

An Integrative Theory of Visual Mentation and Spontaneous Creativity

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ABSTRACT

It has been suggested that creativity can be functionally segregated into two processes: spontaneous and deliberate. In this paper, we propose that the spontaneous aspect of creativity is enabled by the same neural simulation mechanisms that have been implicated in visual mentation (e.g. visual perception, mental imagery, mind-wandering and dreaming). This proposal is developed into an Integrative Theory that serves as the foundation for a computational model of dreaming and site-specific artwork: *A Machine that Dreams*.

Author Keywords

Dreaming; Creativity; Mental Imagery; Mind-Wandering; Perception; Default Mode Network; Generative; Simulation; Art; Neuroscience; Biopsychology

ACM Classification Keywords

J.5 [Arts And Humanities]: Fine arts; I.2.0 [Artificial Intelligence]: Cognitive simulation

INTRODUCTION

Perception does not produce a perfect replica of the world: Percepts are an amalgam of sensory information and our expectations [28]. Indeed, the visual perceptual system has often been described as a *creative process* (e.g., [13]). In this view, visual perception is the result of the construction of highly detailed impressions of our external reality that are not reducible to either the world, or the agent's expectations. The existence of constructive mechanisms in visual perception indicates that certain aspects of creativity may be rooted in ordinary mental processes (see [30]). While perception is constrained by external sensory information, mental imagery involves the construction of images in the absence of, or in conflict with, sensory information.

Dreams are meaningful simulations, however abstract, of a somewhat familiar world and may even have functional value. Dreams can be as simple as banal thoughts or images, or as complex as long recurring melodramas. They are often

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thought of as bizarre, and may include chimeric elements — fusions of multiple places or people. There are two popular biopsychological conceptions of dreaming: Dreams result from our perceptual system's attempt to make sense of random activation in sensory regions of the brain, or dreams are akin to mental imagery and are largely independent of the sensory systems. Mind-wandering (day-dreaming) and dreaming overlap in their content and involve similar modulations of cognition — e.g. the lack of self-reflective awareness. Perception is highly constrained by external stimuli while dreams occur in the absence of external stimuli. Mind-wandering is a diversion away from external stimulus toward internally generated imagery.

It has been established that creativity involves, at least, the generation of ideas or artifacts that are both novel and valuable [26, 4]. This definition of creativity is concerned with the products of a creative process, rather than the characteristics of the process itself. Both novelty and value are evaluations of ideas or artifacts in the context of their production and use. The scope of such evaluations can be relative to the life-time of the individual (*Psychological-Creativity*) or to the whole of human history (*Historical-Creativity*) [4]. The difficulty with the evaluation of both novelty and value is their context dependence; an artifact considered creative in one culture, domain or time-frame may not be in another. The importance of context makes automated evaluation in computational creativity challenging. In this work we segregate generative and evaluative modes and focus on the former.

The contributions of the present work are twofold: First, we propose an Integrative Theory of perception, dreaming, mental imagery, mind-wandering, and spontaneous creativity wherein all of these phenomena exploit overlapping mechanisms of simulation. These mechanisms are enabled by a common set of perceptually-oriented associative representations. Second, our theoretical proposal serves as the foundation of a computational model and artwork that constructs images from sensory components through creative processes manifest during each of three states: (1) perception, (2) mind-wandering and (3) dreaming.

Our computational model, the *Dreaming Machine*, serves three major purposes in itself. First, it formalizes the Integrative Theory and provides a site for the evaluation and refinement of that theory. Second, it is also an artwork contextualized in a series of generative site-specific installations [6]. Thirdly, the manifestation of the theory in an artwork broad-

ens discourse on creativity and visual mentation beyond traditional scientific contexts.

BACKGROUND

Visual aspects of perception, mental imagery, mind-wandering and dreaming are all modes of thought that are experienced visually. Accordingly, in the present paper, we will refer to these modes, collectively, as *visual mentation*. This section of the paper discusses biopsychological theories of both visual mentation and spontaneous creativity. It will be shown that these theories all share certain characteristics that serve as the basis of the Integrative Theory, to be presented in a later section. In terms of creativity, we discuss Dietrich's [8] proposal for a neurobiological basis of creativity. In terms of dreaming, we describe two major theories: (1) Hobson's [11] proposal that dream experiences are the result of random activations of sensory and perceptual regions of the brain, and (2) Nir and Tononi's [20] proposal that dreams are more closely related to mental imagery than perception. Kosslyn's [16] theory of mental imagery compliments Nir and Tononi's proposal. Finally, we present Domhoff's [9] proposal that dreaming and mind-wandering recruit overlapping components of the *default mode network* (DMN).

Two Creative Processes

Dietrich [8] proposes a neurocognitive framework where creativity is considered *integral* [8] to the study of cognition, is a *fundamental* [8] aspect of human activity and is grounded in ordinary mental processes. The consideration of creativity as a general aspect of cognition implies that the study of creativity may provide insights into other mental processes, such as dreaming and mind-wandering, and vice versa.

As illustrated in Figure 1, Dietrich's framework divides the brain into two major functional regions: (1) The temporal, occipital and parietal lobes of the cortex (TOP), shaded in grey in Figure 1, hold high-level and long-term representations of sensory information and enable spontaneous creativity. (2) The prefrontal cortex (PFC) accesses these representations during deliberate creativity and is implicated in executive functions such as self-awareness, planning, decision making, working memory and attention. In Dietrich's framework, the PFC provides the evaluative mechanisms that shape and/or filter novel thoughts, thereby deeming them creative or not. In particular, working memory, which involves the PFC, is important for creative cognition as it provides a facility for the manipulation of representations — required for flexible shifts in cognition and access to the TOP.

Dietrich proposes two major modes of creative insight: (1) a *spontaneous* mode, which results from associative activity within the TOP, and (2) a *deliberate* mode, which results from goal-oriented manipulation and refinement of ideas in the PFC. These modes are not meant to be exclusive; creative practises involve both.

The spontaneous mode generates insights that may be *random, unfiltered, and bizarre* [8] and are promoted to the PFC for evaluation. This mode is enabled by cognitive processes that are unconscious and therefore unconstrained by the bottleneck of conscious thought. Dietrich considers spontaneous creativity as only a *starting point* because “[i]nnumerous insights turn out to be incorrect, incomplete, or trivial, so judging which insights to pursue and which to discard requires

prefrontal cortex integration” [8]. For an idea to be considered creative, it must undergo evaluation in terms of novelty and value. If it is lacking in either area, then it is refined through prefrontal interactions with other brain regions.

The generation of ideas is not limited to the spontaneous mode, but can also occur in the deliberate mode where insights are “structured, rational, and conform. . . to internalized values and belief systems” and are limited to established conceptual structures (*preconceived mental paradigms* [8]). An individual engaged in the spontaneous mode requires only a diverse sensory experience to generate novelty, but knowledge and skill, developed over years, are required for fruitful creativity in the deliberate mode. Creativity requires a balance between both deliberate and spontaneous modes, and yet “[s]ome of the most brilliant ideas in the history of science. . .” [8] appear to arise from the spontaneous mode.

The mechanisms of creativity described in this section highlight a division of labour in creative thinking. The spontaneous mode is education independent, unconscious, and has extreme generative potential. Unfortunately, this mode may generate insights that cannot be considered creative, due to their lack of utility or novelty. The deliberate mode is conscious, reasoned, systematic, and pulls information from TOP as well as being fed the results of the spontaneous mode. The deliberate mode depends on a body of skill and knowledge to determine utility and novelty.

Spontaneous Creativity and Dreaming

Dietrich makes an explicit connection between the attributes of the spontaneous mode and dreaming. He notes that during REM sleep the PFC is less active, leading to a deficit in self-reflection, awareness of time, volition, abstract thinking, active decision making, and focused attention. These deficits are also characteristic of many dreams, as will be discussed later. Dietrich's proposal that spontaneous creativity results from associative activation within TOP is a key component of the Integrative Theory. His assertion that dreaming and spontaneous creativity show a lack of prefrontal activity supports a possible overlap of constituent mechanisms. Dietrich even suggests that dreams could be an ultimate form of spontaneous creativity: “. . . dreaming might be regarded as the most extreme form of the spontaneous processing mode and can give rise to insights that are difficult to come by during normal waking consciousness” [8].

Sleep, Dreaming and Mental Imagery

A description of dreaming is incomplete without an overview of sleep, a behavioural state displayed by many mammals and birds [23] that is modulated by a circadian clock entrained by any one of many zeitgebers (e.g. visual brightness and social interaction) [19]. Sleep is usually divided into stages. Sleep begins with *descending stage 1*, which is quite similar to waking, in terms of the electroencephalogram (EEG), and is characterized by high frequency and low amplitude EEG. Sleep then descends through increasing stages (2 to 4). Each subsequent stage is characterized by an EEG with greater amplitude and lower frequency, with stage 4 being characterized by the lowest frequency and the highest amplitude waves (delta waves). Once a sleeping individual has progressed through sleep stages 1 to 4, the progression reverses back through the stages. An entire cycle typically lasts approximately 90 minutes. The sleeper spends the rest of the night oscillating be-

tween sleep stages. However, an important change occurs as a typical night of sleep unfolds: The first half of a night's sleep contains much more *slow-wave sleep* (SWS; stages 3 and 4), whereas the second half contains much more stages 1 and 2 sleep.

The initial stage 1 episode is relatively uneventful, but thereafter each stage 1 (*emergent stage 1*) tends to be accompanied by a variety of other physiological changes including loss of muscle tone and *rapid eye movements* (REMs). Accordingly, emergent stage 1 is more commonly known as *REM sleep* [1], and the other sleep stages are commonly referred to as *Non-REM (NREM) sleep*.

Dreaming can occur during any stage of sleep. Nevertheless, there are some general conclusions that can be made about the distribution of dream content over a typical night of sleep. Early on in the night, narrative dreams are more likely to be reported when awaking subjects during REM sleep. By contrast, waking a subject from NREM sleep early in the night dreams are more likely to be reported as "... short, thought-like, less vivid, less visual and more conceptual, less motorically animated, under greater volitional control, more plausible, more concerned with current issues, less emotional and less pleasant" [20]. As the night progresses, narrative dreams are more likely to be reported, irrespective of the stage from which they are woken.

In this section, we describe two popular biospsychological theories of dreaming, as well as their links to perception and creativity. First, Hobson's *Activation, Input/Output Gating, and Modulation* (AIM) [11] theory proposes that dreams are the result of high-level cognitive processes attempting to make sense of random activations of early sensory regions. The resulting perceptual experience is a functional *simulation* of reality. Second, Nir and Tononi [20] propose that dreams are more similar to mental imagery than to perception, and are not dependent on the random activation of early sensory regions.

Activation, Input/Output Gating, and Modulation

Hobson's AIM model [11] is the successor to the *activation-synthesis* theory [12]. AIM proposes that, during early development, dreams are important for the emergence of the *protoself* (a precursor to the sense of self); dreams provide a "... virtual reality model of the world that is of functional use to the development and maintenance of waking consciousness" [11]. This *virtual reality* is a free-running simulator of possible sensory and motor scenarios. The protoself develops to *account for and take responsibility* for unconscious cognitive operations that respond to both external (during waking) and internal (during dreaming) stimuli. It is presumed that the protoself develops through the incremental growth of attentional and control mechanisms in the PFC that structure reflex and associative activity in TOP. AIM constitutes a state-space of three dimensions of dream properties:

Activation: During waking and REM sleep, the whole brain is highly activated and during NREM sleep it is minimally activated. Activation during REM sleep is due to waveforms (PGO waves) that originate in the pontine brainstem and cause activation of the various sensory systems, in particular vision; thus, this activation is not driven by external stimuli. This activation is then interpreted by the same mechanisms as external perception, pictured by the top black arrow

in Figure 1 (left).

Input-output gating: During REM sleep, PGO waves begin and the reticular activating system disconnects the body from the brain, resulting in temporary paralysis (output) and a loss of most sensory afferents (input).

Modulation refers to the change of neurotransmitter levels: During REM sleep, aminergic neurons are inhibited and cholinergic neurons are activated. This results in an attenuated influence of the PFC, which accounts for the poor recall of dream material and a lack of self-awareness.

According to Hobson's proposal, perceptual functions transform relatively random brain activity into a cohesive, and even narrative, subjective experience. According to this conception, a dream is the output of our sensory and perceptual functions. Hobson [11] provides no discussion of the structure of these PGO waves, nor exactly what is meant by 'randomness.' Hobson's theory also depends on a strong correlation between REM sleep and dreaming, yet this correlation is weaker than was once believed [24]. Hobson himself acknowledges this inconsistency: "[a]n important caveat is that although the distinctive features of dream consciousness... are maximally correlated with REM sleep, they are also found — to a limited degree — in NREM sleep..." [11]. Aspects of Hobson's theory that are relevant to computational modelling include the degree to which external stimuli effect sensory regions (*gating*), as well as the degree of *activation*.

Dreams as Mental Imagery

Nir and Tononi [20] provide an alternate account of dreaming that is rooted in a criticism of Hobson's theory. Central to their criticism, as mentioned above, is the fact that Hobson's theory depends on a correlation between REM sleep and dreams.

In contrast to Hobson, Nir and Tononi consider dreams as comparable to mental imagery [20]; that is, in their conception, dreaming depends more on the forebrain rather than on the brainstem-created PGO waves. Central to their argument is the observation that damage to portions of the PFC (as occurred to victims of prefrontal lobotomy), led to total cessation of dreaming in 70–90% of subjects. Those same individuals also exhibited a "...lack of initiative, curiosity and fantasy in waking life" [20]. In general, it seems that damage to perceptual areas leads to deficits in both mental imagery and dreaming.

Analysis of children's dreams shows that the younger the child, the more simplistic the dream content. Their dream reports contain "...no characters that move, no social interactions, little feeling, and...do not include the dreamer as an active character. There are also no autobiographic, [or] episodic memories..." [20]. Nir and Tononi provide a compelling argument that dreaming may in fact be more closely related to mental imagery than perception, and therefore that the neural mechanisms implicated in mental imagery are also in play during dreaming.

Nir and Tononi note that there is at least one significant difference between dreaming and mental imagery: "...while imagining, one is aware that the images are internally generated (preserved reflective thought)" [20]. The lack of comparable reflective thought in dreams could be explained by the relative lack of activation in the PFC during sleep.

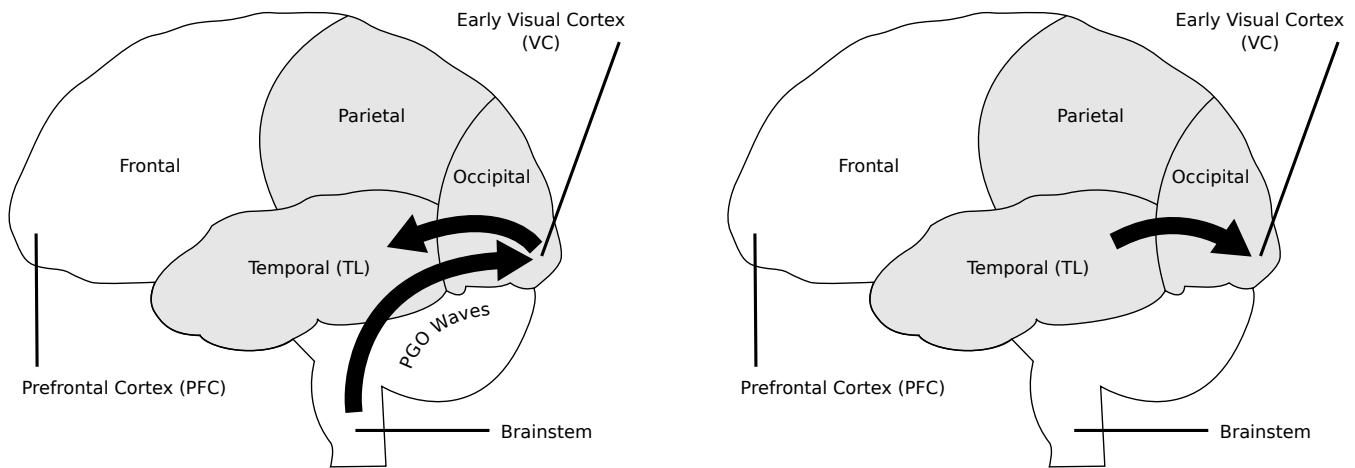


Figure 1. Information flow during: (1) dreaming, according to Hobson (left), and (2) mental imagery, according to Kosslyn (right).

What Causes Activation During Dreaming?

A significant issue with Nir and Tononi's account is the absence of a specified cause of the activation during dreaming. Hobson neatly solves this problem with PGO waves. According to Nir and Tononi, activation could be due to intentional prefrontal control during REM sleep, but where self-awareness is inhibited — dreams are the same as mental images except they are not recognized as being intentional. Alternatively, the activation is not due to the PFC but is rather due to endogenous associative activations of TOP — those same mechanisms implicated in Dietrich's conception of spontaneous creativity [8]. Nir and Tononi also make reference to a possible role of the DMN, due to the partial overlap of brain activity during REM and DMN structures. This latter proposal will be returned to later.

Whether dreams are similar to perception or mental imagery, there appears to be a consensus that dreams are the result of activation of high-level perceptual representations (presumably in TOP). However, two things are in dispute: (1) whether there is intentional control and (2) whether there is functional role for the early sensory regions. Still, the most relevant aspects of Nir and Tononi's theory include the consideration of a possible role of the DMN, and the idea that dreams are enabled by the same mechanisms as mental imagery.

Perceptual Anticipation Theory

Kosslyn's [16] *Perceptual Anticipation Theory* of mental imagery proposes a functional role of the early visual system: "... mental images arise when one anticipates perceiving an object or scene so strongly that a depictive representation of the stimulus is created in [the] early visual cortex" [16]. According to Kosslyn, the patterns that define these mental images are long-term visual representations encoded in the temporal lobe (TL). Unlike the retinotopic arrangement of the visual cortex (VC), where adjacent cortical columns tend to correspond to adjacent patches of the contralateral visual field, these representations are non-topographical. They can only be decoded through constructive activation: "... image generation is not simply 'playing backward' stored information, but rather is necessarily a constructive activity" [16]. This constructive activation is pictured as a black arrow in Figure 1

(right).

Once the images are decoded they are perceived using the same mechanisms as external perception, not pictured in Figure 1 (right). These imagined reconstructions can be used to further conceptualize images propositionally or linguistically. Activation of the VC is expected to occur when the task requires: (1) a higher resolution representation than is afforded by the linguistic system, (2) a specific example of such an object — not a prototype of a class and (3) the inspection of object-centric properties (eg. colour and size) — not spatial relations (eg. position).

Shared Representations in Perception and Imagery

Kosslyn's account is specifically focused on the early visual system and assumes that long term visual memory is located in the TL. According to the *Emergent Memory Account* (EMA) of Graham et al. [10], the TL is not simply a storehouse for memory, but is specialized for high-level visual representations that are used in both memory and perception. Under this conception, visual mental imagery may involve much of the TL and would not depend on the early visual system. If the TL is activated in memory and perception, and stores high-level representations of perceptual information, then a functional role of the early VC during imagery is unclear. Kosslyn supports the stance that mental images are decoded in the early VC through studies that directly relate mental images and visual external perception. These studies have assumed that the similar constraints in mental imagery and perception are due to shared involvement of the early VC.

Summary of Sleep, Dreaming and Mental Imagery

Hobson theorizes that dreams involve mechanisms similar to external perception, while Nir and Tononi consider that dreams involve mechanisms that more closely overlap with those of mental imagery. Both theories posit a key role for high-level perceptual representations. Kosslyn proposes that mental imagery exploits the same functions as external perception. Thus we can consider dreaming, mental imagery and external perception as highly related and that they may share neural mechanisms, including a role for TL-based perceptual representations. The mechanisms that cause the activation of

these TL-based representations is, as yet, unclear. However, consideration of the DMN may resolve the activation source.

The Default Mode Network and Dreaming

As noted by Domhoff [9], current research on dreaming certainly emphasizes a continuity between dreaming and waking cognition. Although notions of dreams as bizarre narratives have captured our collective imagination for a significant period, even early dream content studies from the 1970s indicated that *bizarre* dreams are exceptional; most dream reports are "... clear, coherent, and detailed account[s] of a realistic situation involving the dreamer and other people caught up in very ordinary activities..." (Domhoff [9] citing Snyder [25]). A consideration of dream content as *ordinary* and the inclusion of terms describing meta-awareness (eg. *contemplate, decide, realize, ponder*, etc.) in dream reports supports a continuity between dreaming and waking consciousness. Studies of relaxed waking (such as mind-wandering) in laboratory settings have shown that these states can be "... as fragmented or unusual as dreams" [9]. Physical impossibilities and disconnected thoughts are present in both dreaming and in mind-wandering.

The DMN is a set of neural structures that are highly active when the subject is resting (during mind-wandering) and are inhibited during goal-oriented activity. Domhoff [9] proposes that dreams result from an activation of a subset of the DMN that "... is active when the mind is wandering, daydreaming, or simulating past or future events." Regions that are associated with the DMN include the "... medial prefrontal cortex, the anterior cingulate cortex, and the temporoparietal junction...", which are also implicated in dreaming. Not all neural structures implicated in the DMN are highly active during REM and NREM sleep. Domhoff proposes this lack of activation during dreaming is because sensation, locomotion and executive functions are *not necessary* during dreaming.

Domhoff proposes that DMN activity serves as a bridge between waking and dreaming consciousness: Just before the onset of sleep, the DMN is likely to be active due to a relaxed state. The shift from waking relaxed thought to sleep is rapid and DMN activity continues into NREM. The central component of Domhoff's proposal [9] is the correlation between dreams and the DMN, which provides a link to mind-wandering. This link is compelling as the characteristics of mind-wandering (in particular the lack of volition and self-reflection, and the presence of associative thought) resemble those of both dreaming and spontaneous creativity, as proposed by Dietrich [8].

Domhoff's argument that the DMN may be implicated in dreaming, and therefore that mind-wandering and dreaming may be enabled by shared mechanisms, is compelling. It resolves the colloquial relation between dreaming and daydreaming (mind-wandering) with biospsychological evidence. If it is accepted, then "... dreams can be seen as a unique and more fully developed form of mind wandering, and therefore as the *quintessential cognitive simulation* [emphasis added]" [9]. The key aspects of Domhoff's proposal are that dreams and mind-wandering may easily transition from one to the other, and are enabled by overlapping components of the DMN.

Dreaming, Mind-wandering and Prediction

The general overlap of activity during dreaming and mind-wandering indicates a possible overlap in function. Both Hobson [11] and Schooler [22] describe dreams and mind-wandering as having a predictive function. In both cases, our attention shifts inward, and we show impairments in executive function. For example, during mind-wandering the DMN is most active when subjects are not aware of their mind wandering (e.g. a lack of meta-awareness) [7]. The DMN is also active when people engage in "personal planning concerning the future" [9], supporting the notion that simulation is common to both dreams and mind-wandering.

Summary of Theories

This section covered significant territory, so we will summarize the key aspects of the reviewed theories:

1. Dietrich proposes that creativity can be functionally segregated into two modes: (1) *Deliberate* creativity results from intentional creative effort and is correlated with prefrontal activity, while *spontaneous* creativity results from associative activations in the TOP that are promoted to PFC for evaluation and refinement.
2. Hobson proposes that dreams are the result of our perceptual mechanisms attempting to make sense of the random activation of sensory regions during REM sleep. REM sleep is characterized by: a similar degree of activation to waking, a disconnection of the brain from the rest of the body, and a suppression of feed-back mechanisms. Dreams are considered functional simulations.
3. Nir and Tononi propose that dreaming is less like perception and more like mental imagery.
4. Kosslyn proposes that mental images and external perception are subject to similar constraints. Encoded representations in the TL are rendered in early VC and perceived by the same mechanisms as external perception.
5. Domhoff proposes that dreams are enabled by the same mechanisms that support mind-wandering, specifically a subset of the DMN. Dreams result from the activation of perceptual information and provide the *quintessential* mechanism of simulation, thus extending the function and phenomenology of mind-wandering.

The following two sections describe the details of the contributions of this research. First, the Integrative Theory is described, after which its companion computational and artistic realization is summarized.

INTEGRATIVE THEORY

The previous sections include discussions and a selection of key points of theory regarding possible relations between visual aspects of external perception, mental imagery, mind-wandering, dreaming (visual mentation) and spontaneous creativity. This section unifies theoretical points made in the previous section into a proposal for an Integrative Theory that serves to inform the computational model. Three central hypotheses are made, whose support is described in the following paragraphs:

1. Visual mentation and spontaneous creativity involve the activation of high-level TL representations of sensory information [11, 20, 16, 10].

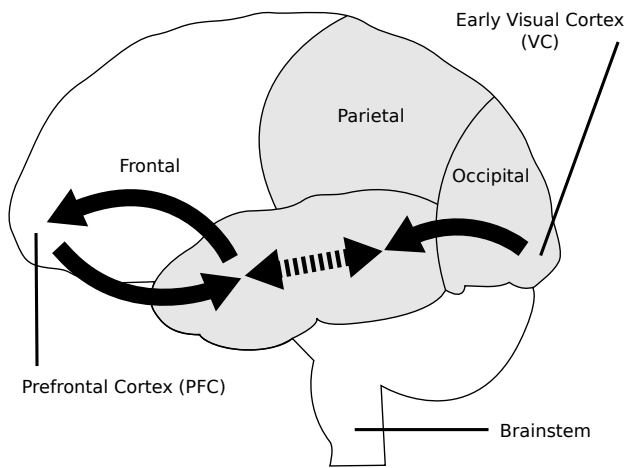


Figure 2. The Integrative Theory unifies external perception, mental imagery, mind-wandering, dreaming and spontaneous creativity.

2. The phenomenological experience of visual mentation is due to activity within the TL [18, 17, 3].
3. Simulation is a key attribute of visual mentation and spontaneous creativity [22, 11, 9].

There is a fairly clear consensus regarding Hypothesis 1, as all theories predict some functional role of representations in the TL — be they encoded or explicit, conceptual or perceptual. For Dietrich, cortical representations in the TL are constantly being activated through associative mechanisms that are unconstrained by evaluation. These representations are promoted to prefrontal systems for constraint and evaluation. Hobson [11] notes that TL epileptics experience seizures commonly characterized as *dreamy states*. He also contends that dreams are perceived using the same mechanisms as external perception, which implies a degree of TL processing. Nir and Tononi [20] link dreaming with mental imagery as the activation of representations implicated in mental imagery. For Kosslyn [16], the TL is the storehouse for visual representations, and overlaps with Hobson in proposing a functional role of early VC. Graham et al. [10] link perception and memory and propose that TL damage leads to deficits in memory recall and perception. The representations implied in mental imagery are shared with external perception, and therefore presumably also in dreams. Domhoff [9] and Nir and Tononi [20] cite studies that show that damage to the TL, in particular at the temporo-occipito-parieto junction, leads to deficit in *initiative, curiosity and fantasy*, and even the total cessation of dreaming.

While Hypothesis 1 is fairly well established, the cause of the activation of TL representations is disputed. In order to arrive at a cohesive conception, some aspects of the discussed theories must be rejected. We identify three explanations: TL activation results from (1) early VC activation, as in external perception (Hobson, Kosslyn), (2) endogenous (self-regulating) TL activation (Dietrich), or (3) prefrontal control (Domhoff, Nir and Tononi).

The functional role of early VC in mental imagery and dreaming is key to the theories proposed by Hobson and Kosslyn. The relation between mental imagery and external perception

has been a topic of study since the 1970s and often conflate image recall (the recall of a particular visual memory), imagery of a memorized image (mental imagery of a learned visual image) and novel imagery (the construction of a new mental image not in memory nor perception). In 1978 it was shown by Podgorny [21] that mental images and perceptual images could be directly compared. The experiment involved the registration of a perceptual grid with a mental image such that the subject reported whether a particular perceptual cell was occupied by a portion of the mental image. This study, and others like it, have shown that perception and mental imagery share similar constraints, including field of view [18], scan time [14] and resolution [15].

In Marzi et al.'s study [18], a subject with damage to the early VC had no perceptual ability in one visual quadrant but was able to construct whole mental images. Most interestingly, perceptual constraints in the blind quadrant (reaction time effects dependent on location of stimulus in the field of view) did not apply to mental images as in normal subjects. This indicates that the early VC modulates mental images but is not functionally required. Recent fMRI decoding studies have allowed a more detailed examination of the role of the early VC in mental imagery.

Decoding studies have attempted to correlate patterns of brain activity with particular visual stimuli. An analysis of brain activity can predict which visual stimulus a subject is currently viewing. Lee et al. [17] demonstrated that activity in the VC and TL could predict an image either seen or imagined (after memorization) by a subject. During imagery, they found a high degree of correlated activation relevant to the memorized stimulus in the TL, and low stimulus-correlated activity in the VC. During perception, they found the opposite pattern, greater stimulus-correlated activation in the VC and less stimulus-correlated activation in the TL. As suggested by Lee [17], visual mental imagery and visual perception are different network dynamics of the same system of temporal representations. The relatively low activity in the VC during imagery has been repeated in other studies (e.g. [3]). These studies indicate that the activation of representations in the TL are due to dynamics independent of early VC.

As dreams occur in the absence of PGO waves, we can conclude that the experience of images in the mind is likely due to activity in the TL (Hypothesis 2) that is independent of the early VC. We are then left with two possibilities: activation of representations is due to intentional control from the PFC, or it is due to endogenous activation of the TL. The intentional control of representations in the TL is analogous to Dietrich's [8] notion of *deliberate* creativity, while endogenous TL activation resembles *spontaneous* creativity. These two options need not be resolved due to the diversity of phenomena in the proposed Integrative Theory: mental imagery results from intentional functions of the PFC, external perception is highly dependent on external stimuli impacting the early VC, and mind-wandering, dreaming and spontaneous creativity are the result of associative endogenous activation.

Figure 2 depicts the causal patterns of three modes of visual mentation: External perception is the result of exogenous activation of early VC which in turn causes the activation of TL representations. Mental imagery is the result of PFC control mechanisms causing activations of TL representations, which result in the experience of mental images. Visual aspects of

spontaneous creativity, dreaming and mind-wandering are all the result of endogenous activation (the dashed line) within the TL, which is modulated by varying degrees of control initiated by the PFC.

The exploitation of shared TL representations in visual mentation and spontaneous creativity means that one cognitive process (e.g. dreaming) could be impacted by and impact another (e.g. external perception). For example, it has been shown that waking perception in the hours before sleep has a significant effect on dream content [27]. Antti Revonsuo describes the continuity of perception and dreaming: “We are dreaming all the time, its just that our dreams are shaped by our perceptions when awake, and therefore constrained” [29]. We can then consider the differences between the various modes of visual mentation and spontaneous creativity as due to the same mechanisms except with differing dynamics.

Hypothesis 3 states that a key functional attribute shared between visual mentation and spontaneous creativity is simulation. Considering the constructive aspects of external perception, we can conceive of our experience of the world as a simulation that is highly constrained by sensory information. By contrast, mental imagery is a simulation relatively unconstrained by external stimuli, but intentionally controlled and constrained by task demands. Dreaming and mind-wandering result from these same mechanisms of simulation, but operating independently of task demands or sensory-oriented controls. These free-running simulations may have diverse functions, for example “... autobiographical predictions necessary to successfully navigate the complex social world” [22], and the development of self [11]. The particular brain systems that enable all of these simulations are possibly a subset of the DMN; which has been implicated in dreaming and mind-wandering. Domhoff characterizes dreams as the *quintessential cognitive simulation* [9] because they are a *more fully developed form of mind wandering*. We can then consider dreams as a free-running manifestation of those very same mechanisms that enable spontaneous creativity.

In summary, the Integrative Theory proposes that visual mentation and spontaneous creativity are a set of closely related phenomena that all exploit the same mechanisms of representation and simulation. The next section discusses the computational model that arises from the Integrative Theory.

COMPUTATIONAL MODEL: A MACHINE THAT DREAMS

The Integrative Theory is the foundation for the computational model and artwork *Dreaming Machine*. While the Integrative Theory includes a role for evaluative mechanisms, the computational model formalizes a subset of the theory, centrally focused on generative mechanisms corresponding to spontaneous creativity. The model is summarized here and further details of the system are available in a companion paper [5]. The key features of the proposed theory manifested in the computational model include: representations shared by perception, mind-wandering and dreaming, and the explicit continuity of those three states. The work follows in a series of site-specific artworks (*Context Machines* [6]) that collect visual material from their contexts of installation in the service of generative image-making processes.

Computational modelling provides a compelling framework for the theorization and critique of biopsychological conceptions. The implementation of these ideas in formal language

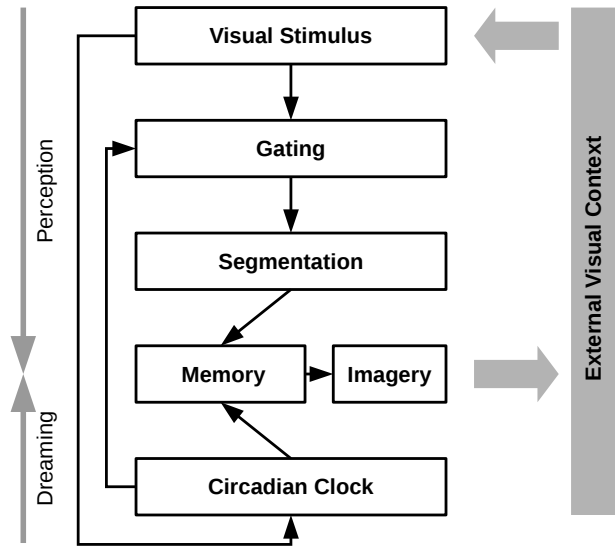


Figure 3. Overview of the Computational Model — Dreaming Machine

requires sufficient detail as to force the specification of tacit aspects. The computational model is a working system that learns from its visual perceptual experience during the day and generates hypothetical (simulated) images constructed from collected perceptual material while ‘dreaming’ at night — all in the absence of evaluative functions associated with the PFC. As an artwork, the model is meant for long-term installation in a public setting in order to be exposed to as much variety of visual material as possible.

The system manifests three modes of visual mentation where images are constructed from associative memory representations of visual information, as pictured in Figure 4: (1) Perception is the construction of perceptual images as constrained by external visual stimulus. (2) Dreaming is the result of spontaneous creativity where generated images are the result of activations of memory representations which are initiated by recent waking perception. The propagation of associative activation results in hypothetical images. (3) Mind-wandering is a fusion of perception and dreaming modes where a static perceptual image (habituated stimulus) emphasizes the associative (dream-like) propagation of activation, resulting in images that are both perceptual and dream-like. In all three modes, associative activation is propagated and modulation causes shifts between the exogenous and endogenous activation of percepts. The system’s habituation to the external environment, and a circadian clock, cause the transition between these contiguous modes. The spontaneous mode of creativity, as manifest in dreaming and mind-wandering modes, is the result of associations based on simple features, and therefore lacks the richness and complexity of human spontaneous creativity. The dreams and mind-wanderings of the system are meant to appear similar to those of children and perhaps non-human animals. The design of the computational model manifests the following key attributes informed by the theories described in previous sections:

- The degree to which perceptual content is activated by external stimuli is controlled by a gating system [11].
- Dreaming and mind-wandering are enabled by the associative activation of shared representations (percepts) constructed by perceptual processes [8].
- External perception, mind-wandering and dreaming are contiguous processes modulated by varying degrees of influence from exogenous stimuli and endogenous activation. That degree of influence is controlled by a circadian clock entrained by the luminosity of the external environment [11].
- The system is a partial artificial agent that contains no analogue of the PFC, nor the limbic system and therefore lacks executive control or emotional tone.

Modules

The relations between modules are depicted in Figure 3. For a more detailed technical overview of the system see [5].

VISUAL STIMULUS provides 1920×1080 pixel video images (captured by an immobile camera) to SEGMENTATION via GATING. The neurobiological analogue of the visual stimulus is the retina-geniculate-striate system, which includes the VC. The mean luminosity of images entrains the CIRCADIAN CLOCK.

GATING controls the degree to which VISUAL STIMULUS causes activations in MEMORY, which is determined by the state of the CIRCADIAN CLOCK. The neurobiological analogue of the gating function are the brainstem nuclei in the reticular activating system and the thalamus.

SEGMENTATION separates the foreground from the background and further breaks the background into contiguous colour regions. These regions are used by MEMORY to generate percepts of the external world. The neurobiological analogue of this function are processes in the TL.

MEMORY is the core of the system, and corresponds to the TOP in biological terms. It is the structure that holds the associative representations used in spontaneous creativity. MEMORY clusters segmented regions such that an object seen in subsequent frames is stored as a single representation. Percepts are atoms of long-term visual memory (analogous to the TL representations discussed in the Integrative Theory) and are the material that are the basis of external perception, dreaming and mind-wandering. All percepts are ordinarily sorted according to their features — position in frame, position in time, area, and mean colour. For each dimension of each feature (the position in frame is an xy pair, while colour is represented by the three CIE Luv channels) there is a graphical model that represents associative links. These FEATURE LISTS correspond to the associative structure of representations in the TL.

Each percept may propagate its activation (initiated by clustering) to its two most similar neighbours. This propagation corresponds to associative activation and the resulting pattern manifests unconstrained simulation (the construction of images that resemble sensory information). For each propagation, the degree of activation decays or is amplified, depending on the state of the CIRCADIAN CLOCK, which represents the day-night cycle. During perception, activation

decays for each propagation. During dreaming and mind-wandering, propagations oscillate between decay and amplification where activated percepts decrease or increase the activation of their neighbours. When propagation reaches the ends of the FEATURE LISTS, or the activating percept is re-activated by its nearest neighbour, activation is propagated to the nearest neighbour in another FEATURE LIST (along another dimension). This shift in dimension supports continuous endogenous associative activation. The selection of which dimension to propagate is determined by the PROMINENT FEATURE of the activating percept. The PROMINENT FEATURE of percept A is the feature that makes A stand out most from other percepts. These associative propagations are the basis of external perception, mind-wandering and dreaming modes, which will be discussed in the next section.

The system also exhibits habituation, as percepts that have been activated are subsequently more difficult to activate — the greater the repetition of a stimulus, the weaker the response. This allows percepts in VISUAL STIMULUS that are constant over time to fade from IMAGERY. While a percept is not being activated, its degree of habituation gradually recovers.

CIRCADIAN CLOCK is an oscillator whose period is entrained by the day-night cycle of light in the environment, manifested in the luminosity of VISUAL STIMULUS. The clock registers the onset of day and night and modulates GATING and the propagation of activation in MEMORY. The neurobiological analogue of this circadian clock is the suprachiasmatic nucleus of the hypothalamus.

IMAGERY presents those percepts in MEMORY with sufficient activation on a 1920×1080 display. The degree of activation determines the degree of opacity of the presented percept. IMAGERY is a window into the current state of activation of MEMORY. What is seen in IMAGERY is analogous to what insights would be promoted into working memory in the PFC, according to Dietrich's framework [8].

Cognitive Modes

The particular mode of the system is determined by the CIRCADIAN CLOCK that both modulates the degree of GATING and the propagation of activation in MEMORY.

During PERCEPTION, associative activations decay with each propagation. The strongest activations are those initial activations caused by perceptual clustering. As percepts corresponding to the current stimulus are most active, IMAGERY is composed of percepts that correspond to the current stimulus and therefore resembles the image captured by the camera — a simulation of perceptual information. With a lack of habituation, this image would appear similar to the camera image, as pictured in Figure 4 (far left). It is presumed that the majority of VISUAL STIMULUS surface area will remain static (background) and will therefore become increasingly habituated to. This would result in the greater activation of novel percepts that would be presented with greater opacity in IMAGERY, as pictured in Figure 4 (middle left). Associative propagations are constant, but due to the decay of activation and continuous external stimuli, these weaker activations are drowned out, and not promoted to IMAGERY. This corresponds to Dietrich's conception that spontaneous and associative activations in TOP happen continuously, but are not always promoted to conscious awareness.

Visual Stimulus

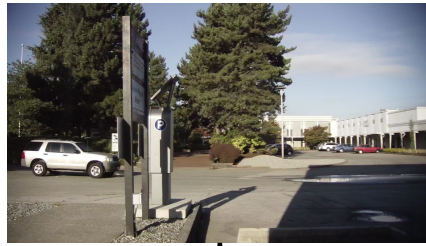


Figure 4. Depiction of VISUAL STIMULUS and corresponding IMAGERY in external perception, mind-wandering and dreaming modes. These images were produced during an exhibition of a prototype of *Dreaming Machine #3*. © Benjamin D. R. Bogart

DREAMING occurs when the latent activation from perception initiates further propagation, while exogenous activations are reduced via GATING. A dream sequence begins during in a state of habituated perception. The CIRCADIAN CLOCK modulates the propagation of activation such that weak activations are initially amplified, rather than decayed, as in external perception. Once the sum activation of all percepts crosses an upper threshold, then propagations once again decay. The ebb and flow of activation resembles the shifts between REM and NREM sleep. During the REM-like state, many percepts are activated to a high degree — resulting in the IMAGERY being dense with percepts, as in Figure 4 (far right). During the NREM-like state, the low activation results in few percepts presented on IMAGERY, or presented at extremely low opacity.

MIND-WANDERING results when highly static external stimuli lead to a high degree of habituation and therefore little activation, the same perceptual state that occurs before a dream is initiated. Mind-wandering is a fusion of perception and dreaming where GATING is open, but activation propagates as during dreaming where activations are amplified during propagation. The result is that percepts are activated both exogenously and endogenously and both internally and externally generated imagery appear, as pictured in Figure 4 (middle right).

FUTURE WORK AND CONCLUSION

The current computational model of simulation is limited to the construction of visual images, but the mechanisms outlined here could be applied in other modalities. Future development will emphasize the simulation aspect of dreams over the associative mechanisms described in this paper. Under the view of generation as simulation, perceptual priming is due to the prediction that a particular percept will occur next. Predictions are learned from perceptual experience and exploited

in visual mentation and creativity. Dreams would still be the result of an unconstrained simulator, but images would result from a predictor that unfolds learned causal chains of perceptual information. Additionally, we will examine Barsalou's theory of Perceptual symbol systems [2], which describes concepts as simulators that recruit perceptually oriented representations on the fly, for the purpose of integrating it with the Integrative Theory proposed in this paper.

Theories of visual mentation provide compelling frameworks for the consideration of cognitive mechanisms that are implicated in creativity. The Integrative Theory considers perception, mental imagery, mind-wandering, dreams and spontaneous creativity as enabled by the same unconscious associative processes of simulation that are correlated with a subset of the DMN. Dreaming and mind-wandering are mechanisms of simulation that are capable of a wide range of variation in their constructive capacity. Spontaneous creativity manifested in dreams and mind-wandering is a simulator run amok in the absence of sensory information to constrain it. Dreams and creativity have the potential to manifest some of the deepest nuances of how we conceptualize and remember the world. Dreams make explicit and conscious the unconscious processes of simulation and association that are the substrate of spontaneous creativity and, perhaps, general cognition.

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