (Hu et al., 2014). PV+ interneurons play a major role in network oscillations (Bartos et al., 2007), and are implicated in perceptual discrimination (e.g., Lee et al., 2012), attention (Zikopoulos and Barbas, 2006), in the regulation of plasticity and learning (e.g., Donato et al., 2013), as well as in reward-related behavior (Sparta et al., 2014).

Finally, PV+ neurons involvement in SCZ is in accordance with the generic role of cortical gain and excitation/inhibition balance, that has been recently proposed to underlie false inference in SCZ (e.g., Adams et al., 2013; Jardri and Denève, 2013). PV+ neuron dysfunction can be primary or secondary to the dysfunction of other pathways and neuromodulators (for a review, Lewis et al., 2012), genetically inherited or environmentally induced (Jiang et al., 2013; Stansfield et al., 2015). While PV dysfunction has recently been proposed as a substrate for cognitive dysfunction in SCZ (e.g., Lewis, 2014), we here focus on its possible connection to the development of positive symptoms and to current theoretical approaches that attempts to explain the complex phenomenology of the disorder.

Reconciling Theory and Physiology

The hypothesis of functional impairment of PV+ neurons doesn't only justify the established deficit in sleep spindles, but also leads to speculation over abnormalities in other functional circuits and their possible correlations with neurophysiological findings and symptoms in SCZ.

The TRN, situated in a strategic position between the neocortex and the thalamus (Pinault, 2004), is related to sensory gating in the thalamocortical and corticothalamic axes (Jones, 2002), as well as in the modulation of attention (Zikopoulos and Barbas, 2006). PV deficiency affects the dynamics of burst discharges of TRN cells, which in turn regulate the activity in the thalamocortical circuit (Albéri et al., 2013). TRN tonic activity during wake inhibits spontaneous background activity in specific thalamocortical reley nuclei, probably under the control of attentional mechanism from frontal and limbic structures, and are implicate in lateral inhibition, optimizing responses to sensory stimulation and their transfer to the cortex (Pinault and Deschênes, 1998; Hartings et al., 2003). A deficit of the TRN leads to loss of sensory-specific inhibition, which results in an increase of spontaneous background activity and a decrease of lateral inhibition in specific thalamic nuclei, thus resulting in a reduction in the signal-to-noise ratio or precision of thalamic relays (Ferrarelli and Tononi, 2011).

Abnormal sensory experience, which characterizes the prodromal phase of SCZ and gives rise to hallucinations, would occur when sensory inputs fail to adequately modulate thalamocortical activity (Behrendt, 2006). It has already been suggested that a deficit in TRN can lead to impaired CD mechanisms through a disruption of the integrative function of corticothalamocortical circuits mediated by the TRN (Vukadinovic, 2011). A deficit in the activity of the TRN would therefore produce abnormal sensory feedbacks along with impaired efferent copies from the motor and associative to the sensory cortices, which would generate an imbalance between predicted and actual feedbacks as well as a reduced sense of agency (Vukadinovic, 2011).

The role of DA in generating positive symptoms of SCZ has been hypothesized since the serendipitous discovery that D2 blocker compounds have strong antipsychotic efficacy in SCZ patients (Howes and Kapur, 2009). Furthermore, Dopamine (DA) receptors (D4) have been established on GABAergic interneurons in the cerebral cortex, the HC and the TRN (Mrzljak et al., 1996), but the neural circuits and the effects of dopamine on PV positive TRN neurons are still not well characterized. Additionally, the reduction of vHC PV expression has been found to increase DA activity in the ventral tegmental area (VTA) and behavioral hyper-locomotor-responsivity to amphetamine in awake rats (Boley et al., 2014) via a multi-synaptic pathway (Lodge and Grace, 2007, 2011). In the case of SCZ a PV+ neuron dysfunction may lead to an increased number of DA neurons in VTA spontaneously active, thus affecting the ability of the cortex to appropriately regulate the gain of incoming stimuli. The same salience is therefore assigned to all stimuli, leading to a disruption of the prediction error weighting in systems responsible for action selection and perceptual synthesis. This provides a simple explanation for false inference implicit in symptoms like hallucinations and delusions (Adams et al., 2013; Fogelson et al., 2014).

Finally, PV+ neuron deficits also suggest the presence of other subtle abnormalities in neural oscillations in SCZ, like an alteration in hippocampal ripples. Basket PV+ cells in the HC fire at high frequency and are phase-locked to ripple oscillations (140–200 Hz), providing an inhibitory temporal structure for large populations of pyramidal cells, and possibly contributing to the synchronization of the entire network (Klausberger et al., 2003, 2005; Fuchs et al., 2007; Klausberger and Somogyi, 2008; Rácz et al., 2009). Importantly, hippocampal ripples occur during SWS and consummatory behaviors (Buzsáki et al., 2003), the same pattern of activation observed in the VS.

This is consistent with the Reward Activation Model (RAM, Perogamvros and Schwartz, 2012), in which the reward system plays a central role not only during wakefulness, but also during sleep and dreaming. In particular, HC and VS have been hypothesized to act in conjunction to link memory traces to a motivational value, possibly through hippocampal ripples during NREM sleep.

Conclusions

We briefly described an approach to SCZ encompassing theoretical models, including disconnection hypotheses and predictive coding abnormalities, as well as neurophysiological findings, from sleep abnormalities to psychopathological signs observed during wakefulness. We suggest that sleep spindles and waking gamma deficit support a dysfunctional role of thalamic and cortical PV+ neurons as a common pathway, either primary or secondary, in SCZ disease, which may explain both cognitive deficits and positive symptoms observed in these patients. Specifically, dysfunction in hippocampal and thalamic PV+ neurons together with more subtle alteration in DA-regulated hippocampal-limbic circuits warrant further investigation and may provide further support to the idea of a disruption in **salience or precision** in SCZ during both wake and sleep. In sum, we believe that the integration of theoretical models and physiological findings will enrich both fields and may lead to the discovery of novel therapeutic targets for patients with SCZ.

References

Adams, R. A., Stephan, K. E., Brown, H. R., Frith, C. D., and Friston, K. J. (2013). The computational anatomy of psychosis. *Front. Psychiatry* 4:47. doi: 10.3389/fpsyt.2013.00047

Albéri, L., Lintas, A., Kretz, R., Schwaller, B., and Villa, A. E. (2013). The calcium-binding protein parvalbumin modulates the firing properties of the reticular thalamic nucleus bursting neurons. *J. Neurophysiol.* 109, 2827–2841. doi: 10.1152/jn.00375.2012

Attneave, F. (1954). Some informational aspects of visual perception. *Psychol. Rev.* 61, 183–193. doi: 10.1037/h0054663

Bartos, M., Vida, I., and Jonas, P. (2007). Synaptic mechanisms of synchronized gamma oscillations in inhibitory interneuron networks. *Nat. Rev. Neurosci.* 8, 45–56. doi: 10.1038/nrn2044

Bastos, A. M., Usrey, W. M., Adams, R. A., Mangun, G. R., Fries, P., and Friston, K. J. (2012). Canonical microcircuits for predictive coding. *Neuron* 76, 695–711. doi: 10.1016/j.neuron.2012.10.038

Beasley, C. L., Zhang, Z. J., Patten, I., and Reynolds, G. P. (2002). Selective deficits in prefrontal cortical GABAergic neurons in schizophrenia defined by the presence of calcium-binding proteins. *Biol. Psychiatry* 52, 708–715. doi: 10.1016/S0006-3223(02)01360-4

Behrendt, R. P. (2006). Dysregulation of thalamic sensory "transmission" in schizophrenia: neurochemical vulnerability to hallucinations. *J. Psychopharmacol.* 20, 356–372. doi: 10.1177/0269881105057696

Boley, A. M., Perez, S. M., and Lodge, D. J. (2014). A fundamental role for hippocampal parvalbumin in the dopamine hyperfunction associated with schizophrenia. *Schizophr. Res.* 157, 238–243. doi: 10.1016/j.schres.2014.05.005

Buzsáki, G., Buhl, D. L., Harris, K. D., Csicsvari, J., Czéh, B., and Morozov, A. (2003). Hippocampal network patterns of activity in the mouse. *Neuroscience* 116, 201–211. doi: 10.1016/S0306-4522(02)00669-3

Carlson, G. C., Talbot, K., Halene, T. B., Gandal, M. J., Kazi, H. A., Schlosser, L., et al. (2011). Dysbindin-1 mutant mice implicate reduced fast-phasic inhibition as a final common disease mechanism in schizophrenia. *Proc. Natl. Acad. Sci. U.S.A.* 108, E962–E970. doi: 10.1073/pnas.1109625108

Celio, M. R. (1990). Calbindin D-28k and parvalbumin in the rat nervous system. *Neuroscience* 35, 375–475. doi: 10.1016/0306-4522(90)90091-H

Donato, F., Rompani, S. B., and Caroni, P. (2013). Parvalbumin-expressing basket-cell network plasticity induced by experience regulates adult learning. *Nature* 504, 272–276. doi: 10.1038/nature12866

Feinberg, I. (2011). Corollary discharge, hallucinations, and dreaming. *Schizophr. Bull.* 37, 1–3. doi: 10.1093/schbul/sbq115

Ferrarelli, F., Huber, R., Peterson, M. J., Massimini, M., Murphy, M., Riedner, B. A., et al. (2007). Reduced sleep spindle activity in schizophrenia patients. *Am. J. Psychiatry* 164, 483–492. doi: 10.1176/ajp.2007.164.3.483

Ferrarelli, F., Peterson, M. J., Sarasso, S., Riedner, B. A., Murphy, M. J., Benca, R. M., et al. (2010). Thalamic dysfunction in schizophrenia suggested by whole-night deficits in slow and fast spindles. *Am. J. Psychiatry* 167, 1339–1348. doi: 10.1176/appi.ajp.2010.09121731

Ferrarelli, F., Sarasso, S., Guller, Y., Riedner, B. A., Peterson, M. J., Bellesi, M., et al. (2012). Reduced natural oscillatory frequency of frontal thalamocortical circuits in schizophrenia. *Arch. Gen. Psychiatry* 69, 766–774. doi: 10.1001/archgenpsychiatry.2012.147

Ferrarelli, F., and Tononi, G. (2011). The thalamic reticular nucleus and schizophrenia. *Schizophr. Bull.* 37, 306–315. doi: 10.1093/schbul/sbq142

Figueredo-Cardenas, G., Harris, C. L., Anderson, K. D., and Reiner, A. (1998). Relative resistance of striatal neurons containing calbindin or parvalbumin to quinolinic acid-mediated excitotoxicity compared to other striatal neuron types. *Exp. Neurol.* 149, 356–372. doi: 10.1006/exnr.1997.6724

Fletcher, P. C., and Frith, C. D. (2009). Perceiving is believing: a Bayesian approach to explaining the positive symptoms of schizophrenia. *Nat. Rev. Neurosci.* 10, 48–58. doi: 10.1038/nrn2536

Fogelson, N., Litvak, V., Peled, A., Fernandez-del-Olmo, M., and Friston, K. (2014). The functional anatomy of schizophrenia: a dynamic causal modeling study of predictive coding. *Schizophr. Res.* 158, 204–212 doi: 10.1016/j.schres.2014.06.011

Friston, K. (2003). Learning and inference in the brain. *Neural Netw.* 16, 1325–1352. doi: 10.1016/j.neunet.2003.06.005

Friston, K. J. (1998). The disconnection hypothesis. *Schizophr. Res.* 30, 115–125. doi: 10.1016/S0920-9964(97)00140-0

Frith, C. (2005). The neural basis of hallucinations and delusions. *C. R. Biol.* 328, 169–175. doi: 10.1016/j.crvi.2004.10.012

Fuchs, E. C., Zivkovic, A. R., Cunningham, M. O., Middleton, S., Lebeau, F. E., Bannerman, D. M., et al. (2007). Recruitment of parvalbumin- positive interneurons determines hippocampal function and associated behavior. *Neuron* 53, 591–604. doi: 10.1016/j.neuron.2007.01.031

Gardner, R. J., Kersanté, F., Jones, M. W., and Bartsch, U. (2014). Neural oscillations during non-rapid eye movement sleep as biomarkers of circuit dysfunction in schizophrenia. *Eur. J. Neurosci.* 39, 1091–1106. doi: 10.1111/ejn.12533

Halassa, M. M., Siegle, J. H., Ritt, J. T., Ting, J. T., Feng, G., and Moore, C. I. (2011). Selective optical drive of thalamic reticular nucleus generates thalamic bursts and cortical spindles. *Nat. Neurosci.* 14, 1118–1120. doi: 10.1038/nn.2880

Hartings, J. A., Temereanca, S., and Simons, D. J. (2003). State-dependent processing of sensory stimuli by thalamic reticular neurons. *J. Neurosci.* 23, 5264–5271.

Howes, O. D., and Kapur, S. (2009). The dopamine hypothesis of schizophrenia: version III–the final common pathway. *Schizophr. Bull.* 35, 549–562. doi: 10.1093/schbul/sbp006

Hu, H., Gan, J., and Jonas, P. (2014). Interneurons. Fast-spiking, parvalbumin? GABAergic interneurons: from cellular design to microcircuit function. *Science* 345:1255263. doi: 10.1126/science.1255263

Jardri, R., and Denève, S. (2013). Circular inferences in schizophrenia. *Brain* 136(Pt 11), 3227–3241. doi: 10.1093/brain/awt257

Jiang, Z., Cowell, R. M., and Nakazawa, K. (2013). Convergence of genetic and environmental factors on parvalbumin-positive interneurons in schizophrenia. *Front. Behav. Neurosci.* 7:116. doi: 10.3389/fnbeh.2013.00116

Jones, E. G. (2002). Thalamic organization and function after Cajal. *Prog. Brain Res.* 136, 333–357. doi: 10.1016/S0079-6123(02)36029-1

Kaalund, S. S., Riise, J., Broberg, B. V., Fabricius, K., Karlsen, A. S., Secher, T., et al. (2013). Differential expression of parvalbumin in neonatal phencyclidine-treated rats and socially isolated rats. *J. Neurochem.* 124, 548–557. doi: 10.1111/jnc.12061

Kapur, S. (2003). Psychosis as a state of aberrant salience: a framework linking biology, phenomenology, and pharmacology in schizophrenia. *Am. J. Psychiatry* 160, 13–23. doi: 10.1176/appi.ajp.160.1.13

Klausberger, T., Magill, P. J., Márton, L. F., Roberts, J. D., Cobden, P. M., Buzsáki, G., et al. (2003). Brain-state- and cell-type specific firing of hippocampal interneurons *in vivo*. *Nature* 421, 844–848. doi: 10.1038/nature01374

Klausberger, T., Marton, L. F., O'Neill, J., Huck, J. H., Dalezios, Y., Fuentealba, P., et al. (2005). Complementary roles of cholecystokinin- and parvalbumin expressing GABAergic neurons in hippocampal network oscillation. *J. Neurosci.* 25, 9782–9793. doi: 10.1523/JNEUROSCI.3269-05.2005

Klausberger, T., and Somogyi, P. (2008). Neuronal diversity and temporal dynamics: the unity of hippocampal circuit operations. *Science* 321, 53–57. doi: 10.1126/science.1149381

Lee, S. H., Kwan, A. C., Zhang, S., Phoumthipphavong, V., Flannery, J. G., Masmanidis, S. C., et al. (2012). Activation of specific interneurons improves V1 feature selectivity and visual perception. *Nature* 488, 379–383. doi: 10.1038/nature11312

Lewis, D. A. (2014). Inhibitory neurons in human cortical circuits: substrate for cognitive dysfunction in schizophrenia. *Curr. Opin. Neurobiol.* 26, 22–26. doi: 10.1016/j.conb.2013.11.003

Lewis, D. A., Curley, A. A., Glausier, J. R., and Volk, D. W. (2012). Cortical parvalbumin interneurons and cognitive dysfunction in schizophrenia. *Trends Neurosci.* 35, 57–67. doi: 10.1016/j.tins.2011.10.004

Lodge, D. J., and Grace, A. A. (2007). Aberrant hippocampal activity underlies the dopamine dysregulation in an animal model of schizophrenia. *J. Neurosci.* 27, 11424–11430. doi: 10.1523/JNEUROSCI.2847-07.2007

Lodge, D. J., and Grace, A. A. (2011). Hippocampal dysregulation of dopamine system function and the pathophysiology of schizophrenia. *Trends Pharmacol. Sci.* 32, 507–513. doi: 10.1016/j.tips.2011.05.001

Manoach, D. S., Demanuele, C., Wamsley, E. J., Vangel, M., Montrose, D. M., Miewald, J., et al. (2014). Sleep spindle deficits in antipsychotic-naïve early course schizophrenia and in non-psychotic first-degree relatives. *Front. Hum. Neurosci.* 8:762. doi: 10.3389/fnhum.2014.00762

Moran, R. J., Jones, M. W., Blockeel, A. J., Adams, R. A., Stephan, K. E., and Friston, K. J. (2015). Losing control under ketamine: suppressed cortico-hippocampal drive following acute ketamine in rats. *Neuropsychopharmacology* 40, 268–277. doi: 10.1038/npp.2014.184

Mrzljak, L., Bergson, C., Pappy, M., Huff, R., Levenson, R., and Goldman-Rakic, P. S. (1996). Localization of dopamine D4 receptors in GABAergic neurons of the primate brain. *Nature* 381, 245–248. doi: 10.1038/381245a0

Oyama, K., Hernàdi, I., and Tsutsui, K. (2010). Reward prediction error coding in dorsal striatal neurons. *J. Neurosci.* 30, 11447–11457. doi: 10.1523/JNEUROSCI.1719-10.2010

Pennartz, C. M., Ito, R., Verschure, P. F., Battaglia, F. P., and Robbins, T. W. (2011). The hippocampal-striatal axis in learning, prediction and goal-directed behavior. *Trends Neurosci.* 34, 548–559. doi: 10.1016/j.tins.2011.08.001

Pennartz, C. M., Lee, E., Verheul, J., Lipa, P., Barnes, C. A., and McNaughton, B. L. (2004). The ventral striatum in off-line processing: ensemble reactivation during sleep and modulation by hippocampal ripples. *J. Neurosci.* 24, 6446–6456. doi: 10.1523/JNEUROSCI.0575-04.2004

Perogamvros, L., and Schwartz, S. (2012). The roles of the reward system in sleep and dreaming. *Neurosci. Biobehav. Rev.* 36, 1934–1951. doi: 10.1016/j.neubiorev.2012.05.010

Phillips, K. G., Bartsch, U., McCarthy, A. P., Edgar, D. M., Tricklebank, M. D., Wafford, K. A., et al. (2012). Decoupling of sleep dependent cortical and hippocampal interactions in a neurodevelopmental model of schizophrenia. *Neuron* 76, 526–533 doi: 10.1016/j.neuron.2012.09.016

Pinault, D. (2004). The thalamic reticular nucleus: structure, function and concept. *Brain Res. Brain Res. Rev*. 46, 1–31. doi: 10.1016/j.brainresrev.2004.04.008

Pinault, D., and Deschênes, M. (1998). Anatomical evidence for a mechanism of lateral inhibition in the rat thalamus. *Eur. J. Neurosci.* 10, 3462–3469. doi: 10.1046/j.1460-9568.1998.00362.x

Rácz, A., Ponomarenko, A. A., Fuchs, E. C., and Monyer, H. (2009). Augmented hippocampal ripple oscillations in mice with reduced fast excitation onto parvalbumin-positive cells. *J. Neurosci.* 29, 2563–2568. doi: 10.1523/JNEUROSCI.5036-08.2009

Réthelyi, J. M., Benkovits, J., and Bitter, I. (2013). Genes and environments in schizophrenia: the different pieces of a manifold puzzle. *Neurosci. Biobehav. Rev*. 37(10 Pt 1), 2424–2437. doi: 10.1016/j.neubiorev.2013.04.010

Rogasch, N. C., Daskalakis, Z. J., and Fitzgerald, P. B. (2014). Cortical inhibition, excitation, and connectivity in schizophrenia: a review of insights from transcranial magnetic stimulation. *Schizophr. Bull.* 40, 685–696. doi: 10.1093/schbul/sbt078

Schneider, K. (1950). *Klinische Psychopathologie. (3. Vermehrte Auflage der Beiträge Zur Psychiatrie Ed.).* Stuttgart: Thieme.

Schwartenbeck, P., FitzGerald, T. H., Mathys, C., Dolan, R., and Friston, K. (2014). The dopaminergic midbrain encodes the expected certainty about desired outcomes. *Cereb. Cortex.* doi: 10.1093/cercor/bhu159. [Epub ahead of print].

Sohal, V. S., Zhang, F., Yizhar, O., and Deisseroth, K. (2009). Parvalbumin neurons and gamma rhythms enhance cortical circuit performance. *Nature* 459, 698–702. doi: 10.1038/nature07991

Sparta, D. R., Hovelsø, N., Mason, A. O., Kantak, P. A., Ung, R. L., Decot, H. K., et al. (2014). Activation of prefrontal cortical parvalbumin interneurons facilitates extinction of reward-seeking behavior. *J. Neurosci*. 34, 3699–3705. doi: 10.1523/JNEUROSCI.0235-13.2014

Stansfield, K. H., Ruby, K. N., Soares, B. D., McGlothan, J. L., Liu, X., and Guilarte, T. R. (2015). Early-life lead exposure recapitulates the selective loss of parvalbumin-positive GABAergic interneurons and subcortical dopamine system hyperactivity present in schizophrenia. *Transl. Psychiatry* 5:e522. doi: 10.1038/tp.2014.147

Stephan, K. E., Friston, K. J., and Frith, C. D. (2009). Dysconnection in schizophrenia: from abnormal synaptic plasticity to failures of self-monitoring. *Schizophr. Bull.* 35, 509–527. doi: 10.1093/schbul/sbn176

Tononi, G., and Edelman, G. M. (2000). Schizophrenia and the mechanisms of conscious integration. *Brain Res. Brain Res. Rev*. 31, 391–400. doi: 10.1016/S0165-0173(99)00056-9

Uhlhaas, P. J., and Singer, W. (2013). High-frequency oscillations and the neurobiology of schizophrenia. *Dialogues Clin. Neurosci*. 15, 301–313.

Uhlhaas, P. J., and Singer, W. (2014). Oscillations and neuronal dynamics in schizophrenia: the search for basic symptoms and translational opportunities. *Biol. Psychiatry*. doi: 10.1016/j.biopsych.2014.11.019. [Epub ahead of print].

Van de Cruys, S., Evers, K., Van der Hallen, R., Van Eylen, L., Boets, B., de-Wit, L., et al. (2014). Precise minds in uncertain worlds: predictive coding in autism. *Psychol. Rev*. 121, 649–675. doi: 10.1037/a0037665

Vukadinovic, Z. (2011). Sleep abnormalities in schizophrenia may suggest impaired trans-thalamic cortico-cortical communication: towards a dynamic model of the illness. *Eur. J. Neurosci*. 34, 1031–1039. doi: 10.1111/j.1460-9568.2011.07822.x

Zanini, M., Castro, J., Coelho, F. M., Bittencourt, L., Bressan, R. A., Tufik, S., et al. (2013). Do sleep abnormalities and misaligned sleep/circadian rhythm patterns represent early clinical characteristics for developing psychosis in high risk populations? *Neurosci. Biobehav. Rev*. 37(10 Pt 2), 2631–2637. doi: 10.1016/j.neubiorev.2013.08.012

Zikopoulos, B., and Barbas, H. (2006). Prefrontal projections to the thalamic reticular nucleus form a unique circuit for attentional mechanisms. *Trends Neurosci*. 24, 330–334. doi: 10.1523/JNEUROSCI.5511-05.2006

Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

HYPOTHESIS AND THEORY
published: 15 July 2016
doi: 10.3389/fpsyg.2016.00922

Free Energy and Virtual Reality in Neuroscience and Psychoanalysis: A Complexity Theory of Dreaming and Mental Disorder

Jim Hopkins *

Research Department of Clinical Educational and Health Psychology, University College London, London, UK

The main concepts of the free energy (FE) neuroscience developed by Karl Friston and colleagues parallel those of Freud's Project for a Scientific Psychology. In Hobson et al. (2014) these include an innate virtual reality generator that produces the fictive prior beliefs that Freud described as the primary process. This enables Friston's account to encompass a unified treatment—a complexity theory—of the role of virtual reality in both dreaming and mental disorder. In both accounts the brain operates to minimize FE aroused by sensory impingements—including interoceptive impingements that report compliance with biological imperatives—and constructs a representation/model of the causes of impingement that enables this minimization. In Friston's account (variational) FE equals complexity minus accuracy, and is minimized by increasing accuracy and decreasing complexity. Roughly the brain (or model) increases accuracy together with complexity in waking. This is mediated by consciousness-creating active inference—by which it explains sensory impingements in terms of perceptual experiences of their causes. In sleep it reduces complexity by processes that include both synaptic pruning and consciousness/virtual reality/dreaming in REM. The consciousness-creating active inference that effects complexity-reduction in REM dreaming must operate on FE-arousing data distinct from sensory impingement. The most relevant source is remembered arousals of emotion, both recent and remote, as processed in SWS and REM on "active systems" accounts of memory consolidation/reconsolidation. Freud describes these remembered arousals as condensed in the dreamwork for use in the conscious contents of dreams, and similar condensation can be seen in symptoms. Complexity partly reflects emotional conflict and trauma. This indicates that dreams and symptoms are both produced to reduce complexity in the form of potentially adverse (traumatic or conflicting) arousals of amygdala-related emotions. Mental disorder is thus caused by computational complexity together with mechanisms like synaptic pruning that have evolved for complexity-reduction; and important features of disorder can be understood in these terms. Details of the consilience among Freudian, systems consolidation, and complexity-reduction accounts appear clearly in the analysis of a single fragment of a dream, indicating also how complexity reduction proceeds by a process resembling Bayesian model selection.

Keywords: free energy, complexity, emotional conflict, memory consolidation, synaptic pruning, dreaming, mental disorder

Edited by:
Roumen Kirov,
Bulgarian Academy of Sciences,
Bulgaria

Reviewed by:
Karl Friston,
University College London, UK
Caroline L. Horton,
Bishop Grosseteste University, UK

****Correspondence:***
Jim Hopkins
jim.hopkins@kcl.ac.uk

Specialty section:
This article was submitted to
Cognitive Science,
a section of the journal
Frontiers in Psychology

Received: *02 April 2016*
Accepted: *03 June 2016*
Published: *15 July 2016*

Citation:
Hopkins J (2016) Free Energy and Virtual Reality in Neuroscience and Psychoanalysis: A Complexity Theory of Dreaming and Mental Disorder.
Front. Psychol. 7:922.
doi: 10.3389/fpsyg.2016.00922

Shortly after starting to analyse his own and his patients' dreams Freud concluded that dreams were produced by the same neurocognitive mechanisms as the neurotic symptoms on which he had previously concentrated. He initially framed this unifying discovery in a "psychology for neurologists"—posthumously published as his *Project for a Scientific Psychology* (Freud, 1974a)—in which he envisaged the brain as operating to minimize free energy (FE). There he noted that "the pathological mechanisms which are revealed in the most careful analysis in the psychoneuroses bear the greatest similarity to dream-processes" (p. 336).

Both dreams and symptoms, Freud now hypothesized, served to defend the conscious self (or ego) by reducing FE from otherwise distressing and functionally disruptive arousals of emotion and conflict. Both did so via the creation of *fictive* experiences and beliefs, forms of virtual reality or phantasy creating an "alienation from reality" that *masked* and *pacified* (or in neuroscientific terms *inhibited*) the arousals. In this he recast a longstanding tradition—exemplified by Kant's (1764/2007) (1764/2007, p. 71) claim that "the deranged person" was "a dreamer in waking"—that linked dreaming with mental disorder.

Freud sought to integrate this tradition with depth psychology, psychiatry, and neuroscience, and it has had many other distinguished advocates in the sciences of the mind since he wrote. The publication of Hobson et al. (2014)—hereafter abbreviated as HHF—seems an important step toward fuller integration. The authors bring the Bayesian neuroscience recently advanced by Karl Friston and his colleagues under the *free energy principle* (Friston, 2010) into a full functional isomorphism with Freud's early formulations. This means that their hypotheses linking dreaming and *complexity* (also described as Bayesian surprise) can naturally be extended to encompass a *complexity theory of mental disorder*[1].

As advanced here this is the theory that the conflicts and traumas that Freud thought responsible for recourse to phantasy/virtual reality in mental disorder should be seen as forms of neurocomputational complexity, and that mental disorder is the product of such complexity together with the mechanisms that have evolved to reduce it. Although, I emphasize Freud in stating this theory it has consequences for mental disorder that go beyond psychoanalysis, and that are also relevant to psychiatry. In what follows I will try to show that this approach flows directly from the account of complexity that informs HHF, and also to operationalize it with examples from dreaming, attachment, and disorder.

Also it is worth noting at the outset that this theory is *partly* supported by the recent work of Alan Hobson, who followed HHF with the publication of two books (Hobson, 2014, 2015) in which he applies the virtual reality/generative model conception to link dreaming and disorder, urging, for example, that the aminergic-cholinergic balance pivotal for dreaming also unites "a wide range of psychopathological conditions" which "have in common the weakness of the aminergic system." (Hobson, 2014, p. 51) Indeed, despite his unrelenting criticism of Freud, Hobson now stresses that his current work "takes up the *Project for a Scientific Psychology* exactly where Freud left it in 1895." (Hobson, 2015, p. 5)

Friston's variational conception of FE derives from the computational work of Geoffrey Hinton and his colleagues (see Dayan et al., 1995), and differs radically from anything Freud could have had in mind. Nonetheless Friston assigns FE the same overall functional role as appears in Freud. In both accounts the brain operates to minimize FE aroused by sensory impingement, with "endogenous [interoceptive] stimuli" a particularly important source. In Freud such impingements reflect "the major needs" or biological imperatives; in Friston they likewise reflect compliance with biological imperatives, predicting departures from homeostasis in a continuously recomputed overall FE-minimizing equilibrium (Pelluzio et al., 2015).

As Freud speaks of these imperatives as creating a "demand for work" to produce "specific actions," so Friston (2012) speaks of "an imperative to minimize prediction error...through action," using "[kinematic and proprioceptive] predictions" to produce the "kinematic trajectories" of bodily movement. For both minimization requires the brain to embody a representation or model of the world, including the agent's body (in Freud the "bodily ego"); and for both this requirement is initially met by the innate generation of a *prior* virtual (or phantasy) version of reality, which will subsequently be modified by experience.

Citing evidence that during the final trimester of pregnancy infants spend most of their time in REM, HHF hypothesize that the brain is "genetically endowed with an innate virtual reality generator" whose working "is most clearly revealed in [REM] dreaming." They thus hold that we are "born with a virtual reality model" of what we will subsequently discover to be the causes of sensory impingement. As well as innate this model is intrinsically predictive, and so is "entrained by sensory prediction errors," particularly during the sensory initialization attending birth, to become "a generative or predictive model of the world," operating to minimize the free energy generated by the precision-weighted prediction error (PE) that constitutes its sensory input.

This accords with other observations, such as that during the same prenatal period infants' facial expressions indicate both positive (laughter-related) and negative (cry-related) emotions (Reissland et al., 2011, 2013); and again with the apparently essential role of REM sleep in early learning (Dumoulin Bridi et al., 2015; Boyce et al., 2016). So like Freud's *primary process* the HHF *virtual reality generator* is an innate producer of fictive (imaginary) prior belief and/or experience, the process that, as Freud says is "in the apparatus first." Thus, Freud describes perception, learning, and action as *secondary processes* prepared for by the innate *primary process*, and set in train by the sensory impact of birth. Comparably, HHF describe these as aspects of *active inference*, the process that implement the transformation from virtual reality to generative model.

Hence also in both Freud and HHF, perceptually informed belief and action replace virtual reality in waking life as memory and the wake-sleep cycle become established, thus relegating

---

[1] For current web resources on these topics see https://en.wikipedia.org/wiki/Free_energy_principle and http://ilab.usc.edu/surprise/. The term "complexity theory" was introduced by Chris Mathys at the 2013 Free Energy conference in Berlin, and used in our joint presentation at the 2014 Neuropsychoanalysis conference in New York.

the unconstrained production of phantasy/virtual reality to dreaming—where, however, it continues to play a role in minimizing FE. In both accounts, therefore, the REM phase of sleep—which although distinct (doubly dissociable) from dreaming nonetheless yields the most frequent dream reports, and those that are "long, vivid, hallucinatory, and bizarre" (Hobson and Friston, 2012, Figure 1)—can be part of the lifelong genetic regulation of neurological functioning, as envisaged in Jouvet (1999).

COMPLEXITY AND ACCURACY

As HHF emphasize, the FE minimized by the brain can be equated with *complexity minus accuracy*. Accuracy is a measure of the success of a model in predicting the sensory impingements that have accumulated over a given period of data collection, and complexity reflects the number of parameters/hypotheses employed in accomplishing prediction and the extent to which they are altered in the course of doing so. From this it follows that FE can be minimized by *increasing* accuracy and/or *reducing* complexity. There is, however, an intrinsic tension in this task.

The data relevant to the minimization of FE encompass those of sensory impingement. As well as the interoceptive impingements mentioned above, these include exteroceptive impingements on sensory surfaces such as the retina and skin, and proprioceptive impingements reflecting muscular and skeletal kinematics and conditions. If we think of these data as points on a graph, and the hypotheses by which the brain's model seeks to predict them as curves drawn to fit the points, then accuracy would be maximized by a curve, however complex, that passed through every data point.

To increase accuracy over a given sample is to approach this goal for the data of that sample; so increasing accuracy characteristically increases complexity as well. To reduce complexity, by contrast, is to seek the *simplest* curve (the simplest or most economic model) for predicting the data overall. Given that any sample is likely to include many data diverging from the overall trend, this must be a simpler curve than maximizing accuracy would determine. The tension between increasing accuracy and reducing complexity thus shows in the way learning that increases accuracy also tends to *overfit* current data, thereby producing excess complexity as well.

DEVELOPMENT, EMOTION, AND CONFLICT

Basic expectations connected with biological imperatives like homeostasis are woven into the functioning of the brainstem. Comprehensive motor responses to the FE produced by these are required for all aspects of thriving and development. From birth such responses are generated by motoric "prototype emotions systems" delineated in Panksepp (1998), which also perform the motivational work that Freud assigned to the drives (see Damasio and Carvalho, 2013). Watt and Panksepp (2009, p. 98) describe these as "sitting over homeostasis proper (hunger, thirst, temperature regulation, pain, etc.)" and "giv[ing] rise to attachment," which in turn serves as "the massive regulatory-lynchpin system of the human brain" exercising "primary influence over the prototype systems below."

The prototype systems are organized around the dopaminergic SEEKING system that apparently energizes purposive activity in waking as well as fictive activity in dreaming. They include "positive" (and rewarding) prototype emotions, such as LUST, PLAY, and CARE, and "negative" (and aversive) prototypes, including the proximity- and attachment-regulating system that Panksepp describes in terms of PANIC, SEPARATION DISTRESS, and GRIEF (hereafter PSG), and those for RAGE and FEAR, which PSG in human infants seems to activate.

The link between homeostasis-maintaining response to interoceptive input by these systems and attachment to caregivers is intrinsic, since human infants cannot maintain life without continual care. As discussed in Hopkins (2015), the vigorous operation of the "negative" systems is essential for the honest signaling of urgent need, so in early infancy both "positive" and "negative" systems are directed at the mother. Infants' cries of distress apparently originate in the (RAGE- and FEAR-generating) hypothalamus and PAG, and they in turn activate the maternal PAG in ensuring rapid response (Parsons et al., 2014).

These systems should accordingly play a major role in the overall integration of behavioral responses to PE—including autonomic and other reflexes, Pavlovian and operant conditioning, and the working of emotion and desire—that Pelluzio et al. (2015) describe the generative model as coordinating over early development. And since the "positive" and "negative" systems tend to generate inconsistent kinematic trajectories toward the same original object of attachment; and since they are parts of an overall structure of emotional opponent processing (Craig, 2015, Ch 8); we should expect a significant part of this postnatal co-ordination to involve the regulation of emotional conflict for the ultimate resolution of interoceptive PE.

PREDICTION, PERCEPTION, AND WAKING CONSCIOUSNESS

The most salient hypotheses by which the brain/model works to minimize PE are those that *constitute* the conscious perceptual (or perception-like) experiences of both waking and dreaming consciousness. A basic claim of FE neuroscience, taken from Helmholz (1874/1971) is that the brain both actively collects, and also "synthesizes," the fragmentary and fleeting manifold of impingements that generate FE in waking, so as to re-represent them as *the subject's conscious perceptual experience of their causes*. Thus, as stressed in HHF, conscious perceptual experience is a form of explanatory hypothesis, that at once unifies, predicts, and inhibits the impingements that cause it, thereby minimizing the FE associated with them.

This task employs a vast range of the subconscious processing that underpins conscious experience. Thus, in reading a paragraph such as this, the reader's brain continually collects visual data, moving the reader's eyes in saccades that focus the most sensitive part of the retina on a series of areas about the size of a thumbnail on an outstretched hand. The focus thus skips from group to group of seven or eight letters, falling on each for about a fifth of a second, while the reader's brain/model continually unifies and predicts these partial scattered retinal snapshots as *conscious experience of understanding the thoughts of the author of the text.*

This continual collection of vanishing impingements at the sensory surface illustrates an "active" aspect of what Friston calls active inference. The inferences appear from the top level of the reader's conscious experience of understanding down through the neurocomputational hierarchy that underpins it. Thus, the reader *can see in the text what the author means*, without consciously attending to the way the author's paragraphs and sentences are compounded from words in accord with the syntax and semantics of the language in which she writes, or how these words are compounded of letters, or how the letters map to the combinations of sounds that enable the author's thoughts to map to the sounds of her language, nor finally to how these sounds relate to the grapheme fragments upon which the reader is focusing at eye level.

This illustrates some of the hierarchical predictive processing that FE neuroscience assigns to the circuity of the cerebral cortices. Roughly, such processing works continually top-down, bottom-up, and side-to-side, with each level in a cortical hierarchy passing predictions to the level below or beside, and each level below or beside passing prediction errors back to modify the hypotheses responsible for them, so as continually to minimize error over the whole cortical model of the causes of impingement at all levels of processing. This suggests that the levels or aspects of processing imagined in the last paragraph should be cortically realized in the same way. Since, again roughly, they also correspond to one or another theoretical domain in the cognitive/affective sciences of the mind, this indicates how the FE approach may prove particularly serviceable in integrating cognitive psychology and cognitive science more generally with neuroscience.

As Clark (2016, Ch 2) describes in detail, hierarchical processing in FE neuroscience is continually regulated by predictive assignments of precision. These "adjust the volume," or synaptic gain, on hypotheses and data (PE's) over all levels of the hierarchy, amplifying or attenuating their causal role in processing. By this means the brain/model organizes coalitions of processing hierarchies for the explanation of data as the minimization of FE requires. Dopamine seems a potent neuromodulator in the optimization of precision (Iglesias et al., 2013), for example in attentional gain and the resolution of competing alternatives in action selection (Friston et al., 2014b; Schwartenbeck et al., 2015)—but with the consequence that aberrant assignments of precision (implementing aberrant salience) can produce both positive and negative symptoms of mental disorder (Kapur, 2003; Deserno et al., 2016; Howes and Nour, 2016). Comparably acetylcholine, maximally active in REM, seems important in regulating emotional memory via the amygdala (Jiang et al., 2016), and so for the role of dreaming in regulating emotion.

PREDICTION, EMOTION, AND DREAMING CONSCIOUSNESS

As discussed in Solms and Turnbull (2002), dreaming requires activation of the same dopaminergic SEEKING system as energizes purposive waking action, and that Panksepp and many others also take to be involved in delusion and other symptoms. Neuromodulation in sleep produces an attending away from sensory input by lowering the precision weighting of sensory prediction errors—to render perceptual accuracy irrelevant. This frees the brain to minimize complexity in REM dreaming, and so, implicitly, to resolve otherwise disruptive (emotional) conflicts. These processes too depend upon an appropriate modulation of precision or synaptic gain—and all seem likely to involve neuromodulatory transmitter systems, including the aminergic and cholinergic systems stressed by Hobson.

This implies, as HHF contend, that the kind of hierarchical precision-engineered processing that produces the conscious perceptual experiences of waking also produces the fictive conscious experiences of dreaming. But given the radical sensorimotor attenuation that attends REM, the FE-arousing data hierarchically processed in REM dreaming cannot derive from sensory impingement. A non-sensory source of FE-arousing data is required, and this would seem to lie in the powerful arousals of *emotion* that attend REM, which in turn seem part of the consolidation/reconsolidation of *memory*.

This accords with the tension in FE-minimization between accuracy and complexity sketched above. For insofar as emotions drive overly complex (overfitting) FE-minimizing responses to sensory PE in waking, then memories embodying such over-complex responses would themselves be a suitable target for FE-minimizing complexity-reduction in sleep and dreaming (and also in waking periods of attending-away from realistic response to perceptual impingement, such as in daydream, children's play, and other activities that Freud described in terms of phantasy). It also accords in interesting detail with Freud's (1974b, Ch VI) account of the *dreamwork* as operating to *condense emotionally significant elements* from a *range of memories associated with the dream*.

As we will illustrate below, the elements chosen for condensation apparently include both recent memories that are being consolidated and remote emotion-laden memories rearoused to be reconsolidated with them. What Freud describes as *condensation* would thus appear to reflect a *collection of data over remembered and associated arousals of amygdala-related emotion* that could be compared with the saccadic collection of sensory data in waking sketched above. Given *associated remembered arousals* as data, the fictive perceptual experiences of dreaming could serve to unify, predict, and inhibit these arousals, thereby minimizing FE (as emotional conflict/complexity) in a way closely analogous to the realistic perceptual experiences of waking.

This in turn would accord with "active systems" descriptions of memory consolidation (Rasch and Born, 2013; for an early version see Cartwright, 2010, and for a psychoanalytic anticipation Palombo, 1978). Sleep consists in stages of

NREM (including SWS) followed by REM, with the latter characteristically lengthening, and the bizarreness of dreams often increasing, over the course of the night. Active systems accounts hypothesize that slow oscillations in SWS effect the downscaling required for synaptic homeostasis (Tononi and Cirelli, 2014), while hippocampal sharp wave ripples activate large areas of the cortex (Logothetis et al., 2012), transferring recent memories from the hippocampus to the cortical loci appropriate for their long-term storage (Staresina et al., 2015). As SWS yields to REM the reactivated memories are rendered increasingly plastic (Calais et al., 2015; Dumoulin Bridi et al., 2015; Ravassard et al., 2015), and associated amygdala-related emotions are rearoused, so that both can be reconsolidated under the impact of dreaming in a new and emotionally revised integration of emotion and declarative content (van der Helm et al., 2011; Genzel et al., 2015).

ACCURACY AND COMPLEXITY IN WAKING, SLEEPING, AND DREAMING

Following Friston (2010) HHF describe how accuracy is maximized and complexity minimized over the wake-sleep cycle, and in a way that accords with the tension between accuracy and complexity, and the differing roles of waking sensory impingement and sleeping memory and emotion, sketched above. During a waking period sensory PE's entrain active inference, and perceptual learning operates to increase the accuracy of the model as it was prior to that period. This is essential for the accurate ongoing computation of sensory targets for waking regulatory action. (Helmholz, 1878/1971, p. 332) stressed that "each movement we make"—from the involuntary movements of the eyeballs and pupils in saccades through the planned and purposive sequences of movements by which we realize full-scale intentional actions and projects—can be thought of as an "experiment" by which we test the models that direct them in our brains. Thus, in waking our models accumulate the adjustments required for accuracy, embodying the increased complexity in synaptic connections that constitute a physiological load on the neurons involved.

Then during the precision engineered sensorimotor attenuation of sleep, processes including SWS, synaptic pruning, REM, and dreaming reduce the excess complexity, together with the synaptic connections in which it is embodied. As would fit such a two-stage process, we would expect the waking stage to maximize accuracy in a way that overshoots (overfits) the longer-term equilibrium, so that, waking accuracy assured, the sleeping stage can winnow back emotional complexity, and as hard as is required to optimize the model for the waking period that follows.

COMPLEXITY REDUCTION AND MEMORY CONSOLIDATION

Such hypothesized complexity reduction in sleep would map directly to the "active systems" accounts of consolidation/reconsolidation above. Combining these with HHF would yield an account in which amygdala-related emotional rearousal and reintegration in REM and dreaming, as envisaged in Genzel et al. (2015), would be the final stage in both memory consolidation and complexity reduction, linking both with the increases in arousal and plasticity characteristic of REM. We could thus see synaptic homeostasis and emotional reintegration as rendering the posterior model of one waking period a simpler and better predictor for the next. And as indicated above, this theoretical unification admits further explication by psychoanalytic hypotheses relating to complexity, dreaming, and mental disorder.

REALISTIC ACTIVE INFERENCE IN WAKING

In waking much minimizing of FE via action takes a familiar realistic form, in which PE's generate alternative parameters of emotion and/or desire for action that are entertained together with the alternative sensorimotor trajectories associated with them in affordance competition and action selection, and then—provided they generate trajectories that find their sensory targets—eliminated from ongoing neurocomputational work. Thus, suppose cells in the hypothalamus like those specified in Oka et al. (2015) respond to a predicted violation of homeostatic equilibrium by generating thirst and a desire to drink, and the brain responds by computing various motor trajectories that would slake this thirst.

Such trajectories terminate at sensory targets that Freud called *experiences of satisfaction*. For thirst this is the experience of drinking, and attaining the experience seems rapidly to inhibit both thirst and the interoceptive signals that generate it (presumably via proprioceptive feedback). In this the signal produced by the target experience acts rapidly, and well before the changes in the bloodstream that will secure homeostasis and inhibition over a longer period. Such an adaptation seems required for the rapid sequential satisfaction of desires in action.

FICTIVE OR COUNTERFACTUAL ACTIVE INFERENCE IN DREAMING

As noted above, both intentional action and dreaming require activation of the dopaminergic SEEKING system, in which aberrant precision-weighting (salience) may also produce delusions and other symptoms. The simple example above enables us to see how such activation works in the sensorimotor attenuation of dreaming, for this is apparent in very simple dreams sometimes produced in response to interoceptive signaling in sleep. These make clear that such signaling yields what we can call *fictive* or *counterfactual* active inference, as opposed to the *realistic* kind that obtains in waking.

Thus, Freud reported that when he had eaten anchovies or some other salty food, he was liable to dream *that he was drinking cool delicious water*. After having this dream, perhaps several times, he would awake, find himself thirsty, and get a drink. Many people have had such a dream, and many are also familiar with its counterpart involving micturition. In waking from such dreams we intuitively regard them as caused by, and representing the satisfaction of, the desires we act on when we wake.

Active inference thus shows a common pattern between the realistic in waking and the counterfactual in dreaming. We can illustrate this in a simple diagram integrating some of the commonsense and neuroscientific notions involved. Abbreviating "desire" "belief" and "experience" by "des," "bel," and "exp," and using P as a variable for which particular sentences that describe these in their relation to the environment can be substituted (**Box 1**).

This spells out, for a simple case, what Freud meant by claiming that dreams and symptoms are *wishfulfilments*, and also indicates how such fictions can inhibit interoceptive signals and their motivational derivatives like thirst or emotion, and thereby eliminate incipient kinematic parameters that might form part of a trajectory of waking action. And Freud also held that dreams exercise this counterfactual but genuinely parameter-eliminating role in the mitigation of *conflict*—in this case, the conflict between the desire for action and the continuation of sleep.

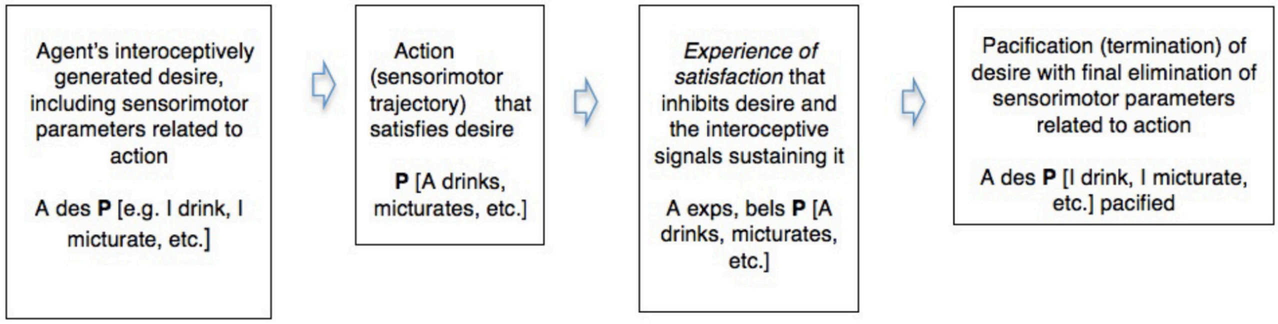
FICTIVE OR COUNTERFACTUAL ACTIVE INFERENCE IN WAKING MENTAL DISORDER: A SIMPLE SYMPTOM IN OCD

We can see how Freud compares dreams and symptoms by briefly considering the one case from which Freud's session-by-session notes partly survive, that of his patient known as the Rat Man (Freud, 1974c,1974d 155ff: hereafter R). His main symptom was a compulsion involuntarily to imagine, as in a waking nightmare, that his beloved father and venerated lady were being subjected to a terrible torture, in which *hungry rats ate their way into the anus of the victim, causing an agonizing death.* This first arose—precipitating a breakdown into what Freud called obsessional neurosis—when R felt forced to listen to the repellant story of the rat-torture, as told by "the cruel Captain," his commanding officer on maneuvers, whom R intensely disliked for his fondness for physical punishment.

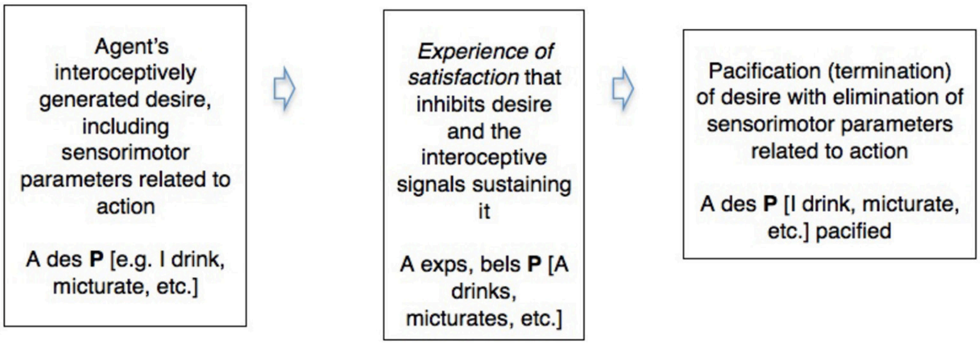
On hearing the story R had felt the earth move, as though a rat were tunneling beneath it, and imagined the torture being applied to his father and lady. Despite R's aversion to physical punishment, one might reasonably think that his repeatedly imagining people being tortured in the way the cruel Captain had described to him was a punitive expression of hostility toward the recipients of the torture. R did not

BOX 1 | A comparison of the pacification or inhibition of desire by a conscious experience of satisfaction in waking action and in dreaming.

Waking action (realistic active inference)



Dreaming (counterfactual active inference)



imagine himself as administering the torture, but said it was done "impersonally." But Freud found that his imaginings could be understood as stemming from unconscious impulsive rage, particularly toward his father, of whom the Cruel Captain had unconsciously reminded him in the episode that precipitated his breakdown.

R had already shown conflict related to rage in other ways. In his first consultation with Freud he described how when his venerated lady had left him alone to visit her grandmother he had felt "commanded" to cut his own throat with a razor, or again "to kill the old lady." Although, R's diagnosis was clearly one of OCD, these commands seem instances of RAGE caused by PSG, in which the rage is also turned against the self, as by the Freudian superego. In the case of Elyn Saks, as we will see below, such anger gave rise to severe guilt and depression; and likewise R was anxious, guilty and depressed about his rat phantasies, saying at one point that he deserved to die for entertaining them.

As emerged in R's analysis, his "wishing the rats" on people was a regular expression of anger. In the preliminary meeting in which Freud told R his fee, R had thought (as he told Freud later) "For each *krone* a rat for [Freud's] children" (Freud, 1974d, p. 288); and this was the first of many such examples. Wishing the rats seemed also to be connected with physical punishment. In analysis R maintained that his father never punished him physically, but became increasingly fearful that Freud was liable to murderous rage, in which would beat him and throw him out the consulting room, or again fall on him like a beast of prey [or again like the rats of his phantasy] "to search out what was evil in him" (p. 285).

These manifestations of transference vanished when R remembered and re-experienced an episode from early childhood in which his father had angrily beaten him for urinating while lying between his parents in their bed. This fouling had apparently enraged his father, and R had felt in terror for his life. Although, R had forgotten this episode, his spectacular rage at his father while enduring the beating was a matter of family legend, and his father never punished him physically again. This immediately preceded the childhood onset of his early anxieties and depression about the likelihood of his father's death; and as R went over these things in his analysis, his "wishing the rats" evolved into a conscious expression of irritation that he used less and less, as he ceased to show the symptoms of OCD that had been related to it.

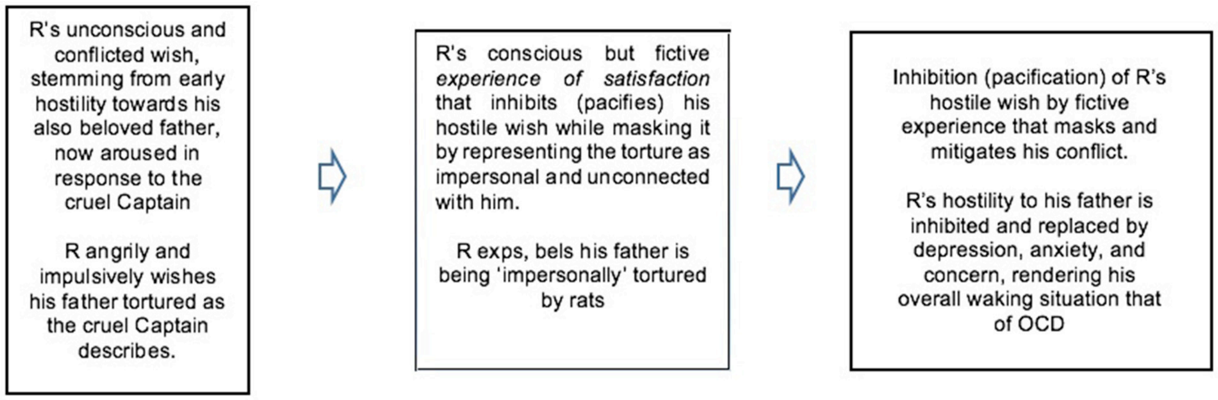
We can thus take R's symptom as instantiating a pattern similar to those above (**Box 2**).

As this makes clear, we can see R's symptom as produced by a dream-like condensation of his current anger at the punitive cruel Captain with his forgotten rage and fear toward his father—who was, therefore, the salient focus of the arousal of FE that his symptom (temporarily) served to reduce. (For relation of this to the psychoanalytic notion of repression see Hopkins, 2012). As this suggests, in both dreaming and disorder the input of FE to the hierarchical processes of complexity reduction by fictive experience would derive from memory and emotion, which must in any case also inform ongoing perceptual processing.

Here we also see a link between conflict, counterfactual inference, and complexity. When a fictive experience of satisfaction serves to mitigate a conflict, it does so by reducing or eliminating some of the conflicting parameters involved, as Freud's dream of drinking temporarily eliminates his nocturnal thirst, and R's imaginary torture temporarily eliminates the unconscious rage that conflicts with his love for his father, replacing it with anxiety and depression. The basic insight here is that conflict, which invariably has emotional or interoceptive aspects, can be equated with complexity in the statistical sense of FE neuroscience.

Such complexity is reported in waking by interoceptive prediction errors and quantifies the divergence between posterior (informed) and prior beliefs, where the latter would include the primary beliefs of infancy or, as above, emotion-laden priors dating from early childhood. From a technical perspective, this means that the resolution of conflict conforms to the

BOX 2 | The pacification or inhibition of a desire involved in unconscious conflict by a conscious experience of satisfaction constituting a symptom. R's symptom



R's unconscious and conflicted wish, stemming from early hostility towards his also beloved father, now aroused in response to the cruel Captain

R angrily and impulsively wishes his father tortured as the cruel Captain describes.

R's conscious but fictive *experience of satisfaction* that inhibits (pacifies) his hostile wish while masking it by representing the torture as impersonal and unconnected with him.

R exps, bels his father is being 'impersonally' tortured by rats

Inhibition (pacification) of R's hostile wish by fictive experience that masks and mitigates his conflict.

R's hostility to his father is inhibited and replaced by depression, anxiety, and concern, rendering his overall waking situation that of OCD statistical imperative to minimize complexity—and thereby normally renders internal models of the causes of sensory impingement better able to provide accurate and parsimonious predictive and regulatory explanations for the impingements themselves.

COMPLEXITY AND ATTACHMENT

Since the regulatory functions of the generative model are built up in attachment and discharged via movement, we should expect the effects of excess complexity to show in relation to this process. As discussed in detail in Hopkins (2015), we can apparently see these regulatory functions in action in the "strange situation" procedure used to assess attachment from the end of the first year. This is conducted in a novel room (the strange situation: for further information see Howe, 2011) in which age-appropriate toys are provided to encourage exploration and play, and hence to activate the systems that Panksepp describes as SEEKING and PLAY. It turns on observation of the infants' reactions to short episodes (reduced in serious distress) in which (despite their angry protests) their mothers leave them alone or with a stranger. This apparently rouses PSG as well as FEAR of the stranger and RAGE toward the mother for inflicting such distress despite protests to the contrary.

Infants are classified as secure in attachment, or again as insecure—avoidant, ambivalent-resistant, or disorganized—depending on how they cope with these conflicts. Roughly, secure infants resolve the conflicts co-operatively, expressing their anger, distress, and fear as they occur, and on reunion accepting comfort and care, and so returning to exploration and play. Avoidant infants suppress the emotions, expressing them perhaps only in angry refusal to be comforted, and remain conflicted and stressed for a longer time. Those classed as ambivalent-resistant amplify the emotions, demanding closeness and comfort while also refusing to be placated; and they too remain longer in conflict and stress.

By contrast disorganized infants—who make up a large percentage of maltreated or abused samples, and are particularly liable to suffer later trauma-related disorders—are unable to adopt any of these overall strategies for coping with conflict. Rather they show various forms of *overt kinematic incoherence* in their behavior toward their mothers. These include contradictory behaviors, such as approach followed by avoidance, or combinations of the two; anomalous postures and mistimed movements; freezing or stilling; and signs of confusion.

That is: in this carefully standardized situation of emotional conflict, which reactivates conflicting parameters set earlier in infancy, the generative models of disorganized infants seize up, becoming incapable of predicting whether an optimal sensorimotor trajectory will approach or avoid their mothers. The only curves they are able to fit to their current data of perception and emotion here fail to yield a coherent social and spatial path. The complexity of affordance competition and action selection in this basic social decision is so magnified by conflict as to render the required computations too emotionally complex for their generative models to manage.

Here are two examples of such (hypothesized) excess complexity, from the behavior of a little boy and girl of 18 months, as described in Solomon and George (1999, p. 131).

In the second reunion Kate approached her mother with her arms outstretched...when she was about two feet away from making contact, she moved her arms to the side and abruptly circled away from her mother like a banking airplane. As she moved away she had a blank, dazed expression on her face.

In the first reunion, Sam approached his mother with his eyes cast down. When he was about two feet away he looked up at her, rising suddenly and making gasping noises with his breath as he did so. He quickly looked down again, bared his teeth in a half-grimace/half-smile and turned away. Hunching his shoulders and holding his arms and legs stiffly, he tiptoed to the other side of the room. He sat motionless in the chair for 30 s, grasping the armrests and staring straight ahead with a dazed expression.

> This disorganization, moreover, bears comparison with that experienced in schizophrenia. Thus, consider Saks, (2008) account of her first experience of the latter, brought on by a critical remark from her father.
>
> My heart sinks at the tone of his voice: I've disappointed him. And then something odd happens: My awareness (of myself, of him, of the room, of the physical reality around and beyond us) instantly grows fuzzy...I think I am dissolving ... like a sand castle with all the sand sliding away in the receding surf. *This is scary, please let it be over!*...Most people know what it's like to be seriously afraid..."disorganization" is a different matter altogether...One's center gives way...
>
> Of course, my dad didn't notice what had happened, since it was all happening inside me. And frightened as I was at the moment, I intuitively knew that this was something I needed to hide from him, and from anyone else as well (Saks, 2008, pp. 12–13).

Freudian hypotheses would explain these disorganizations, like that which struck R on hearing the cruel Captain, via emotional conflicts built into the self by the self-punishing superego/ego-ideal. But one need not adopt this theory to appreciate them as instances of excess complexity.

COMPLEXITY CONFLICT AND TRAUMA

As the foregoing indicates, complexity is conceptually linked with *emotional conflict* and *trauma*. Conflict involves the simultaneous activation of parameters producing inconsistent sensorimotor trajectories, such as we saw above; and these would be a clear target for complexity reduction in sleep. Again, complexity indexes the parametric changes required for *emotional learning* or *emotional adjustment to sensory impingement* (cf *affective load* in Levin and Nielsen, 2009); and experiences are rightly regarded as *traumatic* when, as in PTSD (Enlow et al., 2014) or BPD (Mosquera et al., 2014) the emotional adjustments (complexity) required for integrating them into thought and action are greater than the brain can manage.

Although, these forms of disorder, like disorganized attachment, are linked with traumatic abuse (Cyr et al., 2010), the work of Beebe and Lachman (2014) indicates something subtler. Their second-by-second microanalyses of face-to-face interactions between mothers and infants show that disorganization at 12+ months can be predicted from the 4th month by episodes of *emotional misrecognition* very different from abuse. These involve short (2.5 s) interactions in play, whose fine details are undetectable by unaided sight, and in which, among other things, the mothers concerned *refuse to recognize or co-ordinate empathically with their infants' expressions of distress*. Instead they respond with exaggerated surprise or smiling, or again, as distress increases, by facial freezing and/or looking away. Meanwhile the infants themselves—as in the later patterns of disorganization—respond with *rapidly conflicting expressions of emotion* e.g., whimpering and smiling within the same second or so; and they grow more distraught as no recognitional response is forthcoming. These infants seem frustrated not only by the original causes of their distress, but also in their desire that it be acknowledged and understood; and they respond with a short expression of the complexity/conflict that will later be expressed in approach/avoidance conflicts like those above.

We noted earlier that infants' expressions of distress seem to stem from the activation of the PAG, and in turn activate the PAG and other sources of conflict in mothers (Parsons et al., 2014; Dudek et al., 2016). These mothers are apparently so threatened by PAG-activating communications (or projections) of conflict and distress from their infants that they must block them entirely. This deprives the infants (as their mothers may have been deprived) of opportunities for learning in emotional interaction, and so for internalizing in their own regulative models the understanding responses of others. Instead they apparently learn that their conflicts and distress are unsharable, intolerable, and not to be recognized or known.

REALISTIC AND COUNTERFACTUAL ACTIVE INFERENCE

The differences marked by the terms "realistic" and "counterfactual" thus derive from the distinct functions that active inference performs in the contrasting circumstances of waking and sleeping. All active inference involves selection among multiple competing (and hence so far counterfactual) possibilities for movement. But the function of waking regulatory control requires accuracy in the predictive hypotheses that implement it; hence hypothesis-selection in this context is constrained by PE toward realism.

By contrast complexity-reduction, whether in waking or sleeping, is discharged in respect of previously framed (remembered) hypotheses (including experiences of adverse conflicting emotions) whose complexity renders them unlikely candidates for realistic predictors in future. These would particularly include hypotheses (emotions and feelings) whose original parameters were *not* reduced or eliminated via their regulatory success, and so remained active prior to sleep. So inference relating to such past complex hypotheses would appear to compete with that required for ongoing perception-based regulatory control, as indicated by the relegation of perceptually unconstrained virtual-reality complexity-reduction to REM dreaming.

The observations about conflict and trauma above suggest that excess complexity (affective load) derives from these sources, and that the burden of complexity in infancy reflects the emotional adjustments required for establishing the bonds of attachment given the inescapable fact that parents or carers are the main salient causes of both gratification and frustration. This is exactly the kind of complexity that psychoanalysis finds expressed in the arousal of memory and emotion in both dreams and mental disorder; and accordingly we can see counterfactual active inference as healthy and functional in REM dreaming, but as constituting pathology when rearousals of conflict or trauma render it dominant in waking.

As the foregoing indicates, the complexity theory of disorder as advanced here is nearly a consequence of the account of complexity that informs HHF. For if the accumulation of complexity in waking is so serious a problem for the brain as to require complexity-reduction in sleep, then it would follow that inadequacies or malfunctions in such reduction – like prolonged sleep deprivation itself – might foster accretions of complexity that appeared in waking as mental disorder. In addition, just as the mechanisms of inflammation that have evolved to protect the body from injury can themselves cause bodily disorders, so the mechanisms that have evolved to reduce emotional complexity in sleep might cause disorders of the mind or brain.

COMPLEXITY AND PSYCHOSIS

In order to illustrate this, let us briefly sketch some applications in schizophrenia, depression, and bipolar disorder. A first idea would be that schizophrenic and manic hallucinations and delusions are produced to perform the complexity-reducing function of dreams, but in waking (cf Llewellyn, 2011; Gerrans, 2014; Skrzypinska and Szmigielska, 2015). As an example we can consider the delusions developed by Elyn Saks, whose experience of schizophrenic disorganization was described above.

Saks entered psychiatric hospital in a savagely self-critical state which she kept repeating "I am a piece of shit and I deserve to die" (Saks, 2008, p. 61). Such self-hating internal conflict is a mark of the rage against the self that characterizes "introjective" depression (Blatt, 2004); and when antidepressants gave Saks some relief, she told her doctor that she felt less angry, and remarked on "how much rage I had felt, directed mostly at myself."

Later, however, her self-reproaches returned in force, and her increasingly unbearable depression altered only when came to imagine herself "receiving commands" from "shapeless powerful beings that controlled me with thoughts (not voices) that had been placed in my head." These commanded, e.g., "Walk through the tunnels and repent. Now lie down and don't move. You are evil." She was also commanded to injure herself, which she did by burning herself with cigarette lighters, electric heaters, or boiling water, so that finally she spent most of her time "alone in the music room or in the bathroom, burning my body, or moaning and rocking, holding myself as protection from unseen forces that might harm me."

These delusions fit the generalizations advanced so far. They served to mitigate the conflict, or reduce the complexity, of Saks' self-punishing depression, by replacing it with an imaginary relationship with punitive others. In framing them her generative model behaved as governments or nations (or other groups) often do, that is, shifting attention (precision) from intractable *internal* conflicts (and thereby reducing them) by focusing instead on imaginary *external* conflicts. This change from the internalization to the externalization of punishment constituted Saks' shift from depression to paranoia, and effected a temporary inhibition (reduction of parameters) of her internal self-punishment, and so a reduction in conflict (complexity) and FE overall.

Thus, and greatly simplifying, we can represent Saks's paranoia-like symptoms in a way parallel to the simple dream and symptom diagrammed above (**Box 3**).

This kind of account dates from 1914, when Freud wrote that in schizophrenia, "the voices, as well as the undefined multitude [of imaginary critical psychological presences embodied in the superego/ego-ideal] are brought into the foreground again by the disease" so that the sufferer's superego/ego-ideal "confronts him in a regressive form as a hostile influence from without" (Freud, 1974e, p. 56). In such a case, while the reduction in internal conflict may relieve the unbearable internal hostility and depressive pain that can cause suicide, it also marks a deeper alienation from reality, and a deeper regulatory failure on the part of the generative model.

In constantly berating her as a piece of shit who deserved to die Saks' self-critical faculty was already punishing her dysfunctionally, for some imagined or phantasied transgression; so her resorting to counterfactual active inference to externalize the punishing agency in the "shapeless powerful beings" of her delusions was a *further* step from reality. This is why the externalization constitutes a deeper regulatory failure; why Freud describes it as regressive in the quotation above; and why such paranoia involves a deeper alienation from reality than depression—even though a main risk in schizophrenia is suicide in the depressive phases in which the subject is attempting to re-establish internal regulatory control.

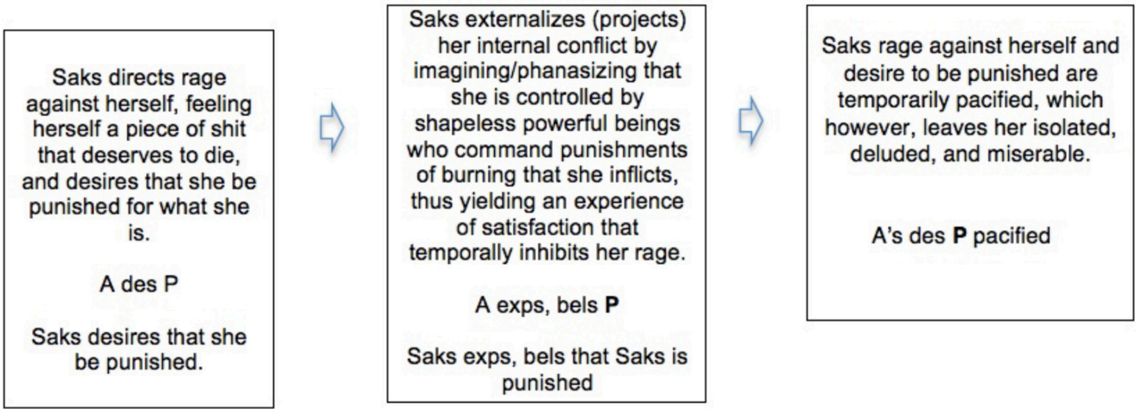
Freud remarked that R's relief from his OCD came with his recognizing *himself* in the invading rats of his phantasy; and we can now see that this symptom, like Saks' delusions, effected an imaginary relocation (projection) of an angry (and biting) part of himself into another. The oscillation between depression and mania in bipolar disorder shows a comparable mechanism, in which attempts to maintain internal but overly depressive regulatory control give way to delusions in which, e.g., the subject expects and imagines himself accomplishing wonderful things, and the SEEKING system is again overactive in a way admitting control by dopamine antagonists such as haloperidol. A third complexity-reducing response, discussed in detail in Watt and Panksepp (2009) and Alcaro and Panksepp (2011), is the inhibition of the SEEKING system itself, as seen in the response to PSG in infant animals. (This reduces FE from sensory impingement in a way comparable to the "dark room" often posed as a problem for Friston's account.)

WAKING DISORDER AND COMPLEXITY REDUCTION IN SLEEP

As these sketches illustrate, the complexity theory integrates the full range of psychoanalytic hypotheses about dreaming, development, and disorder into the perspective of FE neuroscience, where they might receive additional testing. But the theory also implies something further, namely that we should understand mental disorder in terms of *systematic* connections between failures/malfunctions of complexity reduction in sleep and the emergence of symptoms in waking life.

These are clearly visible in PTSD, and the nightmares that abort dreaming are now themselves regarded as causes of waking symptoms, including suicide (Littlewood et al., 2016). More generally, a recent study found that 55% of individuals diagnosed

BOX 3 | The pacification or inhibition of an intrapsychic conflict (between ego and superego) by a conscious experience of satisfaction constituting a projective delusion.



Saks directs rage against herself, feeling herself a piece of shit that deserves to die, and desires that she be punished for what she is.

A des P

Saks desires that she be punished.

Saks externalizes (projects) her internal conflict by imagining/phanasizing that she is controlled by shapeless powerful beings who command punishments of burning that she inflicts, thus yielding an experience of satisfaction that temporally inhibits her rage.

A exps, bels **P**

Saks exps, bels that Saks is punished

Saks rage against herself and desire to be punished are temporarily pacified, which however, leaves her isolated, deluded, and miserable.

A's des **P** pacified

as psychotic (as opposed something less than 5% of the general population) had nightmares at least once a week, and that the emotional severity of these disturbances of sleep was correlated with that of their waking symptoms (Sheaves et al., 2015; see also Levin and Nielsen, 2009).

Nightmare seems best understood as produced by the arousal of fear or panic in the consolidation/reconsolidation of memory that coincides with complexity reduction in sleep. As illustrated below, complexity reduction in dreaming often begins with a phase expressing the conflicts that the dream will go on to mitigate; and in nightmares (such as that by Obama discussed in Hopkins, 2013) this initial expression causes premature waking. Thus, both psychoanalysis and systems consolidations accounts can agree in regarding nightmares as failed attempts at the kind of emotionally pacifying amygdala-related processing hypothesized in active systems consolidation above. The correlation between the emotional severity of the nightmares and the waking symptoms suggests, consistently with the complexity theory, that *both* the sleeping and waking disturbances have a common source in aversive emotional arousal related to memory, and also that the persistence of the waking symptoms is related to failures in complexity reduction in sleep.

A range of waking disorders, including schizophrenia, mania and depression, vary systematically with less obvious disorders in sleep, involving abnormalities in SWS, REM, and the way these relate to dreaming. As the complexity theory would suggest, disorder in sleep seem often to predict that in waking (Krystal, 2012; Reeve et al., 2015; Zanini et al., 2015); and cognitive bizarreness tends to correlate across disorders as between dreaming and waking. Thus, normally bizarreness in dreaming greatly exceeds that in waking. In depression, by contrast, dreaming, when it occurs, is often mundane, emotionally flat, and lacking in bizarreness (Beauchemin and Hays, 1996), so that cognitive bizarreness in dreaming and waking tend toward a level. Something similar appears in schizophrenia and mania, in which both dreaming and waking bizarreness are elevated (Cavallotti et al., 2014).

Cartwright (2010, Ch. 4; see also Nutt et al., 2008; Palagini et al., 2013) describes how severe depression often involves a premature transition from early light sleep to a disordered form of REM. This omits deep SWS in which growth hormone is released, and memory transfer from the hippocampus to the cortex normally takes place. The premature REM is abnormally sparse or dense, coming in "eye movement storms," accompanied not only by high limbic/paralimbic arousal but also by high (and likely conflict-controlling) activity in frontal executive areas. In consequence many severely depressed patients apparently *do not* dream in REM.

Taken together with the mundaneness of dreaming in less severe depression, this suggests that the bizarreness of dreams partly reflects the complexity aroused and available for reduction in them. This would accord with Kirov's (2013) suggestion that complexity reduction takes place periodically during successive NREM-REM cycles over a night, with each cycle potentially broadening and/or deepening the work of consolidation/reconsolidation of its predecessors. Since the sources of complexity in remote memory are intrinsic and inexhaustible, increases in bizarreness during a night would mark ongoing successful reduction; and the bizarreness itself would partly reflect an increasing use of *condensation*, as discussed below.

By contrast disturbances that abort complexity-reduction in dreaming seem also, as in PTSD, to give rise to symptoms in waking. As shown by Vogel et al. (1968, 1977, 1980) symptoms of even severely depressed individuals are altered without medication by 3 weeks of carefully controlled deprivation of REM sleep. This causes an REM rebound in which SWS and REM are restored to a more normal balance and symptoms are relieved. This illustrates the leading role that the complexity theory assigns to processes that have evolved to reduce complexity in sleep; and so do Cartwright's further observations as to the way the quality of patients' sleep and dreaming predicts whether they will recover from depression. (For related recent research incorporating a psychoanalytic perspective see Fischmann et al., 2013)

A comparable situation holds in schizophrenia, the disorder held most closely to resemble dreaming (Llewellyn, 2009, 2011), and in which dreams are often impoverished or short but related to waking symptoms (Chang, 1964; Carrington, 1972; Lusignan et al., 2009; Noreika et al., 2010; Mota et al., 2014). In healthy individuals the slow waves, spindles, and sharp-wave ripples that implement the transfer of memories to the cortex during the consolidation/reconsolidation of memory are tightly synchronized. In individuals diagnosed as schizophrenic they are not (Gardner et al., 2014). Slow wave activity in sleep—which as Cartwright (2010) notes may also be associated with sleepwalking and night terrors—is abnormal and reduced. This goes with an *increase* in slow wave activity in waking, particularly when the disorder is active, and also with abnormal dopamine release (Slifstein et al., 2015), blunted in prefrontal but increased in striatal areas. As Duan et al. (2015) and Lisman (2016) contend, this may impede prefrontal working memory; and since striatal dopamine can also cause delusions, this may also be a source of delusions such as Saks' above.

Friston and his colleagues distinguish *dysconnection*, the dysfuncional integration of distributed neuronal processes, usually at the synaptic level, from *disconnection*, the anatomical disruption of long-range connections at the level of white-matter tracts and axonal processes (Friston et al., 2014a). Recent work on dysconnection (van den Heuvel et al., 2015) suggests that both may be due to the loss of dendritic spines on cortical neurons, which may in turn be caused by the removal of calcium-permeable AMPA receptors in sleep (Lanté et al., 2011; on mechanisms of pruning see also Gonçisalves et al., 2016). Such losses have long been documented in schizophrenia (Glausier and Lewis, 2012) and more recently in bipolar disorder (Konopaske et al., 2014). Since the 1980's neuroscientists have speculated that this is due to synaptic pruning (Feinberg, 1982; Catts et al., 2013), and this has now received striking genetic support (Sekar et al., 2016).

Accordingly Cannon (2015) argues that synaptic pruning is a key explanatory factor in the development of schizophrenia; and the same might hold, although in a different form, for depression (MDD), biolar disorder (BP) and others. This suggests, in accord with the complexity theory, that nocturnal pruning can take aberrant forms that render individuals like Elyn Saks less able to process conflict or trauma in sleep and dreaming, and so in waking to require the excessive recourse to phantasy or delusion that apparently constitutes the disorder. Moreover, as Cannon (2015) reports, it seems that circuit alterations wrought by synaptic pruning might themselves produce the altered dopamine release that, as noted above, may facilitate both delusion and "negative" symptoms in schizophrenia (and would have effects in other disorders as well); and mouse models (Kim et al., 2015) may support this.

Synaptic and axonal degradation can of course have other causes related to complexity, such as the adrenal steroids produced by stress associated with conflict and trauma, as emphasized in Kandel (1999) and Altena et al. (2010) report that such degradation is also caused by insomnia. The patterns of deficit related to schizophrenia and depression, as described in Schultz et al. (2012), Grieve et al. (2013), and Gong et al. (2015), seem to overlap with areas known to be involved in regulating emotion and conflict (Etkin et al., 2015). This, again, might extend to a number of disorders that psychoanalysis explains in terms of trauma, conflict, and phantasy, but current psychiatric classifications describe as at once very diverse but also liable to unexplained co-morbidities and overlapping of symptoms. For as Goodkind et al. (2015) report, a range of Axis 1 mental disorders seem related to such patterns of reduction.

However produced, these patterns can be seen, consistently with the complexity theory, as indicating a reduced capacity on the part of the generative model to cope with trauma and conflict, and a greater reliance on varying forms of phantasy or virtual reality in doing so. Thus, both the commonalities and the varieties in a range of mental disorders and everyday problems in living may be explicable in terms of emotional conflict or complexity and the factors that have evolved to reduce it.

COMPLEXITY REDUCTION IN REM DREAMING

Dreams could evidently play the complexity-reducing role sketched above during the consolidation/reconsolidation of memory, and as already stressed this would fit with recent work on REM dreaming as performing "emotional valence re-evaluation and adjustment" in updating and revising the amygdala-related emotions associated with memory (van der Helm et al., 2011; Genzel et al., 2015 see also Gujar et al., 2011; Goldstein and Walker, 2014; Hutchinson and Rathmore, 2015). We would expect complexity reduction to occur together with the updating of the emotional significance of old memories, and Soeter and Kindt (2015) have recently provided powerful evidence of the plasticity of fear memory under reconsolidation. This suggests that the vivid experiences of dreaming in the apparently plasticity-inducing circumstances of REM could have a powerful revisionary effect on the emotional significance of the whole family of cortically embodied long-term memories undergoing updating in sleep, while at the same time strengthening (and without distortion) their declarative content.

This would provide for the maintenance of accuracy together with the reduction of emotional complexity; and it would also correspond almost exactly with the understanding of the role of dreaming in the consolidation of memory that is to be extracted from Freud. To appreciate this we can observe that Freud's analyses of dreams characteristically contain, among others, three kinds of elements. These and their relations are discussed in more detail in Hopkins (2015), and include the following

(i) *The consciously remembered dream*. The sequence of episodes that make up the dream, or what Freud calls the *manifest content* of the dream.

(ii) *Conscious memories and feelings from the day of the dream.* These include the episodic memories that, according to active systems accounts, are under consolidation in the dream, and so are the emotionally significant new memories that are under transfer to the cortex from the hippocampus during the SWS that precedes the REM in which the dream in (i) occurs. Thus, it seems that in the dream itself these new memories are being consolidated and emotionally integrated with the rearoused cluster of memories and emotions (iii, below) already stored in the cortex.

(iii) *Deeper memories and emotions* (as well as thoughts, feelings, wishes, etc.) *systematically related to (i) and (ii).* These *remote memories* and *significant emotions* are part of what Freud calls the *latent content* of the dream, as collected in his process of free association. In that context they can be seen to relate to (i) and (ii) in such a way as to provide evidence (similar to that in the simple instances of dreaming above) for the hypothesis that *these are the deeper memories and emotions that were unconsciously aroused in active inference on the previous day*, and hence also *the memories and emotions that systems consolidation accounts take to be rearoused and reconsolidated during REM and dreaming.* They are thus also the main targets for the *complexity reduction* taking place, as HFF hypothesize, in REM dreaming, and will thus serve as more efficient predictors in the next waking period.

Psychoanalytic and system consolidation accounts of (REM) dreaming are thus closely related both to one another and to the HHF account of dreaming as complexity reduction. We can summarize this by saying that Freud's conception of *the latent content of a dream* encompasses *the same cortically stored memories and associated emotions* as the systems accounts take to be aroused for reconsolidation and emotional revision under the impact of Freud's *manifest content* in REM.

Thus, both Freudian and systems consolidation accounts can regard the manifest dream experience as caused by the arousal of the same mainly unconscious memories and emotions that were active on the day of the dream; and both regard the manifest dream as working to alter some of these emotions during their arousal. The alterations proposed by both accounts, moreover, are such as would reduce emotional complexity (including conflict and potentials for trauma) in the sense we have been considering.

Taken in combination these three accounts—psychoanalytic, systems consolidation, and complexity reduction—converge not only on the memories and emotions whose arousal causes dreaming in REM, but also on the nature of the emotional changes that the fictive experiences of dreaming produced by counterfactual active inference in REM function to bring about. This in turn indicates that we can further integrate neuroscience and depth psychology by understanding the nature and specifics of complexity reduction in the actual cases in which psychoanalysis enables us to trace the memories and emotions in question and describe instances of alteration and its effects.

To see this briefly but with some detail let us consider the combined accounts as related to a single element of the dream Freud first analyzed. In this dream Freud met his former patient Irma, who introduced the topic for complexity-reduction by complaining to him about her continued suffering after her therapy. He examined her together with Dr. M, the leading figure in their medical circle, and other members of the circle who materialized in the dream. M confirmed Freud's conclusions, and the examination made all present aware that Irma's continued suffering was caused by a thoughtless injection of the toxic chemical trimethylamin, administered shortly before by another member of the circle, Freud's friend and family doctor Otto.

Thus, here is (part of) Freud's description of examining Irma in the dream (Freud, 1974b, p. 107), with the particular element we will be considering emphasized in bold:

> I took [Irma] to the window [to examine her] and looked down her throat...I at once called in Dr. M., and he repeated the examination and confirmed it...[saying] "There is no doubt it is an infection"...We were directly aware, too, of the origin of her infection. Not long before, when she was feeling unwell, my friend Otto had given her an injection of... trimethylamin...***One does not make injections of that sort so thoughtlessly***... And probably the syringe had not been clean.

This imaginary episode was clearly related to two sets of memories and emotions, as described in (ii) and (iii) above. The first derived from the day of the dream, when Otto had called on Freud and mentioned that he had just visited Irma and her family at their summer place, and while there had been called away to give someone an injection. Freud asked how Irma was, and Otto said that she was "better, but not yet well." On hearing this Freud felt vaguely annoyed, as if Otto were impugning his treatment of Irma; and that evening he sat writing out Irma's case history until late at night, to show to M, a leading figure in their medical circle, to justify himself.

These memories are clearly concerned with Freud's feeling of being criticized by Otto and his wish to justify himself; and Freud's discovery in the dream that Otto's thoughtless injection was responsible for Irma's continued suffering provides both justification and grounds for retaliatory criticism. So we see a connection between the manifest content and the emotions of the day that is similar to those in the simple examples above. Just as Freud's dream of drinking and the desire to drink we take to have caused it are related as desire and experience of satisfaction, so Freud's experience in this more complex dream can be seen as fictively satisfying the desire to justify himself and the annoyance with Otto that he felt on the evening of the dream. So here, as before, we naturally take the dream experience as both *caused by*, and also as *serving to pacify* (that is, to *inhibit*) the emotions aroused in REM.

In this account the complexity of Freud's model as he went to sleep mainly reflected the parametric changes produced by the small but genuine trauma of this unpleasant and potentially depressing experience, and his writing up Irma's case history until late that night suggests emotional overfitting on this topic, due to his remote but still active memories connected with it. Hence the construction in this dream of a radically counterfactual *experience of satisfaction*—combining assurance of his medical competence with innocence and vindication against Otto as regards the thoughtless medical misuse of toxic substances—was calculated to produce a prior-restoring (and hence complexity-reducing) alteration in emotion that would render his model optimally prepared for action-directing work on the day to come.

These reflections are strengthened by considering the remote memories and emotions that are part of the latent content of the dream. We can see how Freud's free associations led to these by starting with those to the element on which we have focused.

> *One does not make injections of that kind so thoughtlessly*...this sentence in the dream reminded me once more of my dead friend who had so hastily resorted to cocaine injections...I noticed too that in accusing Otto of thoughtlessness in handling chemical substances I was once more touching upon the story of the unfortunate Mathilde, which gave grounds for the same accusation against myself... (Freud, 1974b, p. 106).

These associations go directly to remote memories freighted with guilt and shame: to Freud's own involvement, as a physician pledged to *primum est nihil nocere*, in the advice and administration of injections that proved lethal. For as Freud says, they indicate that *he felt himself guilty of the kind of thoughtless handling/injection of toxic substances of which he accused Otto in his dream*.

Freud had been an early advocate of the medical use of cocaine, and his enthusiasm—which extended to arguing, on the basis of his own experience, that cocaine was not addictive—"had brought down serious reproaches on me." During this period a beloved friend and mentor, the talented scientist Ernst Fleichel von Marxow, had become addicted to morphine, taken to relieve incurable pain from an infection and amputation resulting from dissecting a cadaver. Freud had recommended that von Marxow use cocaine as a supposedly non-addictive substitute for morphine. He rapidly became addicted and the decline that followed caused Freud great grief and guilt.

The "unfortunate Mathilde" was another about whom Freud had reason to feel intense guilt. He had given her injections of sulphanol, considered harmless up to that time, and she too had died as result. This death, moreover, was associated in Freud's mind with the fate of his own daughter, who had also been seriously ill.

> My patient—who succumbed to the poison—had the same name as my eldest daughter. It had never occurred to me before, but it struck me now almost like an act of retribution on the part of destiny. It was as though the replacement of one person by another was to be continued in another sense: this Mathilde for that Mathilde, an eye for an eye and a tooth for a tooth (Freud, 1974b, p. 111–112)

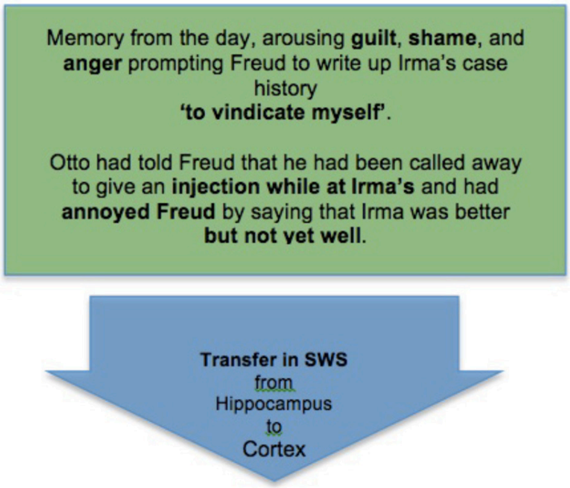
In considering how his associations had led to these topics, Freud remarked that it seemed he "had been collecting all the occasions which I could bring up against myself as evidence of lack of medical conscientiousness." With hindsight we can see that this was the activity of the part of himself that he would later call the superego, which not only accused him with his worst medical derelictions but also threatened him with retribution for them in the form of the death of his own daughter. This was the unconscious version, in Freud, of the kind of conflict with the superego consciously expressed in Saks' berating herself as a piece of shit who deserved to die. And as with Saks, it involved activity of a part or aspect of the self being experienced as coming outside—not from shapeless powerful beings such as Saks described, but as *retribution on the part of destiny*.

Thus, we can diagram the complexity-reducing function of Freud's dream as follows starting from the initial stage of memory consolidation in SWS (**Box 4**).

This is followed by the second stage, of arousal of memory and emotion in REM, as understood in light of the memories recovered by Freud in free association (**Box 5**).

And finally we have the work of counterfactual active inference in response to these arousals, inhibiting (pacifying) them by creating Freud's fictive experience of innocence and vindication, and so reducing the emotional complexity (adversity, conflict, and potential to cause depressive trauma) of the whole family of memories under reconsolidation (**Box 6**).

BOX 4 | An initial stage of memory consolidation: Freud's memory of an emotionally significant experience from the day is transferred to the cortex for long-term storage during SWS.

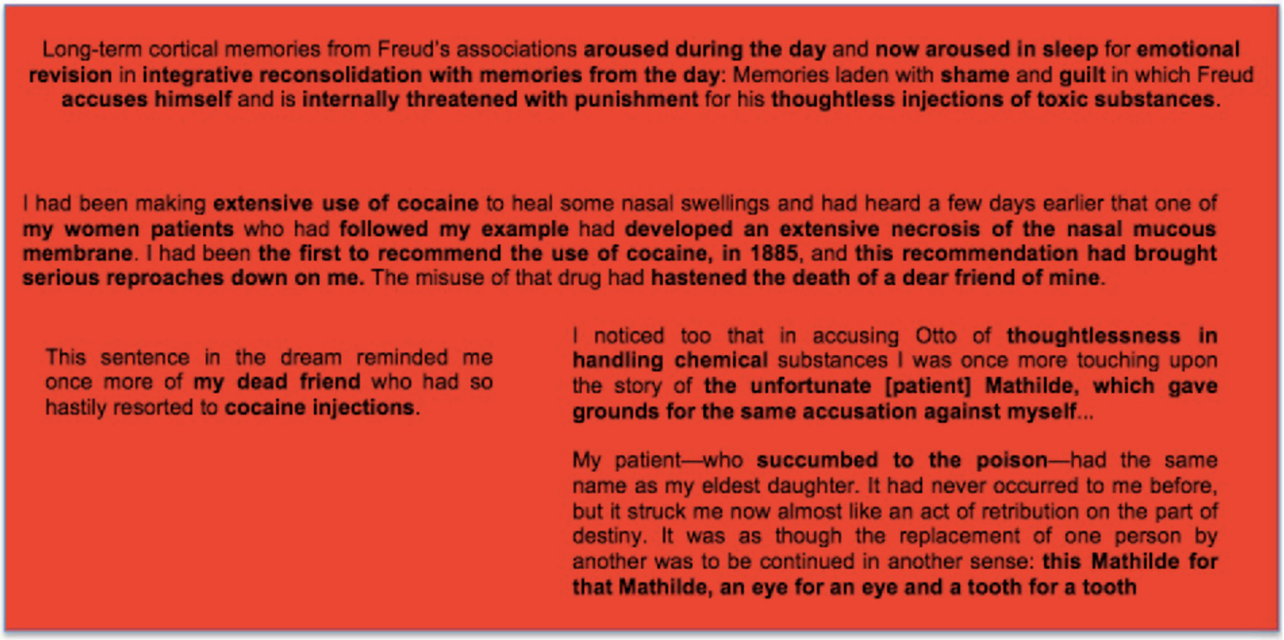


Memory from the day, arousing **guilt**, **shame**, and **anger** prompting Freud to write up Irma's case history **'to vindicate myself'**.

Otto had told Freud that he had been called away to give an **injection while at Irma's** and had **annoyed Freud** by saying that Irma was better **but not yet well**.

Transfer in SWS
from
Hippocampus
to
Cortex

BOX 5 | A second stage in memory consolidation: The cortically stored memories which gave Freud's experience of the day its particular emotional significance are re-aroused in REM so that the new memory can be consolidated together with them as part of a complex that has been emotionally revised (simplified) in light of the day's experience.



Long-term cortical memories from Freud's associations **aroused during the day** and **now aroused in sleep** for **emotional revision** in **integrative reconsolidation with memories from the day**: Memories laden with **shame** and **guilt** in which Freud **accuses himself** and is **internally threatened with punishment** for his **thoughtless injections of toxic substances**.

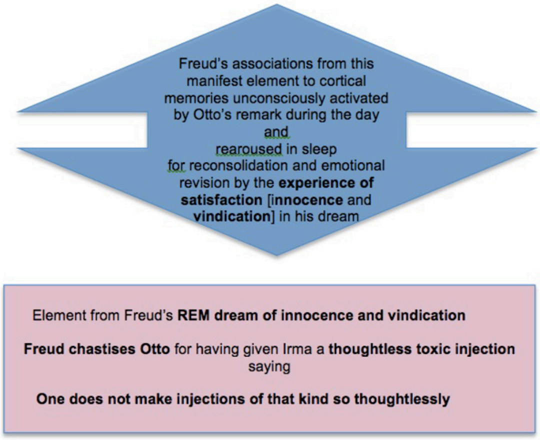
I had been making **extensive use of cocaine** to heal some nasal swellings and had heard a few days earlier that one of **my women patients** who had **followed my example** had **developed an extensive necrosis of the nasal mucous membrane**. I had been **the first to recommend the use of cocaine, in 1885**, and **this recommendation had brought serious reproaches down on me.** The misuse of that drug had **hastened the death of a dear friend of mine**.

This sentence in the dream reminded me once more of **my dead friend** who had so hastily resorted to **cocaine injections**.

I noticed too that in accusing Otto of **thoughtlessness in handling chemical** substances I was once more touching upon the story of **the unfortunate [patient] Mathilde, which gave grounds for the same accusation against myself**...

My patient—who **succumbed to the poison**—had the same name as my eldest daughter. It had never occurred to me before, but it struck me now almost like an act of retribution on the part of destiny. It was as though the replacement of one person by another was to be continued in another sense: **this Mathilde for that Mathilde, an eye for an eye and a tooth for a tooth**

BOX 6 | A final stage in memory consolidation: The complex of memories and emotions rearoused in REM produce a series of emotionally simplifying dream experiences, which enable the complex to be reconsolidated in a less complex (less averse, conflicted, and trauma-producing) form.



CONDENSATION AND SYMBOLIC COGNITION

Above we noted that Freud described the *dreamwork* (Freud, 1974b, Ch. VI) as *condensing* emotionally significant elements from a range of associated memories, including recent memories under consolidation and remote memories rearoused for reconsolidation with them. In this example we can see such condensation clearly in the figure of Irma, whose role as recipient of Otto's toxic injection in the dream condenses her with the "dead friend" and "the unfortunate Mathilde" in Freud's associations. This *condensation* was a form of *symbolization*, bridging Freud's recent upsetting memory of Otto's remark about Irma with his temporally remote memories about the friend and patient who were the deeper sources of his guilt and shame, and preparing for the emotional whitewash provided by the rest of the dream.

This condensation enabled Freud's *fictive conscious experience of innocence in respect of a toxic injection given to Irma* to extend its inhibitory reach to his real remembered arousals of emotion about his role in toxic injections, and in a way that is structurally comparable to the role of consciousness-constituting FE-minimizing inference in waking. Symbolic cognition thus also plays an important role in the minimization of FE, and Hopkins (2000, 2015) describe how the dreamwork in this example makes copious use of symbolism that can be discussed as conceptual metaphor. Malinowski and Horton (2015) discuss conceptual metaphor as part of symbolic embodied cognition in an account of emotion-assimilation in dreaming that also relates it to condensation and memory.

It thus appears that a key role of active inference in the construction of dreaming consciousness is to inhibit and alter adverse and conflicting emotions, so as to reduce or eliminate the overly complex parameters/states introduced in their waking arousal. We can see Freud's dream as accomplishing this in a way akin to Bayesian model selection (cf Fitzgerald et al., 2014). The dream introduced an *ideal alternative counterfactual model* which perforce realized *an ideal fictive sensorimotor trajectory* by which, and in accord with Freud's priors of the previous day, the adverse emotional situation precipitated in him by Otto's unwelcome remark could be restored to a personally satisfactory (and free-energy minimal) equilibrium. Thus, Freud could awake in the morning free from the self-justificatory and depressive trend in which he had spent the day and evening after Otto's remark, and address his problems as a physician and psychiatrist via the creative activity of analyzing his own dream, thereby altering his own theories and practice for the better.

In addition we can see the fictive construction in Freud's dream to have played a role comparable to that in Saks' delusions. In both cases the self was threatened by conflict in the form of severe and depressing self-reproaches, and in both this conflict was mitigated by the creation of a counterfactual virtual reality that externalized the conflict. In Saks the moralistic agency of conflict (the superego) was externalized by projection into the "shadowy, powerful beings" who commanded her to undergo self-tormenting penance. In Freud, this agency remained intact and functioning, but the counterfactual virtual reality, as in a manic episode, directed its critical functioning away from Freud himself and on to Otto instead. Thus, Freud's dream relieved his internal conflict while keeping his internal locus of self-regulation intact and exercised, whereas Saks' delusions fragmented that locus and thereby deepened her illness.

The discharge of this complexity-reducing function evidently requires the collection/organization of emotionally aversive memories, apparently effected in the transfer from hippocampus to the cortex referenced above. As other disturbances in SWS also suggest, this transition seems liable to malfunction. As noted above in nightmares the arousal of aversive memories and emotions renders the dreamer/model incapable of devising any ideal alternative. Again, Saks' depression and paranoia both apparently result from an accumulation of self-directed aversive emotion, caused, we may hypothesize, by destructive phantasies (e.g., those of killing babies discussed in Hopkins, 2013) that made her guilty.

Dahan et al. (2007) report that a kind of "burst firing" of VTA dopamine neurons occurs in both REM and waking consummatory reward. Such firing has recently been modeled as modulated by acetylcholine, which is elevated in REM (Knudstrup et al., 2016). It would fit the account here if the complexity-reducing power of wishfulfilling counterfactual virtual reality in REM dreaming derived from such aminergic/cholinergic engineered precision. (An additional possibility is that this is linked with the reversal of hippocampal theta oscillations, Jackson et al. (2014) that Genzel et al. (2015) speculate may "provide the milieu" for the revision of emotional memory in REM and dreaming).

CONCLUSION

We have seen how Freud's speculative FE neuroscience relates to the rigorous and potentially unifying paradigm now advanced by Friston and colleagues. This in turn enables us to see how the statistical conception of complexity employed by Friston relates to emotional conflict and trauma; how symptoms as well as dreams can be understood in terms of complexity-reduction; how REM dreaming can reduce complexity in the consolidation/reconsolidation of memory; and how complexity and the mechanisms that have evolved to reduce it seem pivotal for the understanding of mental disorder. This linking of complexity, dreaming, and disorder also indicates that Freud and free association offer a distinctive path—but one consilient with cognitive science, FE neuroscience, and computational psychiatry—toward understanding them together. Fuller interdisciplinary co-operation along this path might well make a significant contribution to further progress.

AUTHOR CONTRIBUTIONS

The author confirms that he is the sole contributor to this work and approves it for publication.

FUNDING

This work was not supported by a funding body.

REFERENCES

Alcaro, A., and Panksepp, J. (2011). The SEEKING mind: Primal neuro-affective substrates for appetitive incentive states and their pathological dynamics in addictions and depression. *Neurosci. Biobehav. Rev*. 35, 1805–1820. doi: 10.1016/j.neubiorev.2011.03.002

Altena, A., Vrenken, H., Van Der Werf, Y., van den Heuvel, O., and Van Someren, E. (2010). Reduced orbitofrontal and parietal gray matter in Chronic Insomnia: a voxel-based morphometric study. *Biol. Psychiatry* 67, 182–185. doi: 10.1016/j.biopsych.2009.08.003

Beauchemin, K., and Hays, P. (1996). Dreaming away depression: the role of REM sleep and dreaming in affective disorders. *J. Affect Disord.* 41, 125–133.

Beebe, B., and Lachman, F. (2014). *The Origins of Attachment: Infant Research and Adult Treatment*. New York, NY; Hove: Routledge.

Blatt, S. (2004). *Experiences of Depression*. Washington, DC: APA Press.

Boyce, R., Glasgow, S., Williams, S., and Adamantidis, A. (2016). Causal evidence for the role of REM sleep theta rhythm in contextual memory consolidation. *Science* 352, 812–816. doi: 10.1126/science.aad5252

Calais, J., Ojopi, E., Morya, E., Sameshima, K., and Robiero, F. (2015). Experience-dependent upregulation of multiple plasticity factors in the hippocampus during early REM sleep *Neurobiol. Learn . Mem.* 122, 19–27 doi: 10.1016/j.nlm.2015.01.002

Cannon, T. (2015). How Schizophrenia develops: cognitive and brain mechanisms underlying onset of psychosis. *Trends Cogn. Sci.* 19, 744–756. doi: 10.1016/j.tics.2015.09.009

Carrington, P. (1972). Dreams and Schizophrenia. *Arch. Gen. Psychiatry* 26, 343–350. doi: 10.1001/archpsyc.1972.01750220053010

Cartwright, R. (2010). *The Twenty-Four Hour Mind: The Role of Sleep and Dreaming in Our Mental Lives*. Oxford: Oxford University Press.

Catts, V., Fung, S., Long, L., Joshi, D., Vercammen, A., Allen, K., et al. (2013). Rethinking schizophrenia in the context of normal neurodevelopment. *Front. Cell Neurosci.* 7:60. doi: 10.3389/fncel.2013.00060

Cavallotti, S., Castelnovo, A., Ranieri, R., and D'agostino, A. (2014). Stability of cognition across wakefulness and dreams in psychotic major depression. *Psychiatry Res.* 216, 31–36. doi: 10.1016/j.psychres.2014.01.033

Chang, S. C. (1964). Dream-recall and themes of hospitalized schizophrenics. *Arch. Gen. Psychiatry* 10, 119–122.

Clark, A. (2016). *Surfing Uncertainty: Prediction, Action, and the Embodied Mind*. Oxford; New York, NY: Oxford University Press.

Craig, A. D. (2015). *How Do You Feel: A Moment with your Neurobiological Self*. Princeton, NJ: Princeton University Press.

Cyr, C., Eiuser, E., Bakermans-Kranenburg, M., and Van Ijzendoom, M. (2010). Attachment security and disorganization in maltreating and high-risk families: a series of meta-analyses. *Dev. Psychopathol.* 22, 87–108. doi: 10.1017/S0954579409990289

Dahan, L., Astier, B., Vautrelle, N., Urbain, N., Kocis, B., and Chouvet, G. (2007). Prominent burst firing of dopaminergic neurons in the ventral tegmental area during paradoxical sleep. *Neuropsychopharmacology* 32, 1232–1241. doi: 10.1038/sj.npp.1301251

Damasio, A., and Carvalho, G. (2013). The nature of feelings: evolutionary and neurobiological origins. *Nat. Rev. Neurosci.* 14, 143–152. doi: 10.1038/nrn3403

Dayan, P., Hinton, G., Neal, R., and Zemel, R. (1995). The Helmholtz Machine. *Neural Comput.* 7, 899–904.

Deserno, L., Schlagenhauf, F., and Heinz, A. (2016). Striatal dopamine, reward, and decision making in schizophrenia. *Dialog. Clin. Neurosci.* 18, 77–89.

Duan, A., Varela, C., Zhang, Y., Shen, Y., Xion, L., Wilson, M., et al. (2015). Delta frequency optogenetic stimulus of the thalamic nucleus reuniens is sufficient to produce working memory deficits: relevance to schizophrenia. *Biol. Psychiatry* 77, 1098–1107. doi: 10.1016/j.biopsych.2015.01.020

Dudek, J., Faress, A., Bornstein, M. H., and Haley, D. W. (2016). Infant cries rattle adult cognition. *PLoS ONE* 11:e0154283. doi: 10.1371/journal.pone.0154283

Dumoulin Bridi, M., Aton, S., Seibt, J., Renouard, L., Coleman, T., and Frank, M. (2015). Rapid eye movement sleep promotes cortical plasticity in the developing brain. *Sci. Adv.* 1:e1500105. doi: 10.1126/sciadv.1500105

Enlow, M., Egeland, B., Carlson, E., Blood, E., and Wright, R. (2014). Mother–infant attachment and the intergenerational transmission of posttraumatic stress disorder *Dev. Psychopathol* 26, 41–65. doi: 10.1017/S0954579413000515

Etkin, A., Buchel, C., and Gross, J. (2015). The neural bases of emotion regulation. *Nat. Rev. Neurosci.* 16, 693–700 doi: 10.1038/nrn4044

Feinberg, J. (1982). Schizophrenia: caused by a fault in programmed synaptic elimination during adolescence. *J. Psychair. Res.* 17, 319–334.

Fischmann, T., Russ, M., and Leuzinger-Bohleber, M. (2013). Trauma, dream, and psychic change in psychoanalyses: a dialog between psychoanalysis and the neurosciences. *Front. Hum. Neurosci.* 7:877. doi: 10.3389/fnhum.2013.00877

Fitzgerald, T., Dolan, R., and Friston, K. (2014). Model averaging, optimal inference, and habit formation. *Front. Hum. Neurosci.* 8:457. doi: 10.3389/fnhum.2014.00457

Freud, S. (Rev Ed). (1974a). *Project for a Scientific Psychology*, Vol. I. London: Hogarth Press.

Freud, S. (Rev Ed.). (1974b). *The Interpretation of Dreams*, Vol. IV – V. London: Hogarth Press.

Freud, S. (Rev Ed.). (1974c). *Notes Upon a Case of Obsessional Neurosis*, Vol. X. London: Hogarth Press.

Freud, S. (Rev Ed.). (1974d). *'Original Record'. Notes Upon a Case of Obsessional Neurosis: Addendum: Original Record of the Case*, Vol. X. (London: Hogarth Press), 253–318.

Freud, S. (Rev Ed.). (1974e). *On Narcissism*, Vol. XIV. London: Hogarth Press.

Friston, K. (2010). The free-energy principle: a unified brain theory? *Nat. Rev. Neurosci.* 11, 127–138. doi: 10.1038/nrn2787

Friston, K. (2012). Prediction, perception and agency. *Int. J. Psychophysiol.* 83, 248–252. doi: 10.1016/j.ijpsycho.2011.11.014

Friston, K., Schwartenbeck, P., FitzGerald, T., Moutoussis, M., Behrens, T., and Dolan, R. J. (2014b). The anatomy of choice: dopamine and decision-making. *Philos. Trans. R Soc. Lond. B. Biol. Sci.* 369, pii: 20130481. doi: 10.1098/rstb.2013.0481

Friston, K., Stephan, K., Montague, R., and Dolan, R. (2014a). Computational Psychiatry: the brain as a phantastic orgin. *Lancet Psychiatry* 1, 148–158. doi: 10.1016/S2215-0366(14)70275-5

Gardner, R., Kersante, F., Jones, M., and Bartsch, U. (2014). Neural oscillations during non-rapid eye movement sleep as biomarkers of circuit dysfunction in schizophrenia. *Eur. J. Neurosci.* 39, 1091–1106. doi: 10.1111/ejn.12533

Genzel, L., Spoormaker, V., Konrad, M., and Dresler, M. (2015). The role of rapid eye movement sleep for amygdala-related memory processing. *Neurobiol. Learn. Mem.* 122, 110–121. doi: 10.1016/j.nlm.2015.01.008

Gerrans, P. (2014). Pathologies of hyperfamiliarity in dreams, delusions and déjà vu. *Front Psychol.* 5:97. doi: 10.3389/fpsyg.2014.00097

Glausier, J., and Lewis, D. (2012). Dendritic spine pathology in schizophrenia. *Neuroscience* 251, 90–107. doi: 10.1016/j.neuroscience.2012.04.044

Goldstein, A., and Walker, M. (2014). The role of sleep in emotional brain function. *Annu. Rev. Clin. Psychol.* 10, 679–708. doi: 10.1146/annurev-clinpsy-032813-153716

Gonçisalves, J., Cooper, B., Shtrahman, M., Johnston, M., Schafer, S., Parylak, S. et al. (2016). *In vivo* imaging of dendritic pruning in dentate granule cells. *Nat. Neurosci.* 19, 788–792. doi: 10.1038/nn.4301

Gong, Q., Dazzan, P., Scarpazza, C., Kasai, K., Hu, X., Marques, T., et al. (2015). A neuroanatomical signature for schizophrenia across different ethnic groups. *Schizophr. Bull.* 41, 1266–1275. doi: 10.1093/schbul/sbv109

Goodkind, M., Eickhoff, S., Oathes, D., Jiang, Y., Chang, A., Jones-Hagata, L., et al. and Etkin, A. (2015). identification of a common neurobiological substrate for mental illness. *JAMA Psychiatry* 72, 305–315. doi: 10.1001/jamapsychiatry.2014.2206

Grieve, S., Korgaonkar, M., Koslow., Gordon, E., and Williams, L. (2013). Widespread reductions in gray matter volume in depression. *Neuroimage Clin.* 3, 332–339. doi: 10.1016/j.nicl.2013.08.016

Gujar, N., McDonald, S., Nishida, M., and Walker, M. (2011). A role for REM sleep in recalibrating the sensitivity of the human brain to specific emotions. *Cereb. Cortex*. 21, 115–123. doi: 10.1093/cercor/bhq064

Helmholz, H. (1878/1971). "The Facts of Perception" in *The Selected Writings of Hermann von Helmholtz,* ed R. Karl (Middletown, CT: Wesleyan University Press), 366–408.

Hobson, A. (2014). *Ego Damage and Repair: Towards a Psychodynamic Neurology*, London: Karnac.

Hobson, A. (2015). *Psychodynamic Neurology: Dreams, Consciousness, and Virtual Reality.* New York, NY: Taylor and Francis.

Hobson, A., and Friston, K. (2012). Waking and dreaming consciousness: neurobiological and functional Considerations. *Progr. Neurobiol.* 98, 82–98. doi: 10.1016/j.pneurobio.2012.05.003

Hobson, A., Hong, C. C.-H., and Friston, K. (2014).Virtual reality and consciousness inference in dreaming. *Front. Psychol.* 5:1133. doi: 10.3389/fpsyg.2014.01133

Hopkins, J. (2000). "Psychoanalysis, metaphor, and the concept of mind," in *The Analytic Freud*, ed M. Levine (London: Routledge), 11–36.

Hopkins, J. (2012). "Psychoanalysis representation and neuroscience: the Freudian unconscious and the Bayesian brain," in *From the Couch to the Lab: Psychoanalysis, Neuroscience and Cognitive Psychology in Dialogue*, eds A. Fotopolu, D. Pfaff, and M. A. Conway (Oxford: Oxford University Press), 230–265.

Hopkins, J. (2013). "Understanding and healing: psychiatry and psychoanalysis in the era of neuroscience," in *The Oxford Handbook of the Philosophy of Psychiatry*, eds K. Fulford, M. Davies, R. Gipps, G. Graham, Z. Sadler, G. Stanghellini, and T. Thornton (Oxford: Oxford University Press), 1264–1292.

Hopkins, J. (2015). "The significance of consilience: psychoanalysis, attachment, neuroscience, and evolution," in *Psychoanalysis and Philosophy of Mind: Unconscious Mentality in the 21st Century,* eds S. Boag, L. Brakel, and V. Talvitie (London: Karnac), 47–136.

Howe, G. (2011). *Attachment Across the Lifecourse*. New York, NY: Palgrave MacMillan.

Howes, O., and Nour, M. (2016). Dopamine and the aberrant salience hypothesis of schizophrenia. *World Psychiatry* 15, 3–4. doi: 10.1002/wps.20276

Hutchinson, I., and Rathmore, S. (2015). The role of REM sleep theta activity in emotional memory. *Front. Psychol*. 6:1439. doi: 10.3389/fpsyg.2015.01439

Iglesias, S., Mathys, C., Brodersen, K., Kasper, L., Piccirelli, M., den Ouden, H., et al. (2013). Hierarchical prediction errors in midbrain and basal forebrain during sensory learning. *Neuron* 80, 519–530. doi: 10.1016/j.neuron.2013.09.009

Jackson, J., Amilhon, B., Goutagny, R., Bott, J.-B., Manseau, F., Kortleven, C., et al. (2014). Reversal of theta rhythm flow through intact hippocampal circuits *Nat. Neuros.* 17, 1362–1370. doi: 10.1038/nn.3803

Jiang, L., Kundu, S., Lederman, J., Lopez-Hernandez, G., Ballinger, E., Wang, S., et al. (2016). Cholinergic signaling controls conditioned fear behaviors and enhances plasticity of cortical-amygdala circuits. *Neuron* 90, 1057–1070. doi: 10.1016/j.neuron.2016.04.028

Jouvet, M. (1999). *The Paradox of Sleep: The Story of Dreaming*. Boston, MA: MIT Bradford Press.

Kandel, E. (1999). Biology and the future of psychoanalysis: a new intellectual framework for psychiatry revisited. *Am. J. Psychiatry* 156, 505–524.

Kant, I. (1764/2007). "Essay on the maladies of the head, Trans Wilson, H.," in *The Cambridge Edition of the Works of Immanuel Kant in Translation: Anthropology, History, and Education,* eds P. Guyer and H. Wood (Cambridge: CUP), 63–77.

Kapur, S. (2003). Psychosis as a state of aberrant salience: a framework linking biology, phenomenology, and pharmacology in schizophrenia. *Am. J. Psychiatry* 160, 13–23. doi: 10.1176/appi.ajp.160.1.13

Kim, I., Rossi, M., Aryal, D., Racz, B., Kim, N., Uezu, A., et al. (2015). Spine pruning drives antipsychotic-sensitive locomotion via circuit control of striatal dopamine. *Nat. Neurosc.* 18, 883–891. doi: 10.1038/nn.4015

Kirov, R. (2013). REM sleep and dreaming functions beyond reductionism. *Behav. Brain Sci*. 36, 621–622; discussion 634–659. doi: 10.1017/S0140525X13001362

Knudstrup, S., Zochowski, M., and Booth, V. (2016). Network burst dynamics under heterogeneous cholinergic modulation of neural firing properties and heterogeneous synaptic connectivity. *Eur. J. Neurosci.* 43, 1321–1339. doi: 10.1111/ejn.13210

Konopaske, G., Lange, N., Coyle, J., and Benes, F. (2014). Prefrontal cortical dendritic spine pathology in schizophrenia and bipolar disorder. *JAMA Psychiatry* 71, 1323–1331. doi: 10.1001/jamapsychiatry.2014.1582

Krystal, A. (2012). Psychiatric disorders and sleep. *Neurlo Clin.* 30, 1389–1413. doi: 10.1016/j.ncl.2012.08.018

Lanté, F., Toledo-Salas, J.-C., Ondrejcak, T., Rowan, M., and Ulrich, D. (2011). Removal of Synaptic Ca^{2+} permeable AMPA receptors during sleep. *J. Neurosci.* 31, 3953–3961. doi: 10.1523/JNEUROSCI.3210-10.2011

Levin, R., and Nielsen, T. (2009). Nightmares, bad dreams, and emotion dysregulation. *Curr. Dir. Psychol. Sci.* 18, 84–88. doi: 10.1111/j.1467-8721.2009.01614.x

Lisman, J. (2016). Low-frequency brain oscillations in schizophrenia. *JAMA Psychiatry* 73, 298–299. doi: 10.1001/jamapsychiatry.2015.2320

Littlewood, D., Gooding, P., Panagioti, M., and Kyle, S. (2016). Nightmares and suicide in posttraumatic stress disorder: the mediating role of defeat, entrapment, and hopelessness. *J. Clin. Sleep Med.* 12, 393. doi: 10.5664/jcsm.5592

Llewellyn, S. (2009). In two minds? Is schizophrenia a state 'trapped' between waking and dreaming? *Med. Hypotheses*. 73, 572–579. doi: 10.1016/j.mehy.2009.05.033

Llewellyn, S. (2011). If waking and dreaming consciousness became de-differentiated, would schizophrenia result? *Consc. Cogn*. 20, 1059–1083. doi: 10.1016/j.concog.2011.03.022

Logothetis, N. K., Eschenko, O., Murayama, Y., Augath, M., Steudel, T., Evrard, H. C., et al. (2012). Hippocampal–cortical interaction during periods of subcortical silence. *Nature* 491, 547–553. doi: 10.1038/nature11618

Lusignan, F. A., Zadra, A., Dubuc, M. J., Daoust, A. M., Mottard, J. P., et al. (2009). Dream content in chronically-treated persons with schizophrenia. *Schiz. Res.* 112, 164–173. doi: 10.1016/j.schres.2009.03.032

Malinowski, J. E., and Horton, C. L. (2015). Metaphor and hyperassociativity: the imagination mechanisms behind emotion assimilation in sleep and dreaming. *Front. Psychol.* 6:1132. doi: 10.3389/fpsyg.2015.01132

Mosquera, D., Gonzalez, A., and Leeds, A. (2014). Early experience, structural dissociation, and emotional dysregulation in borderline personality disorder: the role of insecure and disorganized attachment. *Borderline Personal. Disord. Emot. Dysregul.* 1:15. doi: 10.1186/2051-6673-1-15

Mota, N., Raimundo, F., Maia, P.,Copelli, M., and Sidarta, R. (2014). Graph analysis of dream reports is especially informative about psychosis. *Sci. Reports* 4:3691. doi: 10.1038/srep03691

Noreika, K., Markkula, J., Seppäl,ä, A., and Revonsuo, A. (2010). Dream bizarreness and waking thought in schizophrenia. *Psychiatry Res*. 178, 562–564. doi: 10.1016/j.psychres.2010.04.034

Nutt, D., Wilson, S., and Paterson, L. (2008). Sleep disorders as core symptoms of depression. *Dialog. Clin. Neurosci.* 10, 329–336.

Oka, Y., Ye, M., and Zuker, C. S. (2015). Thirst driving and suppressing signals encoded by distinct neural populations in the brain. *Nature* 520, 349–352. doi: 10.1038/nature14108

Palagini, L., Baglioni, C., Ciapparelli, A., Gemignani, A., and Riemann, D. (2013). REM sleep dysregulation in depression: state of the art. *Sleep Med. Rev.* 17, 377–390. doi: 10.1016/j.smrv.2012.11.001

Palombo, S. (1978). *Dreaming and Memory: A New Information-Processing Model.* New York, NY: Basic Books.

Panksepp, J. (1998). *Affective Neuroscience*. Oxford: Oxford University Press.

Parsons, C., Young, K., Joensson, M., Brattico, E., Hyam, J., Stein, A., et al. (2014). Ready for action: a role for the human midbrain in responding to infant vocalizations. *Soc. Cogn. Affect. Neurosci.* 9, 977–984. doi: 10.1093/scan/nst076

Pelluzio, G., Rigoli, F., and Friston, K. (2015). 'Active Inference, homeosatis regulation, and adaptive behavioural control' *Prog. Neurobiol.* 134, 17–35. doi: 10.1016/j.pneurobio.2015.09.001

Rasch, B., and Born, J. (2013). About sleep's role in memory. *Physiol. Rev.* 93, 681–766. doi: 10.1152/physrev.00032.2012

Ravassard, P., Hamieh, A.-M., Malleret, G., and Salin, P.-A. (2015). Paradoxical sleep: a vigilance state to gate long-term brain plasticity? *Neurobiol. Learn. Mem*. 122, 4–10. doi: 10.1016/j.nlm.2014.11.013

Reeve, S., Sheves, B., and Freeman, D. (2015). The role of sleep dysfunction in the occurrence of delusions and hallucinations: a systematic review. *Clin. Psychol. Rev.* 42, 96–115. doi: 10.1016/j.cpr.2015.09.001

Reissland, N., Francis, B., and Mason, J. (2013). Can healthy fetuses show facial expressions of "pain" or "distress"? *PLoS ONE* 8:e65530. doi: 10.1371/journal.pone.0065530

Reissland, N., Francis, B., Mason, J., and Lincoln, K. (2011). Do facial expressions develop before birth? *PLoS ONE* 6:e24081. doi: 10.1371/journal.pone.0024081

Saks, E. (2008). *The Center Cannot Hold: My Journey Through Madness*. New York, NY: Hyperion.

Schultz, C. C., Koch, K., Wagner, G., Nenadic, I., Schachtzabel, C., Güllmar, D., et al. (2012). Reduced anterior cingulate cognitive activation is associated with prefrontal-temporal cortical thinning in schizophrenia. *Biol. Psychiatry*.71, 146–153. doi: 10.1016/j.biopsych.2011.08.015

Schwartenbeck, P., Fitzgerald, T., Mathys, C., Dolan, R., and Friston, K. (2015). The dopimenergic midbrain encodes the expected uncertainty about desired outcomes. *Cereb. Cortex* 25, 3434–3445. doi: 10.1093/cercor/bhu159

Sekar, A., Bialas, A., de Rivera, H., Davis, A., Hammond, T., Kamitaki, N., et al. (2016). Schizophrenia risk from complex variation of complement component 4. *Nature* 530, 177–183. doi: 10.1038/nature16549

Sheaves, B., Onwumere, J., Keen, N., Stahl, D., and Kuipers, E. (2015). Nightmares in patients with psychosis: the relation with sleep, psychotic, affective, and cognitive systems. *Can. J. Psychiatry* 60, 354–361. doi: 10.1177/070674371506000804

Skrzypinska, D., and Szmigielska, B. (2015). Dream-reality confusion in borderline personality disorder: a theoretical analysis. *Front. Psychol.* 6:1393. doi: 10.3389/fpsyg.2015.01393

Slifstein, M., van de Giessen, E., Van Snellenberg, J., Thompson, J., Narendran, R., Gil, R., et al. (2015). Deficits in prefrontal cortical and extrastriatal dopamine release in schizophrenia: a positron emission tomographic functional magnetic resonance imaging study. *JAMA Psychiatry* 72, 316–324. doi: 10.1001/jamapsychiatry.2014.2414

Soeter, M., and Kindt, M. (2015). An abrupt transformation of phobic behavior after a post-retrieval amnesic agent. *Biol. Psychiatry* 78, 880–886. doi: 10.1016/j.biopsych.2015.04.006

Solms, M., and Turnbull, O. (2002). *The Brain and the Inner World: An Introduction to the Neuroscience of Subjective Experience*. London: Karnac.

Solomon, J., and George, C. (1999). *Attachment Disorganization*. New York, NY: Guilford Press.

Staresina, B., Bergmann, T., Bonnefond, M., van der Meij, R., Jensen, O., Deuker, L., et al. (2015). Hierarchical nesting of slow oscillations, spindles and ripples in the human hippocampus during sleep. *Nat. Neurosci.* 18, 1679–1686. doi: 10.1038/nn.4119

Tononi, G., and Cirelli, C. (2014). Sleep and the price of plasticity: from synaptic and cellular homeostasis to memory consolidation and integration. *Neuron* 81, 12–34. doi: 10.1016/j.neuron.2013.12.025

van den Heuvel, M., Scholtens, L., de Reus, M., and Kahn, R. (2015). Associated microscale spine density and macroscale connectivity disruptions in schizophrenia. *Biol. Psychait*. doi: 10.1016/j.biopsych.2015.10.005. [Epub ahead of print].

van der Helm, E., Yao, J., Dutt, S., Rao, V., Saletin, J., and Walker, M. (2011). REM sleep depotentiates amygdala activity to previous emotional experiences. *Curr. Biol.* 21, 2029–2032. doi: 10.1016/j.cub.2011.10.052

Vogel, G., McAbee, R., Barker, K., and Thurmond, A. (1977). Endogenous depression improvement and REM pressure. *Arch. Gen. Psychiatry* 34, 96–97.

Vogel, G., Traub, A., Ben-Horin, P., and Meyers, G. (1968). REM deprivation II. The effects on depressed patients. *Arch. Gen. Psychiatry* 18, 301–311.

Vogel, G., Vogel, F., McAbee, R., and Thurmond, A. (1980). Improvement of depression by REM sleep deprivation new findings and a theory. *Arch. Gen. Psychiatry* 37, 247–253.

Watt, D., and Panksepp, J. (2009). Depression: an evolutionarily conserved mechanism to terminate separation distress? *Neuropsychoanalysis* 11, 7–51. doi: 10.1080/15294145.2009.10773593

Zanini, M., Castro, J., Cunha, J., Asevedo, E., Pan, P., Bittencourt, L., et al. (2015). Abnormalities in sleep patterns in individuals at risk for psychosis and bipolar disorder. *Schizophr. Res.* 169, 262–267. doi: 10.1016/j.schres.2015.08.023

Conflict of Interest Statement: The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The reviewer KF declared a shared affiliation, though no other collaboration with the author to the handling editor, who ensured that the process nevertheless met the standards of a fair and objective review.

frontiers in Psychology

HYPOTHESIS AND THEORY
published: 30 September 2015
doi: 10.3389/fpsyg.2015.01472

Lucid dreams: their advantage and disadvantage in the frame of search activity concept

Vadim S. Rotenberg*

Formerly affiliated with Abarbanel Mental Health Center, Tel-Aviv University, Bat-Yam, Israel

Search activity (SA) is the behavioral and mental activity that is oriented to changes of the environment or of the subject's view and approach to the environment according to personal needs without the definite probability forecast of the outcomes of such activity, but with a regular consideration of the outcomes in the process of active behavior. Dream's lucidity (the subject's realization that he/she is dreaming) protects dreamer from awakenings during emotionally disturbing or frustrating dreams, because lucid dreams allow subject to feel separated from the dream events that may cause a feeling of helplessness. Due to such a protection from awakenings that can bring subject back to the frustration in wakefulness, subject can turn in the further sleep to normal non-lucid dreams that are restoring subject's SA in the subsequent wakefulness (activity in the uncertain situation with the feedback between behavior and its outcome). It is the advantage of lucid dreams. Their disadvantage is that due to the separation from the dream events that are in lucid dreams accepted as rationalized dreams, not as real stories where the dreamer acts like in wakefulness, their ability to restore SA is decreased until they are not displaced by the normal non-lucid dreams accepted as real stories.

Keywords: dream function, lucid dreams, REM sleep, search activity, helplessness

OPEN ACCESS

Edited by:
Roumen Kirov,
Bulgarian Academy of Sciences,
Bulgaria

Reviewed by:
Timo Partonen,
National Institute for Health and
Welfare, Finland
Jim Hopkins,
University College London, UK
Sérgio Arthuro Mota-Rolim,
Federal University of Rio Grande do
Norte, Brazil

***Correspondence:**
Vadim S. Rotenberg,
Mivtsa Yonatan Str. 8/6, 44221
Kfar-Saba, Israel
vadir@post.tau.ac.il

Specialty section:
This article was submitted to
Cognitive Science,
a section of the journal
Frontiers in Psychology

Received: *10 July 2015*
Accepted: *14 September 2015*
Published: *30 September 2015*

Citation:
Rotenberg VS (2015) Lucid dreams:
their advantage and disadvantage in
the frame of search activity concept.
Front. Psychol. 6:1472.
doi: 10.3389/fpsyg.2015.01472

Introduction: The Restoration of Search Activity in Dreams

The problem of dream lucidity is discussed in many scientific publications during the recent few decades. In this article I am not going to cover all aspects of this topic. I would only like to consider the functional role of this relatively rare phenomenon (in comparison to non-lucid dreams) in the context of the general function prescribed to rapid eye movement (REM) sleep and dreams by the Search Activity Concept (SAC, Rotenberg and Arshavsky, 1979; Rotenberg, 2009, 2013).

By search activity (SA) we understand behavioral and mental activity that is oriented to changes of the environment or of the subject's view and approach to the environment according to personal needs without the definite probability forecast of the outcomes of such activity, but with a regular consideration of the outcomes in the process of active behavior. In humans and in other animals with a high level of mental activity complexity, SA is a very important part of subject's relationships with the complicated and dynamic world, and determines the adaptation to it including an overcome of numerous stressful events. Such adaptation cannot be achieved in the process of stereotyped behavior that is relevant only in conditions, where the definite forecast of the outcome of behavior is available. SA is a basis of the personal development and of the development and evolution of the society. It requires a lot of energy, but this energy is restored through the positive feedback between search activity and brain biochemistry (see Rotenberg, 2009).

Our investigations performed on animals (Rotenberg and Arshavsky, 1979) have shown that behavior that includes SA increases the resistance to different forms of artificially induced somatic disorders. On the other hand, renunciation of search that displays itself in giving up and helplessness in front of stressful events and obstacles that subject is unable to cope with, decreases body resistance and causes numerous somatic disorders, typically estimated in humans as psychosomatic diseases, such as peptic ulcer and essential blood hypertension (see Rotenberg, 2009). In humans, renunciation of search is also typical for depression (Rotenberg and Cholostoy, 2004; Rotenberg et al., 2007, 2008).

In real life, subjects are often meeting distressing situations and conditions that they are unable to change or obstacles that prevent achievements of their personally important goals, and such conditions can cause renunciation of search. Obviously, if SA is so important for the survival and development, there must be a natural special biological mechanism that restores the adaptive abilities to cope with numerous stressful events in such conditions. Without this mechanism, any occasional stressful situations even restricted in time, or any terminal but unavoidable obstacle would have a fatal outcome for the subject. According to the SAC (Rotenberg and Arshavsky, 1979; Rotenberg, 2009, 2013), REM sleep dreams in humans and in other animals with a high level of mental activity complexity are performing such restorative function. For instance, healthy subject can go to sleep in a state of giving up with a feeling of being unable to continue search for solution of a given problem and to overcome obstacles, and although after awakening the problem by itself is still not solved, subject is ready to continue efforts to overcome it—in a contrast to the state just before sleep. In our investigations, we have found that in such cases, REM sleep latency is usually decreased, REM sleep percentage in the night sleep is increased, and eye movement density in REM sleep is increased, and when healthy subjects awoke in REM sleep, they often present reports about vivid dreams where they have performed an intense virtual activity (see Rotenberg, 2009).

During SA, the process of this activity by itself is more important than its pragmatic outcomes. The main task of this process is not to stop, not to give up in front of episodic failures. For this reason, REM sleep dreams represent the most relevant condition for the restoration of SA. In dream, subject is isolated from the outward external world including those stressful events that already caused in the previous wakefulness renunciation of search after many failures. SA in dream is a virtual activity, based on imagination. It means that it can be very flexible, polymorphic and chaotic; subject can jump in his dreams from one imagined situation to another and even pass many failures in the process of this activity, because being only virtual, but not real, these failures in reality have no dangerous outcomes for the subject—the only task is not to stop the process. The direction of search can be changed at every moment. The decision to change the direction of search is not made on the basis of rational analysis—it is a sudden impulsive decision, and it costs nothing for the dreamer. This search may be in some way, directly or symbolically, related to the problems that dreamer met in the previous wakefulness. For instance, it may reflect the discharge of suppressed (repressed) motives, otherwise unacceptable for the waking consciousness (according to the psychoanalytical approach). It was confirmed in some investigations. For example, Grieser et al. (1972) have shown that REM sleep deprivation in healthy subjects increases repression and causes emotional tension (anxiety). But often dreams has nothing to do with repressed motives, and are oriented on the occasional imagined goals.

From my point of view, the repression of unacceptable motives is a form of human's renunciation of search—of search for the ability to discharge these motives in real behavior, to realize them or to integrate them into socially acceptable motives, in order to protect the holistic behavior and the Self-concept. However, for the virtual SA in dreams, the topic of the renunciation of search in previous wakefulness is less important than the renunciation by itself, and even if repression of unacceptable motives represents the renunciation of search, the compensatory search in dreams may deal with conditions that are not related to repressed motives. Moreover, the task of the dream is often to turn subject away from the topic that brought him/her to the feeling of helplessness.

REM sleep and dreams characterizes not only humans with their inner motivational conflicts, but also other animals with a high level of mental activity complexity. If we are looking for a common function of REM sleep and dreams in both humans and other animals with a high level of mental activity complexity, restoration of SA seems to be a relevant explanation. In REM sleep, subject is separated from the external reality, from obstacles, mistakes, and punishments that caused renunciation of search, and this separation helps SA in dreams to start as from the very beginning (Rotenberg, 2009; Hobson et al., 2014). However, sometimes the state of giving up and a feeling of helplessness caused by the unavoidable problems in wakefulness are both so strong, so that it spreads on the virtual reality of dreams (Hobson et al., 2014). Painful failures in dream stories can in such conditions cause the incorporation of renunciation of search into these stories. It is common in patients with mental and psychosomatic disorders, but it can appear also in dreams of normal subjects that for occasion, sometimes include in the process of chaotic search some virtual conditions that subject is unable to overcome just now. In this condition, dream is not only accompanied by negative emotions like fear, anger and hate that are often presented in normal dreams as parts of dream stories and stimulate active virtual search, but became occupied by the feeling of inability to cope with these problems that are for dreamer in the non-lucid dream not virtual but real (Rotenberg, 1988, 2009; Goldstein and Walker, 2014). In such a situation, the dreamer is sometimes unable to jump over the traumatic dream images that cause a feeling of being a victim, and to turn to another images, and this feeling suppresses the SA in the dream. The ability to create new imaginative stories in dreams that can restore SA may be restricted also due to the low right hemisphere functional activity (Rotenberg, 1995). The behavior in dream in such cases becomes by itself frustrating and increases feeling of helplessness instead of overcoming it. Dreams turn into nightmares that are leading to awakenings, dreamer awoke with a strong feeling of helplessness and instead of being compensated this state becomes elevated in dream (Goldstein and Walker, 2014). Thus, it may be a vicious circle between helplessness in wakefulness and in dream.

In some cases, dreams are losing their vividness, their content became poor and restricted, and game with images disappeared. It represents the functional inefficiency of dreams, and is leading to a further degradation of dreams and to a progressive disappearance of dream content. It is exactly what we have found in patients with different mental disorders (depression, neurotic anxiety, etc.) and with psychosomatic disorders, and we come to the conclusion that it is a sign of the REM sleep functional insufficiency, exhaustion of dreams that plays an important role in the pathogenesis of these diseases (see Rotenberg, 2009). Like in wakefulness, renunciation of search in dreams is working with a positive feedback and negative outcome, meaning that it progressively increases itself.

The Essence of Lucid Dreams and Their Disadvantage

After this large introduction let us turn to the main topic of the presentation, to the advantage and disadvantage of the so-called "lucid dreams." These are dreams, in which dreamer, in opposite to the more common and typical non-lucid dreams realizes on the conscious level that he/she is dreaming and participating in the own virtual reality, as if looking on him-/herself as a dreamer from outside. This phenomenon has a neurophysiological basis. In opposite to the non-lucid dreams, that are characterized by a decreased activity of the dorsolateral prefrontal cortex (Maquet et al., 2005) responsible for the self-control and for the formation of the Self-Concept, lucid dreams are characterized by the relative increase of the functional and physiological activity of this brain structure, and are according to this activity similar to wakefulness (Kahn and Hobson, 2005; Hobson, 2009; Voss et al., 2009).

However, it does not mean that consciousness is totally absent during non-lucid dreams. In non-lucid dreams, subject is aware while dreaming about all events in dream and about his/her own participation in these events, but accepts them as real events, and it helps him/her to be totally involved in dream story, to participate in it with all vivid emotional feelings. For the dreamer it is not a mental game, it is a real life.

According to some authors (see Noreika et al., 2010) both lucid and non-lucid dreams are using a wide range of cognitive and meta-cognitive activities, and in non-lucid dreams speech and thought play an especially prominent role. From my point of view, they are used for the flexible SA without any rational control.

In wakefulness, even being totally involved in activity, subject is able to ask him-/herself: "What happens with me?" and to look on him-/herself and on his/her behavior as if it were from outside. However, it is necessary to emphasize that such estimation of the own behavior does not totally separate wakefulness from the non-lucid dreams. Even in dream, a feeling that something in subject's behavior is wrong and inappropriate may appear if it does not correspond to the feeling of "Self," to the Self-Image (see Rotenberg, 2012) that is not lost in dream. But in contrast to the normal wakefulness, in dream it is only a general feeling, it is not a result of the analysis of the own behavior and of its possible outcomes that can change the direction of behavior. The Self-Concept, the ability to look at "Self" from outside is absent in non-lucid dreams and is present in lucid dreams, if a lucid dreamer understands what he/she is watching to is a virtual dream story. The peculiarity of the dream experiences in non-lucid dreams in comparison to the lucid dreams is related only to the absence of the self-reflection and of the estimation of him-/herself as a dreamer, of the self-person perspective that is present in wakefulness and in the lucid dreams (Kahn, 2007; Voss et al., 2009; Mota-Rolim et al., 2013).

Of course, the absence of self-person perspective and reflection in the typical non-lucid dreams has a great advantage for the main dream function which I have mentioned above. If such function is the restoration of SA as a process, it does not matter in what domain and in what direction it is oriented, subject's imaginations during dreams have to be very flexible and vivid, the content of dream can be immediately changed and subject has to be totally involved in this process with a doubtless feeling that it is his/her own real life. If a person has some doubts toward the reality of these experiences and is looking at them as if from outside, on what is going in dream, like in a cinema picture, he/she is losing a feeling of being inside in this story, and is no more excited by the events in the own dream and consequently, less active in his/her attempts. As a result, SA grew weak, because it is no more the subject's own life. It means that dream lucidity decreases the restorative potential of dreams and it is their disadvantage.

The Main Task of Lucid Dreams: Their Advantage for Search Activity

So, does it mean that lucid dreaming is a failure of the dream functions? I suppose not. I think that lucid dreams have their own special function protecting subject from the cutting short the dream story when this story became traumatic for the subject. Lucid dreams allow dreamer to pass distressing and disturbing dreams that are functionally insufficient while being still sleeping, and may increase the renunciation of search instead of compensating it, thus to prevent terrible nightmares and to turn without awakenings step by step to the new dream stories that can perform their main function.

My explanation is very close to what La Berge has mentioned. According to La Berge, the insight that appears in lucid dreams and informs dreamer about what he/she is watching is nothing more than dream after some period passes, and lucid dream became displaced by the non-lucid dream. It is like a balance between the readiness to awake and to turn back to the normal sleep with the non-lucid dream (La Berge, 1985).

I believe that this supposition is confirmed by the nightmares treatment with lucid dreaming (Spooremaker and van den Bout, 2006). These authors have shown that in the process of such treatment, the number of nightmares' reports decreased. At the same time, there were no significant changes in subject's sleep quality and PTSD (post-traumatic stress disorder) symptom severity. Moreover, this treatment does not cause a stable reduction of nightmare frequency in general. It means that lucid dreams do not treat subjects from PTSD but can protect subject from the traumatic feelings of some concrete dream nightmares and allow subject to pass through it without awakenings. Thus, it is not a treatment of PTSD, it is a protection of sleep in the concrete dream. It is the reason of the reduction in dream recall (nightmare) frequency in subjects who succeeded in learning lucid dreaming (Holzinger et al., 2015)—they do not awake with a feeling of helplessness and it presents an opportunity to achieve the adaptive function of dreaming in the further dreams.

At this point, it is necessary to turn back to the essence of the functionally insufficient dreams that are not only common in patients with mental and psychosomatic disorders and are related to their pathogenesis, but may also episodically appear in healthy subjects. If the main function of dreams is the restoration of SA that was lost or decreased in different conditions during wakefulness, then the process of searching in dreams must be especially prominent after the renunciation of search in the stressful previous wakefulness.

Lucid dreams help to break the vicious circle between renunciation of search in wakefulness and sleep, because as soon as the dreamer realizes that he/she participates not in a real story but only in a dream, he/she became protected from the negative influence of this story on his/her own affect. Actually, it was shown that the so-called pre-lucid dreams that appear just before lucid dreams are often accompanied by strong negative emotions and feelings that subject who participates in the dream story is not protected from dangerous events. Such dreams may include, for instance, feeling of flying and fall (Hunt, 1989). In these conditions, to get an insight that it is only a dream is very supportive. It was also shown (Stumbrys et al., 2012, 2014) that in lucid dreams the dreamer is often able to influence the ongoing dream content. Lucid dreamers actively plan to accomplish different actions in their dreams like "talking" with dream characters, having sex and even flying (like it happens in non-lucid dreams), but sometimes, they are not able to successfully execute their intentions (like it happens in wakefulness) (Mota-Rolim et al., 2013).

Being in the lucid dream and looking on the dream story as if from outside, subject can continue to stay in REM sleep without awakenings. Because dream stories are in general very flexible, subject can after some period pass this trouble-making dream and turn to another dream that creates an opportunity for the SA. Lucid dream became displaced by the non-lucid dream and subject continues to sleep. Thus, the main advantage of lucid dreams is that these dreams protect the sleep process and help to pass the dreams that may cause nightmares and awakenings and to turn to the normal dreams that are restoring SA.

However, there may be also some other advantages. Bourke and Hannah (2014) have shown that subjects who have frequent lucid dreams are able to solve more insight problems in wakefulness in comparison to non-lucid dreamers. It corresponds to data (see Holzinger, 2009) that lucid dreams are reported by people with strong imagination, as well as to the investigation of Piller (2009) who showed the right hemisphere dominance during lucid dreams, because the right hemisphere plays an important role in creativity and insight (Rotenberg, 1993).

There are different views on the essence of lucid dreams in literature. According to above mentioned point of view, the lucidity is only the realization by the dreamer that the present experience is a dream, and all other features of the experience are similar in both types of dreams. Voss et al. (2009) explain lucid dreaming as a dissociative state combining cognitive elements of waking consciousness with the hallucinatory quality of dreaming. According to another point of view, lucidity may be sometimes accompanied by a full intellectual clarity, availability of the autobiographical memory sources and ability to control the dream content by the increase in the intensity of multimodal hallucinatory imagery (Metzinger, 2009). From my point of view, all these features of dream content are related to the main psychological characteristics of the lucidity—the ability to look on the dream from outside, as on the artificial imagined story created by the dreamer. As a story produced by the dreamer's mentality, it can be analyzed intellectually in details and it may be possible to find relationships between this story and the content of autobiographical memory. Of course, it is a difference between the pure lucid dreaming insight "it is only a dream!" that allows continue to sleep, and the intellectual dream control that makes the search in REM sleep dreams similar to the SA in wakefulness. In any case, whether dreams are lucid or not, they are separated from the information that is coming from the external environment that surrounds the dreamer.

If during wakefulness subject realizes his/her feelings and experiences as an own production, it can save subject from the uncontrollable outcome of these feelings. This represents conceptualization as a defense mechanism. Similar defense appears in lucid dreams—"it is my own dream, something not real." It is a meta-cognition—the mental consideration of the own mental state and own virtual behavior, the realization of him-/herself as a cognitive subject. Meta-cognition is not totally absent also in non-lucid dreams, where what only is absent is a special form of meta-cognition that allows subject to recognize him-/herself being in a dream state, not in wakefulness. In non-lucid dream, subject can accept him-/herself as a person who is really doing something or perceiving something. It is the absence of the Self-Concept but self-feeling is not lost—a feeling that it is "I" who is doing it in these particular real conditions - and it determines the full involvement in the dream story—what is very important for the SA.

Non-lucid dreams represent primary consciousness similar to the consciousness before the development of Self-Concept as an outcome of reflection. The first-person perspective is less prominent in non-lucid dreams in comparison to wakefulness and often is absent, and the non-lucid dreamer is unable to form a conscious conceptual model of his/her current relations with the subjectively experienced dream world. Without the stable first-person perspective, dreamer not only is unable to realize that he/she is dreaming, but is also unable to direct voluntary attention and cognition at his/her own thoughts, emotions and behavior (see Noreika et al., 2010). From my point of view, the absence of the first person perspective and Self-Concept, the inability to feel him-/herself as an agent of the own behavior and the absence of the volitional and definitely directed self-control in dreams is a sign that the process of SA in dream is more important for the dream function than the conscious realization of him-/herself as a searching subject. For the same reason, subject often does not remember the content of dream soon after awakenings: this content has no sense by itself.

In lucid dreams, subject is separated from the virtual reality. It helps him/her to build a model of the own relationships with the dream world and to decrease emotional experiences caused by dreams, to became free from them at least for some period, but at the same time prevents the real awakenings. The realization that it is only a dream presumably does not block the chaotic jumps from one dream content to another, and finally, the dreamer can create a story that is less threatening and does not cause helplessness and turns to the non-lucid dream. It is the important advantage of lucid dreams.

Conclusion

The task of this article was to elucidate the role of dream lucidity in the REM sleep dreams functions. According to the Search Activity Concept, this function is to restore the active behavior (search activity, SA) that dropped during the previous (pre-sleep) wakefulness, to increase it for the adaptation to the environmental demands in the post-sleep wakefulness. To achieve this goal, the content of dreams has to be vivid and challengeable and the subject's virtual behavior in dream must be active and flexible. The dream stories that were leading to failures have to be displaced by dream stories that stimulate search for problem solution.

If the renunciation of search (giving up and feeling helpless) dominates in dreams, like it happens in nightmares or in dreams of depressed patients, dreams are losing their adaptive function and frustrate the dreamer. Exactly in this condition, may help the dream lucidity. It is not the improvement of dream content, but it is an insight that what the subject is looking on is only a dream. A dreamer is looking in the lucid dream on him-/herself and on the dream story as if from outside. For this reason, he/she is not totally immersed by the traumatic dream content, as he/she is usually immersed in non-lucid dream. It is the disadvantage of lucid dream that does not allow lucid dream to perform the adaptive dream function. However, lucid dreams usually start when this adaptive function was already totally or partly lost, and in this condition, dream lucidity allows dreamer not to awoke in a state of frustration, but to pass the disturbing dream content, to continue to sleep and finally to turn to another dream that can be adaptive. It is the main advantage of lucid dreaming.

This hypothesis can be checked by the comparison of the number of lucid dreams (estimated by using volitional non-verbal signals presented by the dreamer during lucid dreams, see La Berge, 2000) with the reports presented after awakenings in non-lucid dreams, as well as with the number of spontaneous awakenings from REM sleep after strong emotional experiences.

References

Bourke, P., and Hannah, S. H. (2014). Spontaneous lucid dreaming. Frequency and waking insight. *Dreaming* 24, 152–159. doi: 10.1037/a0036908

Goldstein, A. N., and Walker, M. P. (2014). The role of sleep in emotional brain function. *Annu. Rev. Clin. Psychol.* 10, 679–708. doi: 10.1146/annurev-clinpsy-032813-153716

Grieser, C., Greenberg, R., and Harrison, R. (1972). The adaptive function of sleep: differential effects of sleep on dreaming and recall. *J. Abnorm. Psychol.* 80, 280–286. doi: 10.1037/h0033641

Hobson, J. A. (2009). The neurobiology of consciousness: lucid dreaming wakes up. *IJoDR* 2, 41–44. doi: 10.11588/ijodr.2009.2.403

Hobson, J. A., Hong, C. C., and Friston, K. J. (2014). Virtual reality and consciousness inference in dreaming. *Front. Psychol.* 5:1133. doi: 10.3389/fpsyg.2014.01133

Holzinger, B. (2009). Lucid dreaming-dreams of clarity. *Contemp. Hypnosis* 26, 216–224. doi: 10.1002/ch.390

Holzinger, B., Klösch, G., and Satetu, B. (2015). Studies with lucid dreaming as add-on therapy to gestalt therapy. *Acta Neurol. Scand.* 131, 355–363. doi: 10.1111/ane.12362

Hunt, H. T. (1989). *The Multiplicity of Dreams: Memory, Imagination and Consciousness*. New Haven, CT: Yale University Press.

Kahn, D. (2007). "Metacognition, recognition and reflection while dreaming," in *The New Science of Dreaming*, Vol. 1, eds D. Barrett, and P. McNamara (Westport, CT: Praeger). 245–268.

Kahn, D., and Hobson, J. A. (2005). State-dependent thinking: a comparison of waking and dreaming thought. *Conscious. Cogn.* 14, 429–438. doi: 10.1016/j.concog.2004.10.005

La Berge, S. (1985). *Lucid Dreaming*. New York, NY: Ballantine Books.

La Berge, S. (2000). Lucid dreaming: evidence and methodology. *Behav. Brain Sci.* 23, 962–963. doi: 10.1017/S0140525X00574020

Maquet, P., Ruby, P., Maudoux, A., Albouy, G., Sterpenich, V., Dang-Vu, T., et al. (2005). Human cognition during REM sleep and the activity profile within frontal and parietal cortices: a reappraisal of functional neuroimaging data. *Prog. Brain Res.* 150, 219–227. doi: 10.1016/S0079-6123(05)50016-5

Metzinger, T. (2009). *The Ego Tunnel*. The Science of the Mind and the Myth of the Self. New York, NY: Basic Books.

Mota-Rolim, S. A., Targino, L. H., Souza, B. C., Blanco, W., Araujo, J. F., and Ribeiro, S. (2013). Dream characteristics in a Brazilian sample: an online survey focusing on lucid dreaming. *Front. Hum. Neurosci.* 7:836. doi: 10.3389/fnhum.2013.00836

Noreika, V., Windt, J. M., Lenggenhager, B., and Karim, A. A. (2010). New perspectives for the study of lucid dreaming: from brain stimulation to philosophical theories of Self-consciousness. Commentary on "The neurobiology of consciousness: lucid dreaming wakes up" by J. A. Hobson." *IJoDR* 3, 36–46. doi: 10.11588/ijodr.2010.1.586

Piller, R. (2009). Cerebral specialization during lucid dreaming: a right hemisphere hypothesis. *Dreaming* 19, 273–286. doi: 10.1037/a0017994

Rotenberg, V. S. (1988). Functional deficiency of REM sleep and its role in the pathogenesis of neurotic and psychosomatic disturbances. *Pavlov. J. Biol. Sci.* 23, 1–3. doi: 10.1007/BF02910537

Rotenberg, V. S. (1993). Richness against freedom: two hemisphere functions and the problem of creativity. *Eur. J. High Ability* 4, 11–19. doi: 10.1080/0937445930040102

Rotenberg, V. S. (1995). Right hemisphere insufficiency and illness in the context of search activity concept. *Dynam. Psychiatry* 150/151, 54–60.

Rotenberg, V. S. (2009). Search activity concept: relationship between behavior, health and brain functions. *Act. Nerv. Super.* 51, 12–44.

Rotenberg, V. S. (2012). Two high levels of Self-identification in relationships to consciousness, social motives and brain laterality. *Act. Nerv. Super.* 54, 77–83.

Rotenberg, V. S. (2013). *Self-Image and Behavior*. Amazon.

Rotenberg, V. S., and Arshavsky, V. V. (1979). Search activity and its impact on experimental and clinical pathology. *Act. Nerv. Super.* 21, 105–115.

Rotenberg, V. S., and Cholostoy, A. (2004). Behavioral attitudes in major depression: a pilot investigation. *Homeost. Health. Dis.* 43, 16–18.

Rotenberg, V. S., Cholostoy, A., Gurwitz, P., and Shamir, E. (2008). The role of behavioral attitudes in sleep estimation in healthy subjects and depressed patients. *Dynam. Psychiatry* 11, 297–307.

Rotenberg, V. S., Cholostoy, A., Gurwitz, P., Shamir, E., and Baruch, Y. (2007). Behavioral attitudes and depression: cause and effect relationships. *Act. Nerv. Super.* 49, 87–92.

Spooremaker, V. I., and van den Bout, J. (2006). Lucid dreaming treatment for nightmares: a pilot study. *Psychother. Psychosom.* 75, 389–394. doi: 10.1159/000095446

Stumbrys, T., Erlacher, D., Johnson, M., and Schredil, M. (2014). The phenomenology of lucid dreaming: an online survey. *Am. J. Psychol.* 127, 191–204. doi: 10.5406/amerjpsyc.127.2.0191

Stumbrys, T., Erlacher, D., Schädlich, M., and Schredil, M. (2012). Induction of lucid dreams: a systematic review of evidence. *Conscious. Cogn.* 21, 1456–1475. doi: 10.1016/j.concog.2012.07.003

Voss, U., Holzman, R., Tuin, I., and Hobson, J. A. (2009). Lucid dreaming: a state of consciousness with features of both waking and non-lucid dreaming. *Sleep* 32, 1191–1200.

Conflict of Interest Statement: The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

OPINION
published: 28 October 2015
doi: 10.3389/fpsyg.2015.01655

Predictive coding in visual search as revealed by cross-frequency EEG phase synchronization

*Paul Sauseng *, Markus Conci, Benedict Wild and Thomas Geyer*

Department of Psychology, Ludwig-Maximilian-University Munich, Germany

Keywords: gamma oscillations, memory matching, phase coupling, theta oscillations, visual attention, visual short-term memory

OPEN ACCESS

Edited by:
Roumen Kirov,
Bulgarian Academy of Sciences,
Bulgaria

Reviewed by:
Viktor Müller,
Max Planck Institute for Human
Development, Germany

Correspondence:
Paul Sauseng
paul.sauseng@lmu.de

Specialty section:
This article was submitted to
Cognitive Science,
a section of the journal
Frontiers in Psychology

Received: *31 August 2015*
Accepted: *13 October 2015*
Published: *28 October 2015*

Citation:
Sauseng P, Conci M, Wild B and Geyer T (2015) Predictive coding in visual search as revealed by cross-frequency EEG phase synchronization.
Front. Psychol. 6:1655.
doi: 10.3389/fpsyg.2015.01655

INTRODUCTION

Our experience, memories, and knowledge have modulatory influence on how we perceive the world. Top-down expectancies are supposed to be implemented as templates in our minds. Mental templates are compared against the current sensory input, which can match or mismatch with the aim of minimizing prediction error (Friston, 2005).

But what are the underlying neuronal mechanisms leading to the activation of mental templates and their comparison with sensory input, i.e., predictive coding? Biasing sensory processing by expectancies has been strongly associated with prefrontal brain activity influencing responses in visual cortex (e.g., Summerfield et al., 2006; Olivers et al., 2011; Spaak et al., 2015). Moreover, electrophysiological evidence gathered in patients with prefrontal cortex lesions (Yago et al., 2004) suggests that the prefrontal cortex acts with excitatory drive on extrastriate cortex within three time windows during template matching in visual attention tasks: as early as 100 ms after target onset through selection of spatial locations; during the analysis of non-spatial features of attended objects around 250 ms after target onset; and in a later phase around 300 ms during which discrimination and template matching occur. This recurrent prefrontal drive on higher visual areas can be interpreted as top-down reactivation of target memory traces, thus, the activation of a mental template that needs to be compared to visual input (Desimone and Duncan, 1995).

A common way of analysing interregional transfer of neural signals in the human brain is by means of coherent oscillatory brain activity. Rhythmical brain activity as recorded with the electroencephalogram (EEG) is an indicator for locally highly synchronized neuronal activity. If two distant brain areas are functionally coupled, it is assumed that a higher level of coherent, synchronous neuronal activity can be found between these distant areas than one would expect from chance. Comprehensive work by von Stein and co-workers suggests that long-range interaction between prefrontal and posterior cortices necessary in top-down control of cognitive processes is reflected by neural activity resonating in large-scale networks and therefore oscillating at rather slow frequencies: so called theta and alpha oscillations (von Stein et al., 1999, 2000; von Stein and Sarnthein, 2000). In humans, coherent, synchronous prefrontal to parietal brain oscillatory activity particularly in slower frequency bands (around 5 and 10 Hz) has been observed when a high level of top-down activity is necessary in a range of different visual tasks (see Sauseng and Klimesch, 2008; Sauseng et al., 2010 for reviews). Long-range communication in the monkey brain has also been attributed to rather slow oscillatory activity (in the theta and delta frequency range) whereas it has been suggested that local, fast rhythmical cortical activity (in the gamma frequency band) is associated more strongly with bottom-up visual processing (Bruns and Eckhorn, 2004; Eckhorn et al., 2004; Bastos et al., 2015; Zheng and Colgin, 2015).

WHAT IS THE BRAIN OSCILLATORY SIGNATURE OF PREDICTIVE CODING?

There is a large body of evidence that coherent gamma activity in the visual system is associated with binding of visual features in perception (Singer and Gray, 1995; von der Malsburg, 1999; Fries et al., 2007; Singer, 2009 see also Conci et al., 2004), and gamma band activity might be relevant for bottom-up as well as for top-down visual processes (Engel et al., 2001). This idea has been applied to template matching in a theoretical model (memory match and utilization model; MUM) put forward by Herrmann et al. (2004). The MUM suggests two distinct, sequential oscillatory patterns in the brain's response to visual stimuli: The first evoked gamma band response (phase-locked to stimulus onset) at around 100 to 150 ms after stimulus presentation reflects the matching of mental templates to visual input. Next, an induced gamma band response (with jittered phase in relation to stimulus onset) in a time window around 300 ms post-stimulus is related to the usage of this matched information for later, higher cognitive processes. However, the evidence for MUM with regard to memory matching mostly pertains to how semantic knowledge represented in long-term memory affects visual feature binding. An open question is whether there would be a comparable matching process reflected by evoked, phase-locked gamma activity in a visual attention or search task, where a mental template has to be held in *short-term memory*. To our knowledge, so far there is no evidence supporting MUM when information held in short-term or working memory rather than in semantic long-term memory needs to be matched with sensory input.

Sauseng et al. (2008, 2010) put forward a conceptual model which integrates top-down working memory processes as associated by means of fronto-parietal theta activity with bottom-up visual processing manifested by gamma activity in visual areas. They suggested that holding a mental template in mind would increase fronto-parietal phase synchronization (coupling) at theta frequency in time intervals during which a certain visual input is expected (Sarnthein et al., 1998; Sauseng and Klimesch, 2008; Griesmayr et al., 2014). This could reflect the reactivation of a memory trace in working memory, monitored by prefrontal cortex and replayed into higher visual areas. Around 100 ms after onset of visual input (target presentation), posterior theta oscillations would reset their phase. This local resetting of theta phase enables a transient synchronization with high frequency activity in the gamma band range in a time window between 100 and 200 ms post-stimulus. Transient synchronization between theta and gamma phase in posterior parietal cortex has been found to be significantly stronger in trials where expectancies (mental templates) and visual input were matched, i.e., in valid or congruent trials compared to when the template did not match the presented visual target (invalid or incongruent trials; Sauseng et al., 2008; Holz et al., 2010). This suggests that transient parietal phase synchronization between theta and gamma oscillations reflects the integration of top-down controlled mental templates with bottom-up visual processing. The time window around 150 ms post-stimulus for this process to take place is in good agreement with MUM. The major difference, however, is that matching between basic semantic memory and visual input does not require activation of a long-range fronto-parietal theta network. Therefore, there is no necessity for matching incoming visual information with a working memory trace, as reflected by theta activity. Instead, evoked gamma band response as suggested in the MUM would be sufficient for matching semantic knowledge with visual input. However, as soon as a mental template needs to be actively held in working memory, in the alternative model this is achieved via activity of a fronto-parietal theta network; and only the synchronization of theta and gamma at the brain sites where it comes to a spatial overlap between these two oscillations will allow the matching of top-down and bottom-up information.

THETA:GAMMA PHASE COUPLING—THE NEURAL MARKER OF PREDICTIVE CODING?

Recently it has been shown that retention of multiple items in short-term memory and control of working memory functions are also associated with synchronization between theta and gamma oscillations (Canolty et al., 2006; Sauseng et al., 2009; Axmacher et al., 2010; Griesmayr et al., 2010; Kamiñski et al., 2011), and so are processes of context binding in episodic long-term memory (Friese et al., 2013; Staudigl and Hanslmayr, 2013; Köster et al., 2014). This clearly shows that theta:gamma phase coupling is not an exclusive neural marker for predictive coding alone. Cross-frequency coupling plays an important role in a variety of cognitive processes (Jensen and Colgin, 2007; Jirsa and Müller, 2013); and predictive coding can also be reflected by coupling (phase as well as amplitude) of frequencies other than theta and gamma oscillations, or can be associated with a range of other neural processes (Huang and Rao, 2011; Seth et al., 2012; Spaak et al., 2015). Thus, the underlying neural dynamics might strongly depend on the particular cognitive task in question. It seems that for visual search, where a template needs to be held in working memory, theta:gamma coupling is a strong candidate for the neuronal signature of predictive coding, though.

HOW TO INVESTIGATE WHETHER EVOKED GAMMA ACTIVITY OR THETA:GAMMA PHASE COUPLING REFLECTS PREDICTIVE CODING?

Ways of investigating predictive coding are using a visuospatial attentional cueing task or by comparing match and non-match trials in a delayed match-to-sample task. With these paradigms the above described effects of transient theta:gamma phase coupling have been obtained (Sauseng et al., 2008; Holz et al., 2010).

However, predictive coding may derive from both short- and long-term learning in visual search (e.g., Conci et al., 2012 for an overview). One elegant way of how predictive coding can be investigated is the repeated presentation of target-distractor configurations in a visual search task in the so-called *contextual cueing* paradigm (Chun and Jiang, 1998; Geyer et al., 2010a,b; Zellin et al., 2014). The typical finding in contextual cueing is that visual search performance is facilitated in repeated configurations, compared to random target-distractor configurations due to implicit perceptual memory of previously presented search arrays. Geyer et al. (2012) were able to show that memory processes leading to contextual cueing rely on medial temporal lobe (MTL) functions.

Of relevance here is that this form of predictive coding is not so much relying on the matching of semantic long-term information with sensory input as suggested in the MUM. Neither does it require maintenance of an explicit mental template in working memory as suggested in the theoretical framework put forward by Sauseng et al. (2010). Nevertheless, a mental template of target-distractor configurations will be stored in memory, however, without explicit access [and in contrast to paradigms used in (Sauseng et al., 2008) and (Holz et al., 2010) the template will be stored in long-term rather than working memory]. Therefore, what would one expect to be the brain oscillatory correlate of matching such a mental template with visual information in a visual search task? Evoked early gamma activity or rather cross-frequency phase synchronization between theta and gamma activity? To answer this question we first need to discuss brain oscillatory signatures of MTL mnemonic processes.

Theta and gamma activity have both been reported major oscillatory phenomena in the MTL (see Buzsaki, 2006; Lisman and Jensen, 2013; Draguhn et al., 2014). Coherent gamma oscillations have mainly been reported within the MTL (i.e., Fell et al., 2001, 2002). And although there is good evidence of coherent theta activity within the hippocampal formation (see Fell et al., 2003), synchronous theta oscillations between the MTL and the neocortex (particularly prefrontal cortex; Klimesch, 1996; Siapas et al., 2005; Mitchell et al., 2008; Young and McNaughton, 2009) can be found. Consequently, if contextual information stored in the MTL is used in visual search, this information is more likely propagated into the prefrontal cortex via MTL-neocortical theta than gamma networks. Already paced at theta frequency such top-down information could then, as suggested by Sauseng et al. (2010), be transferred to visual areas via fronto-parietal theta networks. Note that context information may be replayed into prefrontal structures because these areas are involved in maintenance of implicit information from MTL memory (e.g., Annac et al., 2013). The main finding of Annac et al. was that implicit contextual cueing vanished when the visual search task was performed concurrently with a secondary spatial working memory task, suggesting that contextual cueing requires working memory resources. In higher visual cortex, top-down predictions would then be matched with bottom-up information by theta:gamma phase synchronization. Following the MUM one might rather expect that bottom-up information is matched with gamma activity already at the level of the MTL. This would make it difficult to impact back on visual cortex in a visual search task, however.

CONCLUSION

We conclude that in visual search, predictive coding seems to be reflected by transient coupling of slow oscillations (at theta frequency), alongside more distributed cortical activity, and high frequency oscillatory brain activity occurring particularly in visual areas. Evoked gamma activity as a signature of predictive coding is very compelling in visual perception of semantically congruent information (Herrmann et al., 2004). However, it might not be the most plausible neural correlate of predictive coding in a selective attention task, i.e., in spatial cueing and visual search.

AUTHOR CONTRIBUTIONS

All four authors were involved in the conceptualization of the topic, the preparation and writing of the manuscript. And all four authors have approved submission of the paper.

FUNDING

This research has been supported by the Deutsche Forschungsgemeinschaft DFG (SA 1872/2-1).

REFERENCES

Annac, E., Manginelli, A. A., Pollmann, S., Shi, Z., Müller, H. J., and Geyer, T. (2013). Memory under pressure: secondary-task effects on contextual cueing of visual search. *J. Vis.* 13, 6–15. doi: 10.1167/13.13.6

Axmacher, N., Henseler, M. M., Jensen, O., Weinreich, I., Elger, C. E., and Fell, J. (2010). Cross-frequency coupling supports multi-item working memory in the human hippocampus. *Proc. Natl. Acad. Sci. U.S.A.* 107, 3228–3233. doi: 10.1073/pnas.0911531107

Bastos, A. M., Vezoli, J., Bosman, C. A., Schoffelen, J.-M., Oostenveld, R., Dowdall, J. R., et al. (2015). Visual areas exert feedforward and feedback influences through distinct frequency channels. *Neuron* 85, 390–401. doi: 10.1016/j.neuron.2014.12.018

Bruns, A., and Eckhorn, R. (2004). Task-related coupling from high to low frequencz signals among visual cortical areas in human subdural recordings. *Int. J. Psychophysiol.* 51, 97–116. doi: 10.1016/j.ijpsycho.2003.07.001

Buzsaki, G. (2006). *Rhythms of the Brain*. Oxford: Oxford University Press.

Canolty, R. T., Edwards, E., Dalal, S. S., Soltani, M., Nagaraian, S. S., Kirsch, H. E., et al. (2006). High gamma power is phase-locked to theta oscillations in human neocortex. *Science* 313, 1626–1628. doi: 10.1126/science.1128115

Chun, M. M., and Jiang, Y. (1998). Contextual cueing: implicit learning and memory of visual context guides spatial attention. *Cogn. Psychol.* 36, 28–71. doi: 10.1006/cogp.1998.0681

Conci, M., Elliott, M. A., Müller, H. J., Wendt, J., and Becker, C. (2004). The dynamics of operations in visual memory: a review and new evidence for oscillatory priming. *Exp. Psychol.* 51, 300–310. doi: 10.1027/1618-3169.51.4.300

Conci, M., Zellin, M., and Müller, H. J. (2012). Whatever after next? Adaptive predictions based on short- and long-term memory in visual search. *Front. Psychol.* 3:409. doi: 10.3389/fpsyg.2012.00409

Desimone, R., and Duncan, J. (1995). Neural mechanisms of selective visual attention. *Ann. Rev. Neurosci.* 18, 193–222. doi: 10.1146/annurev.ne.18.030195.001205

Draguhn, A., Keller, M., and Reichinnek, S. (2014). Coordinated network activity in the hippocampus. *Front. Neurol. Neurosci.* 34, 26–35. doi: 10.1159/000357026

Eckhorn, R., Gail, A., Bruns, A., Gabriel, A., Al-Shaikhli, B., and Saam, M. (2004). Neural mechanisms of visual associative processing. *Acta Neurobiol. Exp.* 64, 239–252.

Engel, A. K., Fries, P., and Singer, W. (2001). Dynamic predictions: oscillations and synchrony in top-down processing. *Nat. Rev. Neurosci.* 2, 704–716. doi: 10.1038/35094565

Fell, J., Klaver, P., Elfadil, H., Schaller, C., Elger, C. E., and Fernández, G. (2003). Rhinal-hippocampal theta coherence during declarative memory formation: interaction with gamma synchronization? *Eur. J. Neurosci.* 17, 1082–1088. doi: 10.1046/j.1460-9568.2003.02522.x

Fell, J., Klaver, P., Elger, C. E., and Fernández, G. (2002). The interaction of rhinal cortex and hippocampus in human declarative memory formation. *Rev. Neurosci.* 13, 299–312. doi: 10.1515/REVNEURO.2002.13.4.299

Fell, J., Klaver, P., Lehnertz, K., Grunwald, T., Schaller, C., Elger, C. E., et al. (2001). Human memory formation is accompanied by rhinal–hippocampal coupling and decoupling. *Nat. Neurosci.* 4, 1259–1264. doi: 10.1038/nn759

Fries, P., Nikoliæ, D., and Singer, W. (2007). The Gamma cycle. *Trends Neurosci.* 30, 309–316. doi: 10.1016/j.tins.2007.05.005

Friese, U., Köster, M., Hassler, U., Martens, U., Trujillo-Barreto, N., and Gruber, T. (2013). Successful memory encoding is associated with increased cross-frequency coupling between frontal theta and posterior gamma oscillations in human scalp-recorded EEG. *Neuroimage* 66, 642–647. doi: 10.1016/j.neuroimage.2012.11.002

Friston, K. (2005). A theory of cortical responses. *Philos. Trans. R. Soc. B* 360, 815–836. doi: 10.1098/rstb.2005.1622

Geyer, T., Baumgartner, F., Müller, H. J., and Pollmann, S. (2012). Medial temporal lobe-dependent repetition suppression and enhancement due to implicit vs. explicit processing of individual repeated search displays. *Front. Hum. Neurosci.* 6:272. doi: 10.3389/fnhum.2012.00272

Geyer, T., Shi, Z., and Müller, H. J. (2010a). Contextual cueing in multiconjunction visual search is dependent on color- and configuration-based intertrial contingencies. *J. Exp. Psychol. Hum. Perc. Perf.* 36, 515–532. doi: 10.1037/a0017448

Geyer, T., Zehetleitner, M., and Müller, H. J. (2010b). Contextual cueing of pop-out visual search: when context guides the deployment of attention. *J. Vis.* 10, 1–11. doi: 10.1167/10.2.3

Griesmayr, B., Berger, B., Stelzig-Schoeler, R., Aichorn, W., Bergmann, J., and Sauseng, P. (2014). EEG theta phase coupling during executive control of visual working memory investigated in individuals with schizophrenia and in healthy controls. *Cogn. Affect. Behav. Neurosci.* 14, 1340–1355. doi: 10.3758/s13415-014-0272-0

Griesmayr, B., Gruber, W. R., Klimesch, W., and Sauseng, P. (2010). Human frontal midline theta and ist synchronization to gamma during a verbal delayed match to sample task. *Neurobiol. Learn. Mem.* 93, 208–215. doi: 10.1016/j.nlm.2009.09.013

Herrmann, C. S., Munk, M. H., and Engel, A. K. (2004). Cognitive functions of gamma band activity: memory match and utiliztion. *Trends Cogn. Sci.* 8, 347–355. doi: 10.1016/j.tics.2004.06.006

Holz, E. M., Glennon, M., Prendergast, K., and Sauseng, P. (2010). Theta-gamma phase synchronization during memory matching in visual working memory. *Neuroimage* 52, 326–335. doi: 10.1016/j.neuroimage.2010.04.003

Huang, Y., and Rao, R. P. N. (2011). Predictive coding. *WIREs Cogn. Sci.* 2, 580–593. doi: 10.1002/wcs.142

Jensen, O., and Colgin, L. L. (2007). Cross-frequency coupling between neuronal oscillations. *Trends Cogn. Sci.* 11, 267–269. doi: 10.1016/j.tics.2007.05.003

Jirsa, V., and Müller, V. (2013). Cross-frequency coupling in real and virtual brain networks. *Front. Comput. Neurosci.* 7:78. doi: 10.3389/fncom.2013.00078

Kamiñski, J., Brzezicka, A., and Wróbel, A. (2011). Short term memory capacity (7 ± 2) predicted by theta to gamma cycle length ratio. *Neurobiol. Learn. Mem.* 95, 19–23. doi: 10.1016/j.nlm.2010.10.001

Klimesch, W. (1996). Memory processes, brain oscillations and EEG synchronization. *Int. J. Psychophysiol.* 24, 61–100. doi: 10.1016/S0167-8760(96)00057-8

Köster, M., Friese, U., Schöne, B., Trujillo-Barreto, N., and Gruber, T. (2014). Theta-gamma coupling during episodic retrieval in the human EEG. *Brain Res.* 1577, 57–68. doi: 10.1016/j.brainres.2014.06.028

Lisman, J. E., and Jensen, O. (2013). The theta-gamma neural code. *Neuron* 77, 1002–1016. doi: 10.1016/j.neuron.2013.03.007

Mitchell, D. J., McNaughton, N., Flanagan, D., and Kirk, I. J. (2008). Frontal-midline theta from the perspective of hippocampal "theta". *Prog. Neurobiol.* 86, 156–185. doi: 10.1016/j.pneurobio.2008.09.005

Olivers, C. N., Peters, J., Houtkamp, R., and Roelfsema, P. R. (2011). Different states in visual working memory: when it guides attention and when it does not. *Trends Cogn. Sci.* 15, 327–334. doi: 10.1016/j.tics.2011.05.004

Sarnthein, J., Petsche, H., Rappelsberger, P., Shaw, G. L., and von Stein, A. (1998). Synchronisation between prefrontal and posterior association cortex during human working memory. *Proc. Natl. Acad. Sci. U.S.A.* 95, 7092–7096. doi: 10.1073/pnas.95.12.7092

Sauseng, P., Giesmayr, B., Freunberger, R., and Klimesch, W. (2010). Control mechanisms in working memory: a possible function of EEG theta oscillations. *Neurosci. Biobehav. Rev.* 34, 1015–1022. doi: 10.1016/j.neubiorev.2009.12.006

Sauseng, P., and Klimesch, W. (2008). What does phase oscillatory brain activity tell us about cognitive processes? *Neurosci. Biobehav. Rev*. 32, 1001–1013. doi: 10.1016/j.neubiorev.2008.03.014

Sauseng, P., Klimesch, W., Gruber, W. R., and Birbaumer, N. (2008). Cross-frequency phase synchronisation: a brain mechanism of memory matching and attention. *Neuroimage* 40, 308–318. doi: 10.1016/j.neuroimage.2007.11.032

Sauseng, P., Klimesch, W., Heise, K. F., Gruber, W. R., Holz, E., Karim, A. A., et al. (2009). Brain oscillatory substrates of visual short-term memory capacity. *Curr. Biol.* 19, 1846–1852. doi: 10.1016/j.cub.2009.08.062

Seth, A. K., Suzuki, K., and Critchley, H. D. (2012). An interoceptive predictive coding model of conscious presence. *Front. Psychol.* 2:395. doi: 10.3389/fpsyg.2011.00395

Siapas, A. G., Lubenov, E. V., and Wilson, M. A. (2005). Prefrontal phase locking to hippocampal theta oscillations. *Neuron* 46, 141–151. doi: 10.1016/j.neuron.2005.02.028

Singer, W., and Gray, C. M. (1995). Visual feature integration and the temporal correlation hypothesis. *Ann. Rev. Neurosci.* 18, 555–586. doi: 10.1146/annurev.ne.18.030195.003011

Singer, W. (2009). Distributed processing and temporal codes in neuronal networks. *Cogn. Neurodyn.* 3, 189–196. doi: 10.1007/s11571-009-9087-z

Spaak, E., Fonken, Y., Jensen, O., and de Lange, F. P. (2015). The neural mechanisms of prediction in visual search. *Cereb. Cortex.* doi: 10.1093/cercor/bhv210. [Epub ahead of print].

Staudigl, T., and Hanslmayr, S. (2013). Theta oscillations at encoding mediate the context-dependent nature of human episodic memory. *Curr. Biol.* 23, 1101–1106. doi: 10.1016/j.cub.2013.04.074

Summerfield, C., Egner, T., Greene, M., Koechlin, E., Mangels, J., and Hirsch, J. (2006). Predictive codes for forthcomng perception in the frontal cortex. *Science* 314, 1311–1314. doi: 10.1126/science.1132028

von der Malsburg, C. (1999). The what and why of binding: the modelers perspective. *Neuron* 24, 95-104, 111–125. doi: 10.1016/s0896-6273(00)80825-9

von Stein, A., Chiang, C., and König, P. (2000). Top down processing by interareal synchronisation. *Proc. Natl. Acad. Sci. U.S.A.* 97, 14748–14753. doi: 10.1073/pnas.97.26.14748

von Stein, A., Rappelsberger, P., Sarnthein, J., and Petsche, H. (1999). Synchronisation between temporal and parietal cortex during multimodal object processing in man. *Cereb. Cortex* 9, 137–150. doi: 10.1093/cercor/9.2.137

von Stein, A., and Sarnthein, J. (2000). Different frequencies for different scales of cortical integration: from local gamma to long range alpha/theta synchronization. *Int. J. Psychophysiol.* 38, 301–313. doi: 10.1016/S0167-8760(00)00172-0

Yago, E., Duarte, A., Wong, T., Barceló, F., and Knight, R. T. (2004). Temporal kinetics of prefrontal modulation of the extrastriate cortex during visual attention. *Cogn. Affect. Behav. Neurosci.* 4, 609–617. doi: 10.3758/CABN.4.4.609

Young, C. K., and McNaughton, N. (2009). Coupling of theta oscillations between anterior and posterior midline cortex and with the hippocampus in freely behaving rats. *Cereb. Cortex* 19, 24–40. doi: 10.1093/cercor/bhn055

Zellin, M., von Mühlenen, A., Müller, H. J., and Conci, M. (2014). Long-term adaptation to change in implicit contextual learning. *Psychon. Bull. Rev.* 21, 1073–1079. doi: 10.3758/s13423-013-0568-z

Zheng, C., and Colgin, L. L. (2015). Beta and gamma rhythms go with the flow. *Neuron* 85, 236–237. doi: 10.1016/j.neuron.2014.12.067

Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers
in Psychology

REVIEW
published: 10 March 2016
doi: 10.3389/fpsyg.2016.00275

Links of Consciousness, Perception, and Memory by Means of Delta Oscillations of Brain

Erol Başar and Aysel Düzgün*

Brain Dynamics, Cognition and Complex Systems Research Center, Istanbul Kültür University, Istanbul, Turkey

The aim of this report is threefold:

(1) First, we accomplish a survey integrating the description of consciousness, perception, and memory according to the views of descriptions of Hermann Helmholtz, Sigmund Freud, Henri Bergson, and Gustav Jung.

(2) In the second step, we present experimental results for defining the machineries of sensation and perception: (a) electrical responses of isolated ganglion of *Helix pomatia* were measured upon odor stimuli that elicited varied degrees of responses. Such a model may give an idea of the control of sensation in the preconscious state of a living tissue. (b) We also describe experiments at the human hearing threshold level. (c) Further, the omission of working memory will be shown with the attenuation of delta response in Alzheimer's subjects in P300 measurements. (d) Finally, the measurement of auditory evoked potentials during slow-wave sleep in the cat brain explains the auditory responses that are not heard at this level of consciousness.

(3) In the third step, we aim to provide a synopsis related to *integration of perception, memory, and consciousness.* By using concepts of important scientists as S. Freud on consciousness, we also tentatively discuss the boundaries of the transition of unconsciousness states to conscious states.

Keywords: top–down, P300, working memory, perception, consciousness, unconsciousness, brain oscillations

Edited by:
Roumen Kirov,
Bulgarian Academy of Sciences,
Bulgaria

Reviewed by:
Thorsten Fehr,
Universität Bremen, Germany
Sirel Karakaş,
Istanbul Şehir University, Turkey

****Correspondence:***
Erol Başar
e.basar@iku.edu.tr

Specialty section:
This article was submitted to
Cognitive Science,
a section of the journal
Frontiers in Psychology

Received: *20 November 2015*
Accepted: *12 February 2016*
Published: *10 March 2016*

Citation:
Başar E and Düzgün A (2016) Links of Consciousness, Perception, and Memory by Means of Delta Oscillations of Brain.
Front. Psychol. 7:275.
doi: 10.3389/fpsyg.2016.00275

INTRODUCTION

What Are the Main Principles of Perception, Memory, and Consciousness?

In the present paper, we aim to address an important chain of questions related to ground properties of the mindful brain. Several outstanding neuroscientists tried to describe machineries of cognitive processes and consciousness. However, the transition from unconscious to conscious states also merits special emphasis. Although most of the scientists realized the importance of the research accomplished by Sigmund Freud and Gustav Jung, none of the studies succeeded in exactly defining the boundaries of the conscious and unconscious states due to several reasons.

In the present paper, we aim to develop an essay including few steps analyzing the dynamic balance (equilibrium) between conscious and unconscious states. In order to approach this problem, we will use the rules of EEG-neurophysiology as well as the time frame needed during cognitive performances of the brain.

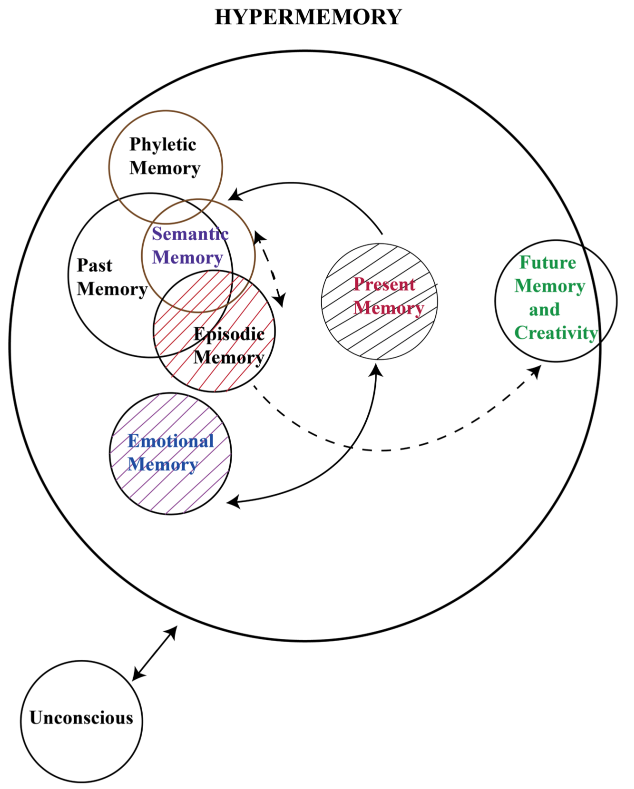


FIGURE 1 | In this illustration, past memory includes semantic memory and episodic memory. Semantic memory and episodic memory are mostly overlapping in time, and possibly, they share similar neural networks. Emotional memory is also based on our past memory. Therefore, it is designed in an adjoining way to episodic memory. The illustration also indicates that present memory relies on past memory, and that there possibly are links from past memory to future memory and creativity. As stated by Bergson (1920), the consideration of future events requires past and present memories. As stated in the text, the time space, which we call hypertime space, requires a physical time period of approximately 0.5 s. In this illustration, the functioning of working memory and implicit memory are not yet incorporated. Modified and extended from Başar and Düzgün (2015).

The physiology of the brain is anchored to important functions that also act in an integrative way: "Perception" and "Sensation".

Several research scientists defined sensation as perception by means of sense organs. The philosopher Henri Bergson indicates "pure perception" as the simple reaction coming from sense organs. On the contrary, the perception can be defined according to Helmholtz as the integration of pure sensation with unconscious inference. Gustav Jung has analyzed the problem of consciousness by "integrating intuition," "sensation," "feeling," and "thinking." For Jung, expressing sensation is equivalent to perception. As feeling presently, psychologists prefer the expression "emotion".

According to Freud (Brown, 1914), the mind can be divided into three different levels:

1. The conscious mind includes everything that we are aware of. Examples are sensations, perception, and memory. A major part of this includes our memory, which is not always part of consciousness but can be retrieved easily at any time and brought into our awareness. Freud called this the "preconscious".
2. The preconscious mind is the state of the mind that represents memory in the common sense. While we are not consciously aware of this information at any given time, we can retrieve it and pull it into consciousness when needed.
3. The unconscious mind is a reservoir of feelings, thoughts, urges, and memories that exists outside of our conscious awareness. Başar and Düzgün (2015) used the expression "Hypermemory" instead of "memories". The concept of hypermemory is illustrated in **Figure 1**.

Most of the contents of the unconscious are unacceptable or unpleasant, such as feelings of pain, anxiety, or conflict. According to Freud, the unconscious continues to influence our behavior and experience, even though we are unaware of these underlying influences.

Freud likened these three levels of mind to an iceberg. The top of the iceberg that you can see above the water represents the conscious mind. The part of the iceberg that is submerged below the water but is still visible is the "preconscious". The bulk of the iceberg lies unseen beneath the waterline and represents the unconscious (see **Figure 2**).

View of Herman Helmholtz

Helmholtz (1867/1910) discussed the psychological effects of visual perception.

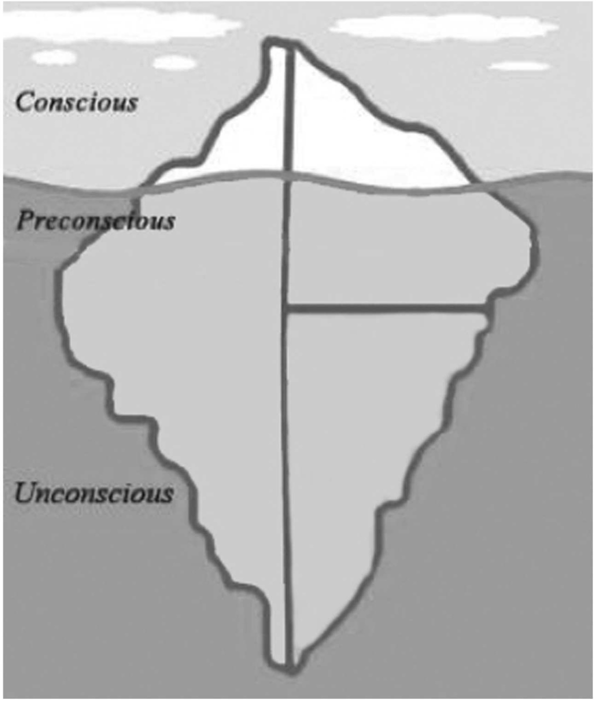


FIGURE 2 | Explanation see in the text.

According to Helmholtz, the formation of visual impressions is achieved primarily by unconscious judgments, the results of which "can never once be elevated to the plane of conscious judgments" and thus "lack the purifying and scrutinizing work of conscious thinking."

As the process is spontaneous and automatic, we are unable to account for just how we arrived at our judgments. Through our eyes, we necessarily *perceive things as real*, for the results of the unconscious conclusions are interpretations that "are urged on our consciousness (Helmholtz, 1867/1910)."

Definitions of Gibson's and Gregory's Perception Concepts

In order to define sensations and perceptions to different processing:

Gibson (1966) has proposed a "direct" theory of perception, which is a bottom–up theory. On the contrary, Gregory (1970) has proposed a constructive undirected theory of perception expressed as "top–down" theory.

Figure 3 is a tentative presentation of neuronal networks to explain bottom–up and top–down processing. Sensations are

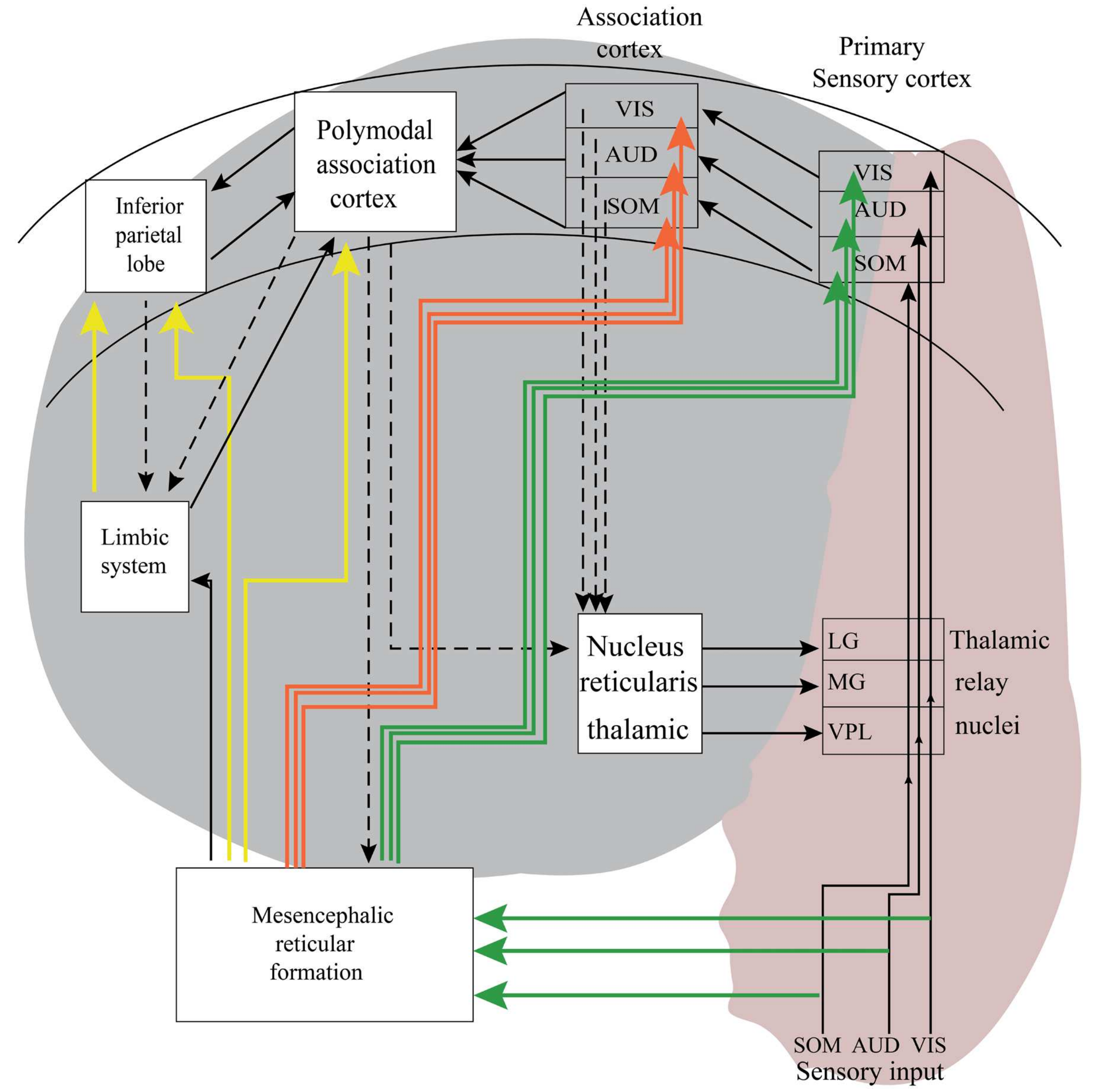


FIGURE 3 | The pink area in this schematic description of neural pathway is involved with bottom–up processing. The gray areas in this illustration are tentative neural pathways, in which complex top–down processing may take place. As indicated with arrows during top–down processing, there are several possible loops generating recurrent reverberations. According to Fessard (1961), it is impossible to predict exactly in which areas the signal transmission ends. The exact duration of transmission is not possible, and this case is dependent on cognitive states. It is also possible to express that the results are probabilistic and also include the unconsciousness inference of Helmholtz.

elicited in the peripheral organs of the body, such as eyes, ears, and skin receptors. If we track visual information, the electrical impulses that are elicited in retina reach the occipital cortex (visual cortex), and travel through the visual pathway. These signals coming from the retina reach the visual cortex over thalamus (LG). This is a simple way of bottom–up processing. In real life, the subject's cell receives pure sensory signals as a light stimulus. In general, more complex visual patterns contain elements from the history of subjects are presented. In **Figure 3**, there are also connections from the reticular formation and connections to the limbic system. Further, there are links from the visual cortex to other association areas of the brain. In the top–down processing, the signal flow in the brain hits several neuronal populations. This is a more complex signal processing, which usually ends in no predictable areas of the brain; therefore, this is a complex signal processing which shows uncertain reactions (see also Fessard, 1961).

WORKING MEMORY: ODDBALL P300-PARADIGM AND CONSCIENT TARGET RESPONSES

In performing many complex tasks, it is necessary to hold information in temporary storage to complete the task. The system used for this is referred to as "working memory"(Baddeley, 1996). Working memory is the temporary ad hoc activation of an extensive network of short- or long-term perceptual component of that network would be, as any other perceptual memory, retrievable and expandable by a new stimulus or experience. Fuster (2013) states that working memory has the same cortical substrate as the kind of short-term memory traditionally considered the gateway to long-term memory.

The component analysis by means of event-related oscillations provide a real advantage over conventional ERP analysis as, for example, the results of cross-modality measurements demonstrate: in occipital areas, auditory stimulation does not evoke 10 Hz responses, although an ERP is measured upon visual stimulation. This demonstrates the dependence of the 10-Hz response on visual perception. Accordingly, the spatial resolution of ERPs is highly increased.

As to the delta response in the auditory P300 paradigm, a distributed highly enhanced response in the whole cortex is observed (Başar-Eroğlu et al., 1992), the maxima being in frontal and parietal areas.

Figure 4 illustrates visual evoked potentials with non-target and target responses as grand average of nine subjects. The delta responses filtered in the 1–3 Hz frequency window have largest values upon target stimuli. For further explanations related to delta responses we refer to (Schürmann et al., 1995).

Working Memory in Mild Cognitive Impairment (MCI) and Alzheimer's Disease (AD)

As the most common cause of dementias, Alzheimer's disease (AD) is one of the most intensively researched subjects in neuroscience. AD is the most common and devastating cause of degenerative dementias and is generally found in people aged over 65. Approximately 24 million people worldwide have dementia, of which two-thirds are due to AD (Ferri et al., 2005). Clinical signs of AD are characterized by progressive cognitive deterioration, together with declining activities in daily life, and by neuropsychiatric symptoms.

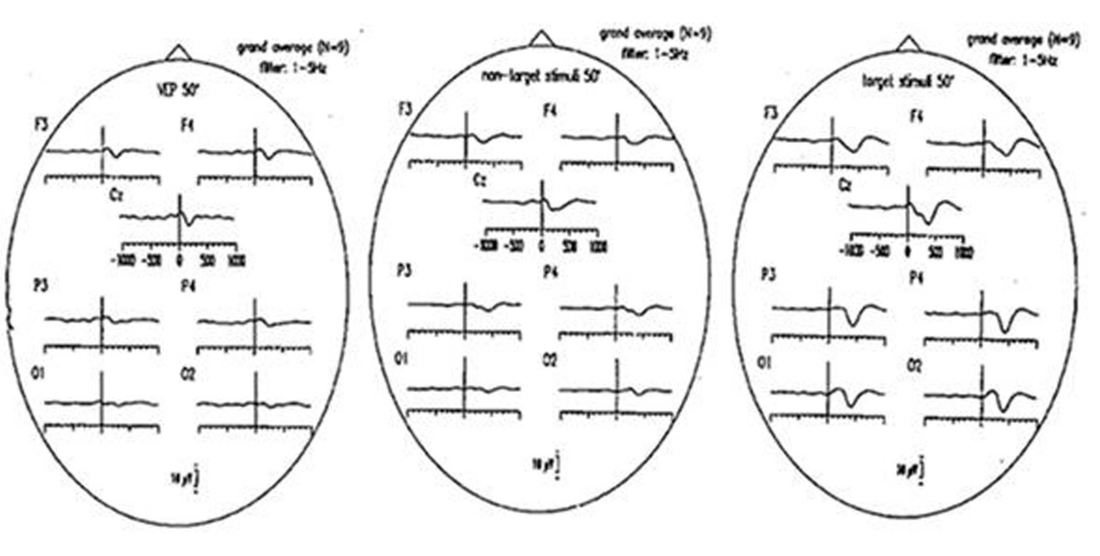


FIGURE 4 | Grand average ERPs (50 checkerboards; *N* = 9 subjects), filtered 1–5 Hz, respectively. (Left) Visual evoked potentials (VEP), **(middle)** responses to non-target stimuli; **(right)** responses to target stimuli.

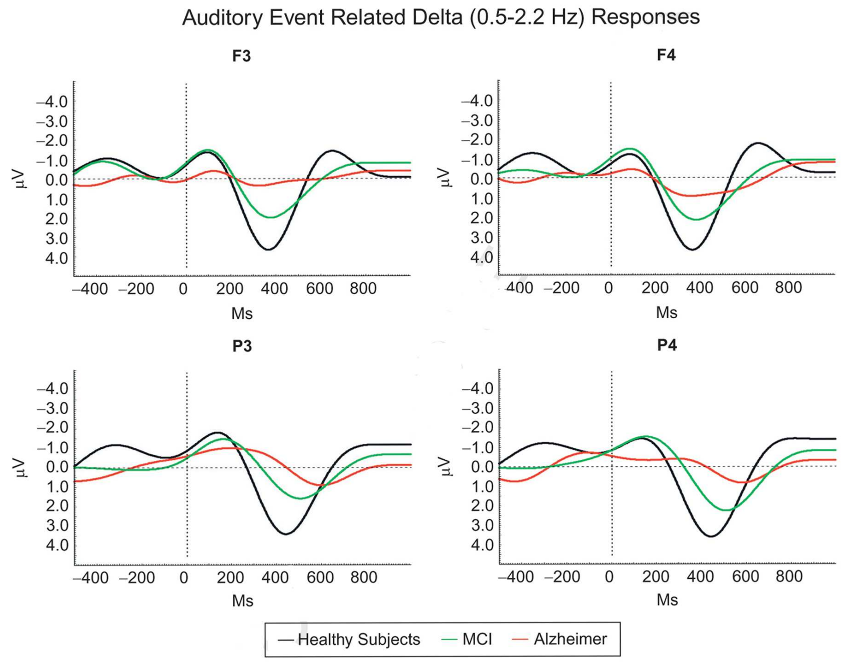


FIGURE 5 | Mild cognitive impairment (MCI) and Alzheimer's disease (AD) continuity is prominent in auditory event-related delta oscillatory activity, showing gradually decreasing delta amplitudes and delayed delta peak responses among healthy subjects, MCI, and mild Alzheimer subjects (Modified from Yener et al., 2011).

Delta responses of AD patients are almost completely abolished, whereas in mild cognitive impairment (MCI) patients, delta responses are gradually decreased.

As seen **Figure 5**, in AD patients that are not capable of performing cognitive functions, the late delta response is gone. The explanation is as follows:

The top–down processing does not take place or it is attenuated. It is further noted that AD-diseased frontal lobes or hippocampus have lesions. The anatomical evidence indicates that the cognitive circuitry is partially out of function.

HOW CAN WE FIND A NEURAL TISSUE SHOWING ONLY SENSORY RESPONSES (PHYLETIC RESPONSES)?

We are in search of a biological model that does not perform a cognitive function but does perform a pure sensation. We have performed measurements with the isolated ganglion of *Helix pomatia* (snail), which responds with increased electrical activity upon electric stimulation. This is possibly due to the machinery of electrical susceptibility, which can be recorded *in vitro*. Do we have another possibility to find an isolated tissue that responds to sensory stimulation? Such a model was published by Schütt et al. (1999), who measured responses of a pedal ganglion of *H. pomatia* (snail) to different odorous stimulations.

Figure 6 illustrates the snail ganglion, which is composed of several almost identical neurons.

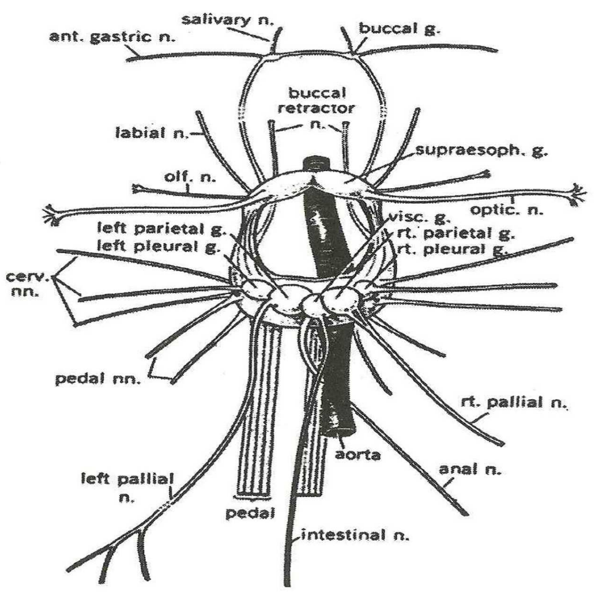


FIGURE 6 | The central nervous system and major nerves of a young *Helix aspersa* (Modified from Courtesy G. Kerkut).

Ganglia of *Helix* are composed from approximately 2000 neurons.

Figure 7 shows different reaction patterns to an odorous stimulation. The bottom–up aspect of the stimulation is power

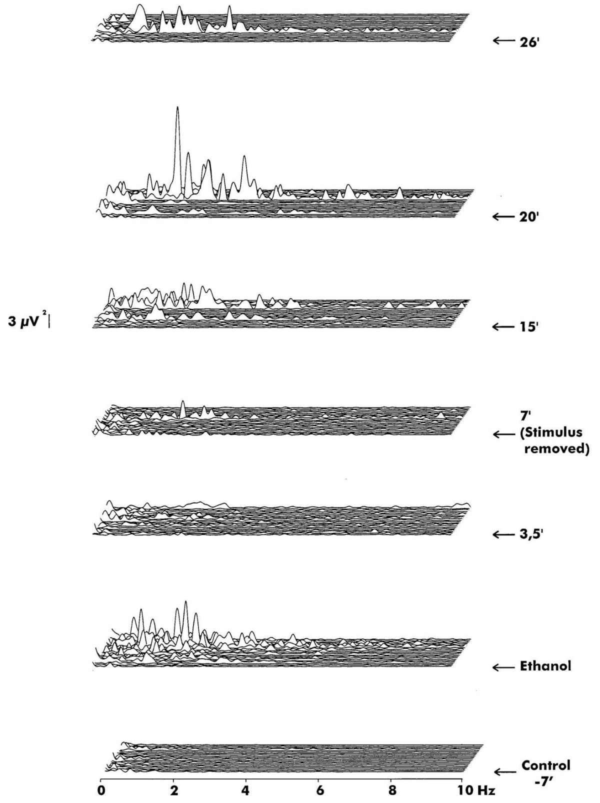


FIGURE 7 | The power spectra of recordings from the corresponding experiment. Each panel consists of 20 single epochs (204.8 s). From bottom: control (prestimulus), immediately after application of ethanol and the following recordings at different times. The stimulus was removed at 7 min after stimulus onset. Note that fluctuation with multiple frequency components reaching well into 10 Hz and beyond was induced shortly after ethanol, most strongly in the 0.5–5 Hz range (panel 2). Then it subsided to occasional small bursts (panels 3 and 4). Firing continued intermittently even after removal of stimulus (panels 5–7).

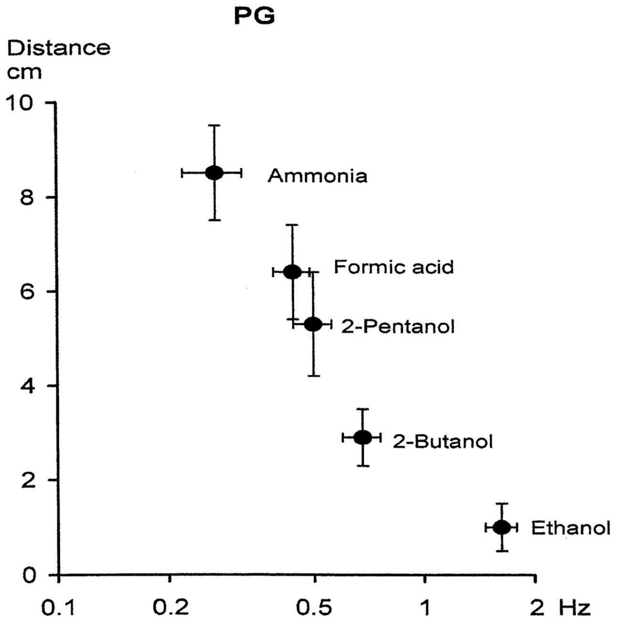


FIGURE 8 | Relationship between degree of aversion and frequency of odorant-induced activity of the *Helix* pedal ganglion. The bars represent 95% confidence limits for the means. Note that there was a linear relationship between degree of averseness and peak power frequency of odorant-induced FP activity in the *Helix* ganglion. This diagram suggests: (a) order of averseness appears to reflect that of molecular affinity: the stronger in affinity an odorant, the more aversive it is to the snail; (b) order of affinity is correlated to peak power frequency of induced FP: the stronger in affinity an odorant, the lower the odorant-induced frequency; (c) the more aversive an odorant, the lower the peak power frequency; (d) extrapolation of the curve to the abcissa yields a value of ~2.5 Hz. This is the area for an appetitive odorant (ethanol) for the snail. These curves suggest that the odorant-specific low frequencies may, together with other frequency components, be involved in identification, classification, and discrimination of odorants or their classes and that the most crucial FP activities relevant for this function may exist below ~2.5 Hz (Modified from Schütt et al., 1999).

spectral activity under control. In the second step, ethanol stimulation activates the *Helix* ganglion, and power spectra show great responsiveness that declines following removal of stimulation.

The increase in the concentration of ethanol elicits higher power spectral peaks in the delta frequency ranges, similar to the reaction of ethanol. The formic acid also elicits high amplitude reactions in the delta frequency range similar to the reaction of formic acid. Phentonol also induces higher spectral responses in the delta frequency range. **Figure 8** illustrates the effects of distance of *Helix* delta response to various odor stimuli.

The most ample odor, ammonia, elicits the highest delta responses. This is a crucial point. According to our experience, human control subjects are most excited with the odor of ammonia, which almost always elicits a very unpleasant sensation. This comparison demonstrates the great similarity between sensations of human beings and of isolated unconscious (preconscious) *Helix* ganglion. Possibly, it can be assumed that the delta responses are manifestations of preconsciousness and consciousness reactions in living beings. Is it possible to say that the transition from unconsciousness states is performed in the delta frequency range? We confine our attention to this odorous stimulation and describe delta frequency range. However, we tentatively pronounce that the slow oscillations possibly can solve a pivot function during transition to the different states of consciousness.

HOW TO MEASURE PERCEPTION AT THE HUMAN HEARING THRESHOLD?

In this section, we confine our attention to another type of problem. We consider a paradigm that encompasses measurement of a process to detect sensations and judge sensations:

How to measure perception at the human hearing threshold model? We report here measurements performed by Parnefjord and Başar (1999) by application of auditory stimuli at the hearing threshold level. The subjects sat in a dimly illuminated and 120 dB isolated room and were exposed to auditory stimuli at different tone levels. The measurements have started with 80 dB signals and were step-wise decreased first to 20 dB level and finally to the hearing threshold level. In **Figure 8**, the unfiltered evoked potentials and filtered evoked potentials in the delta frequency range are presented. The measurements of Parnefjord and Başar (1999) have shown that at the threshold level of all oscillatory responses besides delta response disappeared (**Figure 9**).

At the hearing threshold level, the remaining response is the delta response. These facts are also seen in the unfiltered evoked potentials. These authors have interpreted that the responses are correlated to simple sensation, threshold perception, and decision making. In other words, in comparison to experiments on *H. pomatia,* the response is correlated with cognitive tasks. However, the cognitive task does not contain working memory task, which is performed in the target response during the P300 experiment, (see Parnefjord, 1996).

Figure 9 shows the results of experiment with single subjects in different frequency windows for the wide band evoked potentials at 80 dB and at the hearing threshold level.

Figure 10 shows the following: At the hearing threshold level the remaining responses has only a delta oscillatory component. Other higher frequency response oscillations are gone.

AUDITORY EVOKED OSCILLATIONS AND COHERENCES DURING SLOW-WAVE SLEEP OF THE CAT

During slow-wave sleep, evoked spectra, and the connectivity between intracranial structures of the cat brain are also changed (see **Figure 11**). The spatial coherency is presented in **Figure 12**, in which coherences between these five structures of the brain are shown. Here again, the coherence functions reach maximal strength in the delta frequency range, dominantly in deeper structures as reticular formation, hippocampus, and thalamus.

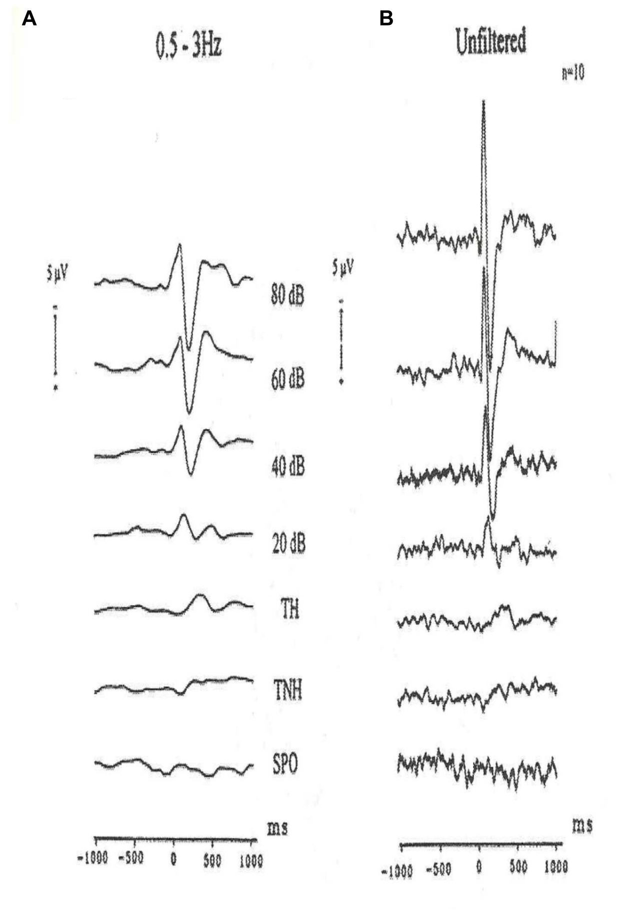


FIGURE 9 | Grand average auditory evoked potentials recordings of ten subjects (vertex). (A) 0.5–3 Hz digitally filtered AEPs to different stimulation intensities. TH (tone heard) and TNH (tone not heard) are subgroups of the threshold experiments. SPO are the spontaneous activity experiments. **(B)** The same potentials are reproduced unfiltered. Negativity is upward.

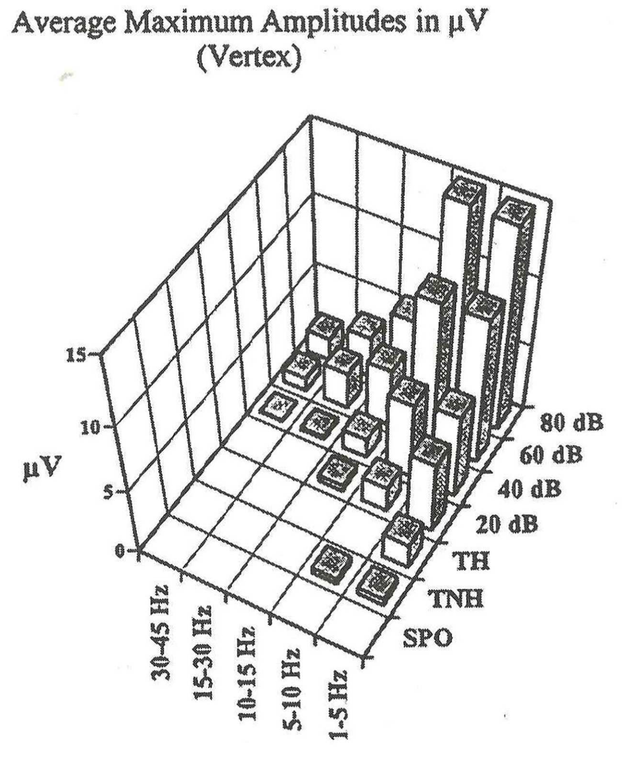


FIGURE 10 | Grand average peak-to-peak AEP amplitudes of ten subjects (vertex recording). Below are the absolute values, together with standard deviations, above a histogram representation. TH; TNH: both subgroups of threshold stimulation. SPO = spontaneous activity experiments. The evoked potentials to the different stimulation intensities have been digitally filtered in different frequency ranges. The resulting peak-to-peak amplitudes of the digitally filtered activities in different frequency ranges. The resulting peak-to-peak amplitudes of the digitally filtered activities are presented.

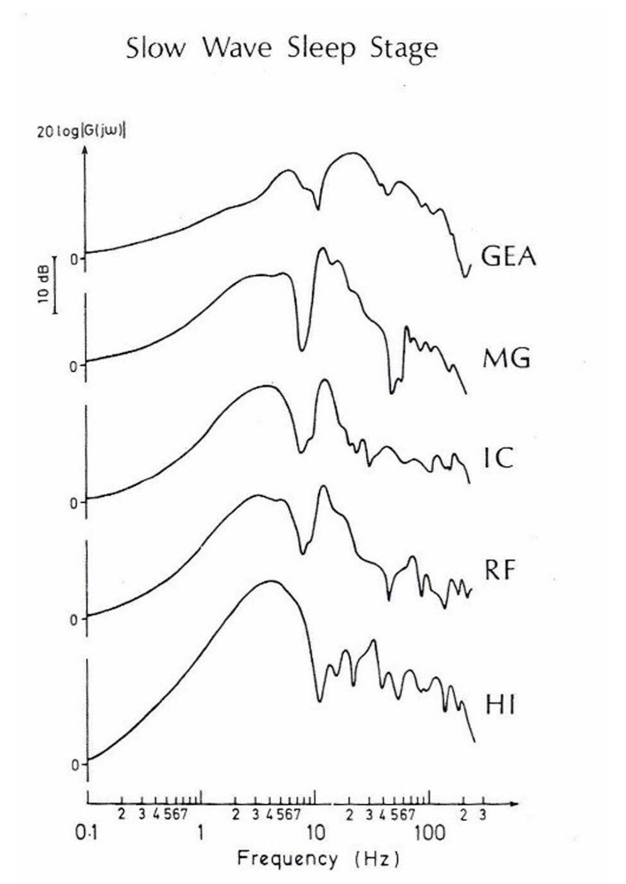


FIGURE 11 | A typical set of amplitude-frequency characteristics obtained by means of the frequency response analyze method and using the selectively averaged evoked potentials (SAEPs), which were simultaneously recorded from different brain nuclei of the cat during the slow-wave sleep stage. Direct computer plottings. Along the abscissa is the input frequency in logarithmic scale, along the ordinate is the potential amplitude, | G(jω)| , in decibels. The curves are normalized in such a way that the amplitude at 0 Hz is equal to 1 (or 20 log 1 = 0). (Modified from Başar et al., 1979).

The simple interpretation of coherence results show that during SWS sleep, the connectivity is performed mostly in the delta frequency channel. In other words, the cat in the deep sleep stage does not perform conscious hearing, but the electrical processes further take place dominantly in the delta frequency range.

A SYNOPSIS BASED ON MULTIPLICITY OF PERCEPTS

(1) In the present comparative study, we described five major experimental designs in order to establish a progressive synopsis for the understanding of perception and perception-related concepts. Further, as we have analyzed in previous sections, it is not possible to isolate the concept of perception without combination of attention, memory, and learning processes. Further, the concept of unconscious inference by H. Helmholtz should be considered as an important enrichment to episodic memory.

In **Figures 7** and **8,** we explained experiments with an isolated pedal ganglion of *Helix* and assumed that this ganglion *in vitro* is a tissue that is in a preconscious state, but not in a conscious state since this odorous stimulation is not processed as odor. This ganglion behaves as an odor sensitive organ that is not able to perform cognitive functions, or in other words, not able to transfer the odor sensation to a conscious process. The ganglion does not have the ability to consciously differentiate the degree of odor sensations or the quality of sensations, but certainly the ganglion *in vitro* can differentiate odors without being aware of this basic function, which could be also denoted as phyletic memory. We have to emphasize that this tissue is an example showing only *phyletic memory,* and this memory cannot be influenced or altered by unconscious inference.

(2) After comparing different experimental designs shown in **Figure 10**, we can experimentally differentiate several perceptions and "perception-action cycles". Delta response as a major component. We also emphasize that delta oscillations are correlated at least with two different functions:

Delta in the first 200 ms is a bottom–up process. Beside this, the late delta response in the oddball experiment is a cognitive perception upon increased attention in a working memory process. It is also mentioned that, vice versa, delta component is participating in two different types of processes.

In **Figure 13**, we also compared evoked potentials and event-related potentials upon extended stimuli in multiple areas. It is known that one of the major components of the oddball P300 response is "delta response" measured 400 ms following target stimulations. In the recordings of sensory-evoked potentials, upon simple light stimulation, no late delta response is observed. In the first 200 ms, a preliminary delta response is recorded upon simple light. Here it is noted that cognitive processing requires a longer time period. Further, the absence of the delta response in the simple evoked potentials indicates almost a pure bottom–up response in the first 200 ms. In other words, by comparing the delta response in simple evoked potential and in the target response, it is possible to separate the top–down and bottom–up components (**Figure 3**). The next step: will it be possible to find a situation or an experimental procedure to further support this statement?

(3) Third step (in **Figure 13**) involves an experimental design to measure the oscillatory responses at the human hearing threshold level. In this experiment, the subject attentively hears an auditory stimulation at the threshold level, and the subject is involved with a hearing process and following the hearing, he has performed the cognitive processes of "threshold perception" based also on a "decision making process". Accordingly, auditory delta response in this experiment highly differs from the delta response of the

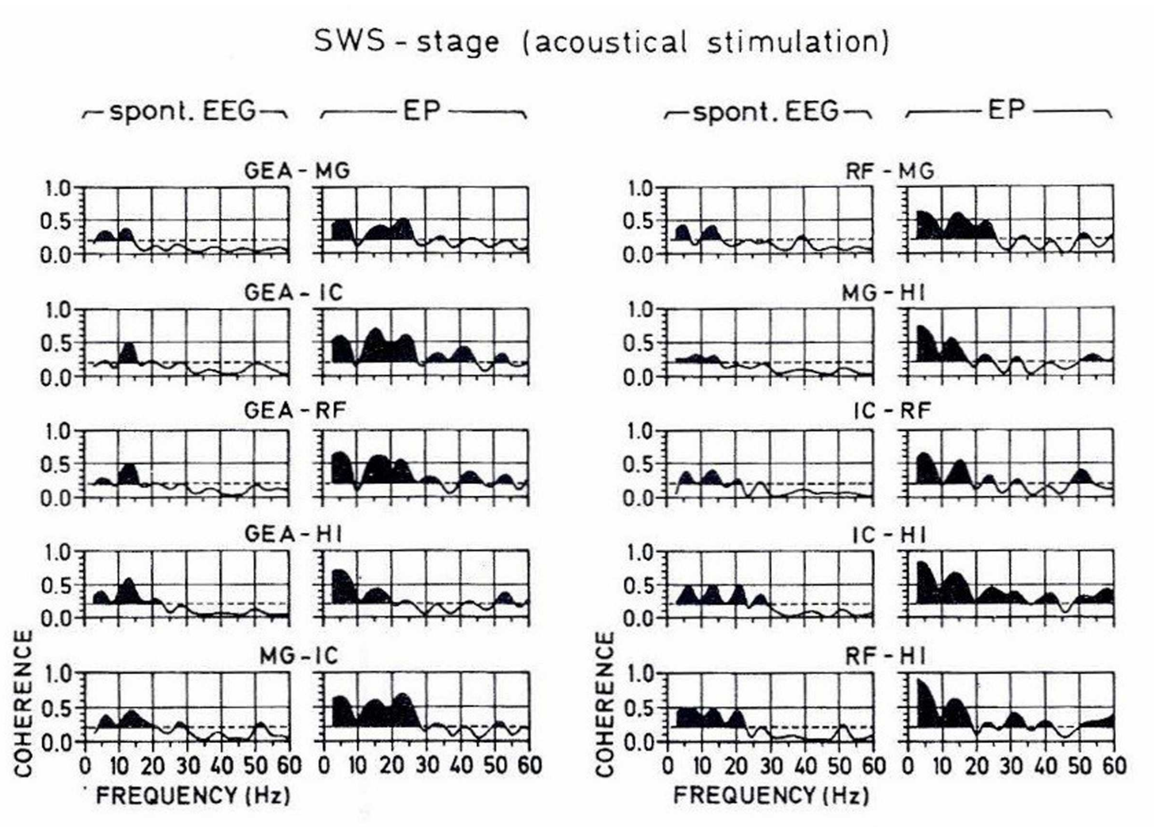


FIGURE 12 | A typical set of coherence functions computed from the spontaneous and evoked potentials of all possible pairings of the studied brain structures during the slow-wave sleep stage. The scale is indicated at the bottom. Along the abscissa is the frequency from 0 to 60 Hz, along the ordinate is the coherency between 0 and 1. The horizontal broken lines indicate the significance level, which is 0.2 for all plots. The area under the coherence functions is darkened only if the curve surpasses this level. In order to facilitate a comparison between the coherence values computed from spontaneous and evoked parts of the EEG, the respective coherence functions are presented adjacently as couples for all the pairings of recording electrodes (From Başar et al., 1979).

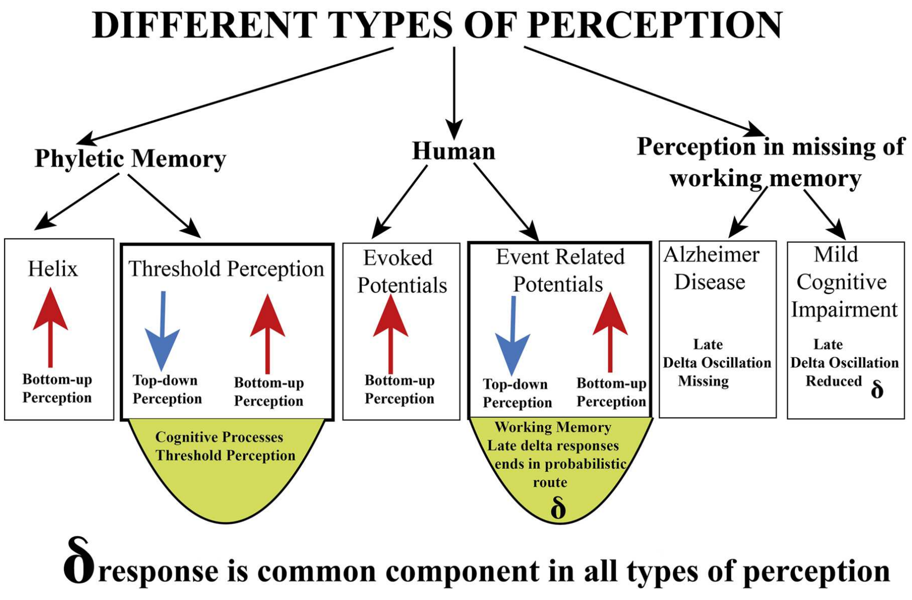


FIGURE 13 | Delta responses in different types of perception.

Helix ganglion to odorous stimuli. The subject is conscious about the heard tones whereas the *Helix* delta response is most probably a "preconscious" process. Further, the auditory delta response at the hearing threshold is result of an activation of bottom–up and top–down networks (see **Figure 3**). We also compare sensory delta responses and target delta responses in MCI and AD patients.

Delta response of the isolated *H. pomatia* ganglion can be considered as a preconscious (unconscious) state-response.

(4) Delta response in slow-wave sleep. During SWS, we observed phase-locked delta oscillations and increased delta connectivity. This delta-response is a manifestation of sensory processing in an unconscious state (deep sleep). The auditory stimulation is not consciously heard by sleeping animals. The hearing threshold is very high in SWS sleep.

CONCLUSION

In conclusion, we emphasize the following points:

(1) Delta response is recorded during P300 Oddball paradigm as response to target stimuli, indicating the manifestation of working memory. The conscious observation of light stimuli is absent in AD patients. Accordingly, conscious detection of cognitive stimulation disappeared.
(2) Non-conscious *H. pomatia* Pedal Ganglion is also able to manifest a delta power increased to different odorous stimulation.
(3) At the human threshold level, the heard tones also manifest with a dominant delta response. Other frequency responses are absent.
(4) During slow-wave sleep, ample acoustic stimuli of 80 dB elicits a large delta response. Further, the delta coherency between long distance structures of the cat brain shows highly increased delta components. In other words, during deep sleep, the delta response is existent, although the cats cannot consciously hear the auditory stimuli.

According to this observations, the following concept could be tentatively addressed:

"Does the delta response manifest a transition through the gates between conscious, preconscious, and unconscious states?

In this report, we used the modifications of percepts at elementary level. As we have previously described for other EEG frequency components are also important for generation of percepts. However, for this report, we used only delta activity at the conscious level. Descriptions of all other components cannot be described in a short paper with limited volume.

AUTHOR CONTRIBUTIONS

The authors EB and AD have jointly analyzed the outcome of earlier performed and published experiments. The comparisons and final conclusions related to transition between conscious and unconscious states were developed and written together by EB and AD.

REFERENCES

Baddeley, A. D. (1996). Exploring the Central Executive. *Q. J. Exp. Psychol.* 49A, 5–28. doi: 10.1080/713755608

Başar, E., and Düzgün, A. (2015). The brain as a working syncytium and memory as a contin-uum in a hyper timespace. Oscillations lead to a new model. *Int. J. Psychophysiol.* doi: 10.1016/j.ijpsycho.2015.02.019 [Epub ahead of print].

Başar, E., Durusan, R., Gönder, A., and Ungan, P. (1979). Combined dynamics of EEG and evoked potentials. II. Studies of simultaneously recorded EEG-EPograms in the auditory pathway, reticular formation, and hippocampus of the cat brain during sleep. *Biol. Cybernetics* 34, 21–30. doi: 10.1007/BF00336853

Başar-Eroğlu, C., Başar, E., Demiralp, T., and Schürmann, M. (1992). P300-response: possible psychophysiological correlates in delta and theta frequency channels. A review. *Int. J. Psychophysiol.* 13, 161–179. doi: 10.1016/0167-8760(92)90055-G

Bergson, H. (1920). *Mind-energy. Lectures and Essays*. London: Greenwood Press.

Brown, W. (1914). Freud's theory of unconscious. *Br. J. Psychol.* 6, 265–280. doi: 10.1111/j.2044-8295.1914.tb00095.x

Ferri, C. P., Prince, M., Brayne, C., Brodaty, H., Fratiglioni, L., Ganguli, M., et al. (2005). Alzheimer's disease. International global prevalence of dementia, a Delphi consensus study. *Lancet* 366, 2112–2117. doi: 10.1016/S0140-6736(05)67889-0

Fessard, A. (1961). "The role of neuronal networks," in *Sensory Communications within the Brain*, ed. W. A. Rosenblith (Cambridge, MA: MIT Press).

Fuster, J. M. (2013). *The Neuroscience of Freedom and Creative*. Cambridge: Our Predictive Brain. doi: 10.1017/CBO9781139226691

Gibson, J. J. (1966). *The Senses Considered as Perceptual Systems*. Boston: Houghton Mifflin.

Gregory, R. (1970). *The Intelligent Eye*. London: Weidenfeld and Nicolson.

Helmholtz, H. L. (1867/1910). "Handbuch der physiologischen Optik Leipzig: L. Voss. Reprinted, with extensive commentary," in *Handbuch der physiologischenOptik,* 3rd Edn, eds A. Gullstrand, J. von Kries and W. Nagel (Hamburg: L. Voss), 27.

Parnefjord, R. (1996). *Untersuchungenzur Dynamik der evoziertenPotentiale an der Horschwelle*, with Dissertation, Medizinische Universitatzu Lubeck, Lubeck.

Parnefjord, R., and Başar, E. (1999). "Evoked delta oscillations on the hearing threshold," in *Brain Function and Oscillations II: Integrative Brain Function Neurophysiology and Cognitive Processes*, ed. E. Başar (Berlin: Springer-Verlag), 161–175.

Schürmann, M., Başar-Eroğlu, C., Kolev, V., and Başar, E. (1995). A new metric for analyzing single trial event related potentials (ERPs) application to human visual P300 delta response. *Neurosci. Lett.* 197, 167–170. doi: 10.1016/0304-3940(95)11912-G

Schütt, A., Bullock, T. H., and Başar, E. (1999). Odorant-induced low-frequency activities of the Helix pedal ganglion are odorant-specific and related to behaviour. *Comp. Biochem. Physiol. Part A* 124, 297–311. doi: 10.1016/S1095-6433(99)00112-9

Yener, G. G., Güntekin, B. and Başar, E. (2011). "Evoked and event related oscillations in Alzheimer's preliminary report on mild cognitive impairment," in *Proceeding of the Brain Oscillations in Cognitive Impairment and Neurotransmitters Conference/Workshop*, Istanbul, 15–16.

Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Advantages of publishing in Frontiers

OPEN ACCESS
Articles are free to read,
for greatest visibility

COLLABORATIVE PEER-REVIEW
Designed to be rigorous
– yet also collaborative,
fair and constructive

FAST PUBLICATION
Average 85 days from
submission to publication
(across all journals)

COPYRIGHT TO AUTHORS
No limit to article
distribution and re-use

TRANSPARENT
Editors and reviewers
acknowledged by name
on published articles

SUPPORT
By our Swiss-based
editorial team

IMPACT METRICS
Advanced metrics
track your article's impact

GLOBAL SPREAD
5'100'000+ monthly
article views
and downloads

LOOP RESEARCH NETWORK
Our network
increases readership
for your article

Frontiers
EPFL Innovation Park, Building I • 1015 Lausanne • Switzerland
Tel +41 21 510 17 00 • Fax +41 21 510 17 01 • info@frontiersin.org
www.frontiersin.org

Find us on